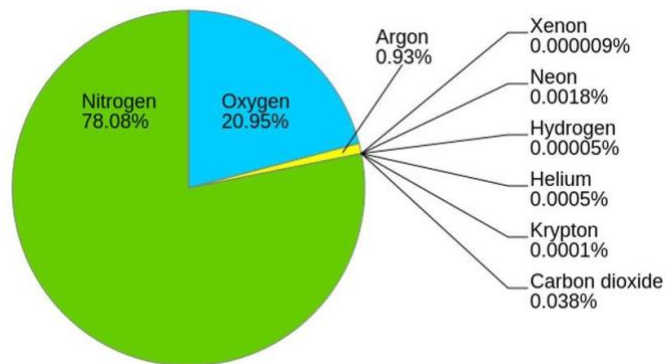


INTRODUCTION

(Definition, sources, classification and characterization of air pollutants, effects of air pollution on health, vegetation & materials, types of inversion, photochemical smog)

Air is the homogeneous mixture of gaseous substances like nitrogen, oxygen and smaller amounts of other substances, in the earth's atmosphere. Clean and dry air contains 78.09% nitrogen and 20.94% oxygen. The remaining 0.97% is composed of a gaseous mixture of carbon dioxide, helium, argon, krypton, xenon, as well as very small amounts of some other organic and inorganic gases whose amount in the atmosphere vary with time and place. Such substances enter in to the atmosphere in various quantities from both natural and human activities. Some of these substances which interact with environment to cause toxicity, disease, aesthetic distress, physiological effects or environmental decay, have been labelled as 'Pollutants'.



Definition of Air pollution

Air pollution is basically the presence of foreign substances in air. Some specific definitions are given below.

Engineer's joint council of USA defines air pollution as "Presence in the outdoor atmosphere of one or more contaminants, such as dust, fumes, gas, mist, odour, smoke, or vapour, in quantities, with characteristics, and of durations such as to be injurious to human, plant or animal life or to property, or which unreasonably interfere with the comfortable enjoyment of life and property."

According to **bureau of Indian standards, IS-4167(1966)**, "Air pollution is the presence in ambient atmosphere of substances, generally resulting from the activity of man, in sufficient concentration, present for a sufficient time and under circumstances which interfere significantly with the comfort, health or welfare of persons or with the full use or enjoyment of property."

According to the **American medical association**, "Air pollution is the excessive concentration of foreign matter in the air which adversely affects the well being of the individual or causes damage to the property."

Identification of Air pollution

The Air pollution in the surroundings can be identified by following three methods.

1. Sensory recognition

Basically, Sensory perception may provide the first indication of the presence of contaminants in the air.

At first, an air pollution problem is identified through effects on the individuals. These are

- a) Strong or unusual odours
- b) Reduction in visibility
- c) Eye irritation
- d) Acid taste in the mouth
- e) Feel of grit under foot

These effects are highly subjective phenomena and vary from one to the others

2. Physical measurement of pollution

It is often not possible to detect trace quantities of many air-borne toxic substances or the presence of radioactive matter through the senses. Their identification requires physical measurement by standard methods of sampling and analysis.

3. Effects on plants, animals and buildings

Plants, animals and buildings act to some extent as indicators of certain atmospheric impurities. Effects of air pollution can be observed on the growth of plants and health of animals. Similarly its adverse effect on buildings can also be observed.

Classification of Air pollutants

Air pollutants can be classified as follows,

1. Natural contaminants (e.g., natural fog, pollen grains, bacteria, and products of volcanic eruptions)
2. Aerosols (Particulates) (e.g., dust, smoke, mists, fog and fumes)
3. Gases and vapours

1. Natural contaminants

The first and foremost source of air pollution is nature itself. Some naturally produced contaminants are also there to pollute the air. The quantities of artificial pollutants released into the atmosphere are very less compared to the quantities of natural pollutants. However, large the natural pollutants may be they are evenly distributed over the entire globe whereas the artificial pollutants are concentrated only in highly industrialised and urbanised areas.

Among those pollen is important because of its strange properties irritating to some people. Pollen grains (usually 10 to 50 μ and also 5 to 100 μ) are the male gametophytes of gymnosperms and angiosperms and they are discharged into the atmosphere from weeds, grasses and trees. Because of wind pollination, thousands of pollen grains are liberated. These produce allergic problems in sensitive people. Many people suffer from asthma or hay fever, bronchitis, dermatitis.

The water vapours present in the atmosphere cause isonphelia, asthma and other respiratory problems and bring electrical storms.

Temperature which decreases with elevation, intensifies the chemical actions of various other air pollutants on materials. Being the main meteorological factor it plays vital role in controlling the concentrations of pollutants in atmosphere.

Usually salt particles are emanated from the sea. These sea sprays are highly corrosive, as a result structures in the coastal areas have less life. In addition, the abrasive action of sea breezes damage the building materials and art treasures.

2. Aerosols

It is a colloidal system in which finely divided solid or liquid particles of microscopic size suspended and dispersed in a gas (i.e., dispersion medium) or in atmosphere as in the case of dust, mist, fog, haze or smoke. The term Aerosol is used only when the particle is suspended in the air. The term no longer be used once the particle settles down on a solid or liquid surface. Thus that particle is an air pollutant only when it is an aerosol. However it is a nuisance both as an aerosol (visibility reduction) and as settled or deposited matter (soiling of surfaces, corrosion). Sizes of aerosol in the atmosphere range from 0.01μ to 100μ .

Dusts

These are small solid particles generated by crushing, grinding, blasting, processing or handling of organic or inorganic materials such as coal, cement or grains. Their size ranges from 1 to 200μ . They remain temporarily in suspension and do not diffuse but they settle down by the action of gravity. Most of the dusts settle on the ground as dust-fall but particles less than 5μ in size become stable substances in the atmosphere.

Smoke

Smoke consists of finely divided particles produced by incomplete combustion of fuels. It mainly consists of carbon and other combustible material. Generally the size of the particles is less than 1μ . The size of the coal smoke particles range from $0.2-0.01\mu$ and oil smoke particles from $1.0-0.03\mu$.

Mists

Mist means a light dispersion (low concentration dispersion) of minute water droplets suspended in the atmosphere. Natural mist particles formed from water vapour in the atmosphere range from $500 - 40\mu$ in size. The term mist usually applied to water droplets in air where visibility is more than 1 km.

Fog

Fog is a visible aerosol consisting of minute water droplets or ice crystals suspended in the air (i.e., dispersed phase is liquid) at or near the earth's crust. Fog implies reduction of visibility to less than 1 km. Size of the particles in natural fog ranges from $40 - 1.0\mu$. Fog can be considered a type of low-lying cloud and is heavily influenced by nearby water bodies, topography and wind conditions.

Fumes

These are very fine solid or liquid particles, 0.001 to 1μ in diameter. Often, they are metallic oxides like zinc oxide and lead oxide, formed by the condensation of vapours of solid materials. They are formed by sublimation, distillation, calcinations or molten metal processes. They may flocculate, coalesce and settle out. The word fumes is commonly used to imply unpleasant and smelling airborne effluents.

Smog

Fog intensified by smoke is called smog. It is the term derived from smoke and fog (Smoke + Fog = Smog).

This kind of visible air pollution is composed of nitrogen oxides, sulphur oxides, ozone, smoke or dirt particles and also less visible particles such as CFC's. Human made smog is derived from coal emissions, vehicular emissions, industrial emissions, forest and agricultural fires and photochemical reactions of these emissions.

3. Gases

Sulphur Dioxide

The oxides of sulphur (SO_2 or SO_3) are principal constituents of air pollution. SO_2 is a colourless gas, non flammable and non explosive. SO_2 has a suffocating odour. It is moderately soluble in water forming weak-acidic sulphurous acid (H_2SO_3). It is oxidized slowly in clean air to sulphur trioxide (SO_3). In a polluted atmosphere, SO_2 reacts photochemically and catalytically with other pollutants at normal atmospheric temperatures to form SO_3 , H_2SO_4 and salts of H_2SO_4 .

Sources: The main source of sulphur dioxide is the combustion of fuels, especially coal. Therefore its concentration in the atmosphere depends upon the sulphur content of the fuel used for heating and power generation. The other sources of SO_2 are boilers, ore processing, roasting and heating of non-metallic minerals, sulphuric acid plants, fertilizer manufacturing, plastics, paints and varnish manufacturing, oxidation towers, volcanoes, oceans and biological decay by sulphide bacteria.

Effects: SO_2 is an irritant gas, when inhaled, affects our mucous membranes, causes irritation of respiratory tract. It causes effects on breathing rate and oxygen deficit in the body leading to bronchial-spasms. SO_2 is responsible for acidity in fogs, smokes and in rains. SO_2 causes interveinal chlorotic bleaching of leaves, necrosis in interveinal areas and skeletonised leaves. SO_2 is the major pollutant which is responsible for corrosion and deterioration of different materials.

Oxides of Nitrogen

Out of seven oxides of nitrogen (N_2O , NO , NO_2 , NO_3 , N_2O_3 , N_2O_4 , N_2O_5) only nitric oxide (NO) and nitrogen dioxide (NO_2) arise from many human activities and are classified as pollutants. In atmospheric analysis they are usually reported as NO_x . N_2O (nitrous oxide) is a colourless, odourless, non toxic gas present in the natural atmosphere.

Sources: Sources of NO_x production and emission are fuel combustion from both stationary and mobile sources, heating of non-metallic minerals, processing of cement, glass refractories, Lightning and electrical storms, bacterial action in soil, fossil fuels, biomass burning etc. Major source of N_2O in the atmosphere is the biological activity of the soil and there are no anthropogenic sources.

NO (Nitric oxide) is a colourless, odourless gas produced largely by fuel combustion. It is oxidized to NO_2 through photochemical – secondary reactions. NO_2 is a reddish brown gas with irritating odour. It absorbs sunlight and initiates a series of photo chemical reactions. NO_2 is emitted by fuel combustion and nitric acid plants.

Effects: NO at low levels relatively harmless, but high concentrations cause asphyxiation and respiratory discomfort. NO_2 causes eye and nasal irritation. Long time exposure to larger concentrations of NO_2 may cause emphysema, increased susceptibility to pneumonia, lung cancer and even death.

Asphyxiation – The loss of consciousness due to the interruption of breathing. The loss of consciousness due to the extreme decrease in the concentration of oxygen in the

Carbon monoxide

Carbon monoxide is a colourless gas, odourless gas, has its origin in the incomplete combustion of carbonaceous materials. It is a toxic gas, chemically inert under normal conditions.

Sources: The chief source of CO in the atmosphere is combustion. Vehicular exhausts are the largest source of CO as the number of vehicles have increased around the world. Certain industrial operations, such as electric and blast furnaces, some petroleum refining operations, gas manufacturing plants, and coal mines are potential contributors of CO to the atmosphere.

Effects: CO reacts with the haemoglobin (Hb) of blood to give carboxy haemoglobin (COHb). This reduces the capability of blood to carry oxygen. CO inhalation causes headache, dizziness, nausea, abnormal heart beat, difficulty in breathing. At higher levels of CO, if the half of the haemoglobin is used in forming the COHb, death occurs.

Hydrogen sulphide

Hydrogen sulphide (H_2S) is a foul smelling gas. It is evolved naturally due to anaerobic biological decay processes on land, in marshes and oceans.

Sources: Major source of H_2S is Kraft pulp industry as it uses sulphide process for manufacturing of paper. Other sources of H_2S are petroleum refineries, coke-oven plants, viscose rayon plants, industrial waste disposal ponds, sewage treatment plants and some chemical operations.

Effects: Even at low concentrations, hydrogen sulphide causes headaches, conjunctivitis, sleeplessness, and pain in the eyes. High concentrations can lead to blockage of O_2 transfer, act as cell and enzyme poison and damage nerve tissues. Young plant tissues are easily damaged by H_2S . Scorching of young roots is observed when plants are exposed to H_2S . It discolourates and tarnishes paints, copper, zinc and silver.

Hydrogen fluoride

HF is a colourless and toxic gas, it is non-flammable having pungent smell and forms corrosive and penetrating hydrofluoric acid upon contact with moisture.

Sources: The major sources of hydrogen fluoride are the manufacture of phosphate fertilisers, the aluminium industry, brick plants, pottery, and ferro-enamel works. Small amounts are also emitted from zinc foundries, open hearth steel furnaces, burning of coal.

Effects: The exposed cattle and children can suffer from fluorosis. Causes irritation of eyes, nose and throat. HF gas can attach itself to particles in the air, which gets deposited on the surfaces and plants causing corrosion of metallic surfaces and harmful effects on plant functioning.

Hydrocarbons

Hydrocarbons are the group of compounds consisting of carbon and hydrogen atoms. Nature releases hydrocarbons from swamps, marshes and water bodies. 'Methane' known as natural gas evolved due to anaerobic decomposition of organic matter. Hydrocarbons are washed out of the air when it rains and join surface water bodies.

Sources: HCs are evaporated into the atmosphere from petroleum supplies (petrol, diesel, etc), and emitted out from the automobiles as unburnt remnants. HCs may also be contained in the smokes of incinerators using petroleum fuels and also in the fumes of oil refineries.

Effects: HCs in higher concentration cause irritation of eyes, and respiratory tract, and atleast eight of them have been responsible for causing chronic body cancers. HCs are responsible for formation of photochemical smog.

Aldehydes and Ketones may also be considered under hydrocarbons because they are formed by the photochemical oxidation of hydrocarbons, as secondary pollutants, although they may also be released from the automobiles and incinerators along with hydrocarbons. Aldehydes are produced by combustion of gasoline, diesel oil, fuel oil and natural gas. Incomplete combustion of motor fuel and lubricating oils leads to the formation of aldehydes. Substances like formaldehydes cause irritation of eyes, skins and lungs, and hence quite injurious to health.

Ozone

Ozone is a colourless gas. Ozone is poisonous and odorous at ground levels. It exists in great abundance under natural conditions in the upper atmosphere, it is known as ozone blanket or ozone layer. It does not allow the dangerous incoming UV rays.

Sources: The origin of the ozone at ground level has not been yet clarified, but it is likely that combustion and sunlight are involved in its production. It is a secondary pollutant, created by chemical reactions between oxides of nitrogen and volatile organic compounds in the presence of sunlight.

Effects: Breathing of ozone can trigger a variety of health problems including chest pain, coughing, throat irritation and congestion. It can worsen bronchitis and asthma. Ozone at ground level interferes with the ability of sensitive plants to produce and store food. It damages leaves of the plants, negatively impacting the appearance of urban vegetation (decorative plants in the urban cities).

Primary and secondary air pollutants

Air pollutants can also be classified as primary and secondary air pollutants based upon their origin.

Primary air pollutants are those emitted directly into the atmosphere from identifiable (and definite) sources. Important primary pollutants are,

- 1) Particulate matter: Coarse particles ($>100\mu$) and finer particles ($<100\mu$) including particles of metal, carbon, tar, resin, pollen, bacteria etc.
- 2) Sulphur compounds
- 3) Oxides of nitrogen
- 4) Carbon monoxide
- 5) Halogen compounds
- 6) Organic compounds
- 7) Radioactive compounds

Secondary air pollutants are those which are produced in the air by the interaction among two or more primary pollutants, or by reaction with normal atmospheric constituents like sunlight, water vapour etc., with or without **photoactivation**. Important secondary air pollutants are,

- 1) Ozone
- 2) Formaldehyde

- 3) PAN (Peroxy Acetyl Nitrate)
- 4) Photochemical smog
- 5) Formation of acid mists ($\text{SO}_2 + \text{Moisture} = \text{H}_2\text{SO}_4$)

Stationary and mobile sources

Sources of air pollution are categorised as stationary and mobile sources based on the position of the sources. Stationary sources are the sources of air pollutants which are located at a fixed place.

Mobile sources are the sources of air pollutants which are mobile or non-stationary, which are not located at any fixed place.

Another method of classifying emission sources is by

- 1) Point sources - Large stationary sources
- 2) Line sources - mobile sources with definite routes
- 3) Area sources - small stationary sources and mobile sources with indefinite routes

<u>Total sources</u>			
<u>Stationary sources</u>		<u>Mobile sources</u>	
Point sources	Area sources	Line sources	Area sources
Industrial processing	Domestic burning	Highway lines	Motor vehicles – light, medium, heavy duty
Power plants	Open burning	Trains	Railyard locomotives
Solid waste disposal – municipal incinerators	Evaporative losses	Channel vessels	Port vessels
-	-	-	Aircrafts (airports)

Sources of Air Pollution

No.	Class	Aerosols	Gases and Vapours
1	Combustion processes (Domestic Burning, thermal power plants, cars, trucks, aeroplanes, railways and also refuse burning)	Dust, fumes, smoke	SO_2 , NO_2 , CO, organic vapours, odours
2	Chemical processes (Paper mills, cement, fertilisers etc.)	Dust, fume, mist	Process-dependent (SO_2 , NO_2 , CO, NH_3 , NO_2 , organic vapours, odours)
3	Petroleum operations	Dust, mist	SO_2 , H_2S , NH_3 , CO, hydrocarbons, mercaptans
4	Metallurgical Processes (Aluminium refineries, Steel plants)	Dust, fume	SO_2 , CO, fluorides, organic vapours
5	Mineral processing	Dust, fume	Process dependent (SO_2 , CO, fluorides, organic vapours)
6	Food and feed operations	Dust, mist	Odourous materials
7	Agricultural activities 1. Crop spraying 2. Field burning	Dust, mist Smoke, Fly ash	Organic phosphates, chlorinated hydrocarbons, sulphur oxides, organic vapours
8	Nuclear energy programmes 1. Fuel fabrication 2. Ore preparation 3. Bomb explosion	Dust	Fluorides Iodine-131 and Argon-41 Radioactive gases (Sr-90, Cs-137, C-14, etc.)

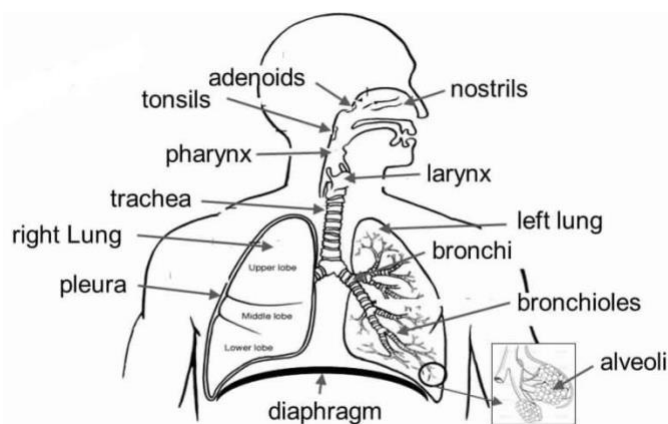
Effects of air pollution on human health

All the impurities in the inhaled air do not necessarily cause harm. It affects human health depending upon the following prime factors.

1. Nature of the pollutants
2. Concentration of the pollutants
3. Duration of exposure
4. State of health of the receptor
5. Age group of the receptor

Effects of air pollution on human health occur after the contact of air pollutants with the body. Generally bodily contact occurs at the surface of skin and exposed membranes. Pollutants may cause irritation of the membranes of the eyes, nose, throat, larynx, tracheo-bronchial tree and lungs. Contact with exposed membranous surface is most important because of their high absorptive capacity as compared to the skin. Some pollutants even reach the mucosa of the digestive tract.

Respiratory system is affected more than any part of the body because basic function of the respiratory system involves inhaling oxygen present in the air and exhaling CO_2 . Pollutants enter the body through respiratory system consisting of nasal and oral cavity, trachea, bronchial trees and lungs. At the entrance to the lungs, the trachea divides in to two bronchial trees. At the end of the bronchioles, there is large collection of tiny sacs called alveoli. It is across alveolar membranes that oxygen diffuses from the air in the sacs to the pulmonary capillaries and CO_2 diffuses in the opposite direction.



Health effects

1. Eye irritation.
2. Nose and throat irritation
3. Irritation of the respiratory tract
4. Gases like hydrogen sulphide (H_2S), ammonia (NH_3), mercaptans cause odour nuisance even at low concentrations.
5. Increase in the mortality rate and morbidity rate.
6. A variety of particulates like pollens, initiate asthmatic attacks.
7. Chronic pulmonary diseases like bronchitis and asthma are aggravated by a high concentration of SO_2 , NO_2 , particulate matter and photochemical smog.
8. CO combines with the haemoglobin in the blood and consequently increases stress on those suffering from cardiovascular and pulmonary diseases.

9. Hydrogen fluoride causes diseases of the bone (fluorosis) and mottling of teeth.
10. Carcinogenic agents cause cancer.
11. Dust particles cause respiratory diseases. Diseases like silicosis, asbestosis etc, are caused from specific dusts.
12. Certain heavy metals like lead may enter the body through the lungs and cause poisoning.
13. The biological effect of radiation may be somatic or genetic damage. Radioactive fallout causes cancer, shortening of life span and genetic effects or mutation.

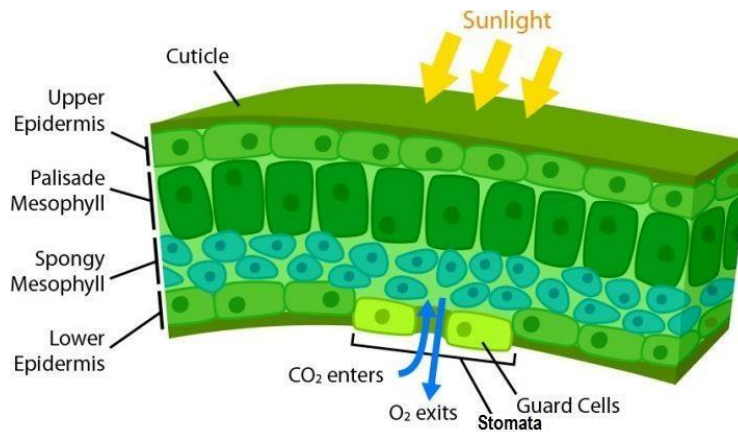
Effects induced in man by toxic substances

Skin	Altered appearance, irritation, sensitization, corrosion
Eye	Irritation, corneal opacity, retinal damage, cataract
Lung	Irritation, sensitization, pneumoconiosis, fibrosis, adenoma, carcinoma, neoplasia, mesothelioma, asphyxiation
Reproductive system	Germ cell mutation, embryotoxicity, teratogenesis, infertility, abortion, malformation of foetus, neonatal death, developmental defects
Nervous system	Behavioural changes, peripheral neuropathy, mental depression, ataxia, narcosis, parkinsonism, stupor, vomiting and drowsiness
Immune system	Suppression, modulation
Musculoskeletal system	Osteoporosis, dystrophy
Hemopoiesis	Bone marrow depression, leukemia, aplastic anemia, methemoglobinemia
Liver	MFO induction, neoplasia, cirrhosis, necrosis
Kidney	Uremia, lithiasis, aminoaciduria

Susceptibility to the effects of air pollution is more in case of infants (pre-school and school children) and also elder people and those who are suffering from diseases. Those people with chronic diseases of lungs and heart are thought to be at great risk. The effect of air pollution on human health is worst during the winter seasons, when pollution levels reach a maximum.

Effects of air pollution on vegetation

Air pollution has a damaging effect on plants also. The effect of air pollutants on vegetation depends upon their chemical nature, level of concentration and duration of exposure. The most obvious damage caused by air pollutants to vegetation occurs in leaf structure. A cross section of a leaf shows four principal layers, the upper epidermal cells, the palisade parenchyma, the spongy parenchyma and the lower epidermal cells. The surface of the leaf is covered by a waxy layer known as cuticle. Between the waxy layers, epidermis is present, which is a single layer of cells forming the surface skin of the leaf. The leaf surface has a large number of openings called stomata, which are bounded by guard cells which also control the opening and closing of stomata to allow gases to enter or leave the leaf. Such gases of course include pollutants which cause damage to the leaf in many forms.



Damage to the leaves takes place in several forms.

1. Necrosis – It is the killing or collapse of tissue. Tissue injured by phytotoxicants often has a characteristic colour. For example, bleaching is associated with SO_2 , yellowing with NH_3 , browning with fluoride and silvering or bronzing of under surfaces of some leaves with PAN.
2. Chlorosis – It is the loss or reduction of the green plant pigment, chlorophyll. The loss of chlorophyll usually results in pale green or yellow patterns. Chlorosis generally indicates a deficiency of some nutrients required by the plant.
3. Abscission – Leaf abscission is dropping of leaves.
4. Epinasty – Leaf epinasty is a downward curvature of the leaf due to higher rate of growth on the upper surface.
5. Pigmented lesions – may result with dark brown, black, purple or red spots appearing on the leaf surface.

Air pollutants affecting plants

1. Sulphur dioxide
2. Fluoride compounds (like HF)
3. Ozone
4. Hydrogen chloride
5. Nitrogen oxides (NO , NO_2 etc.)
6. Ammonia
7. Hydrogen sulphide
8. Hydrogen cyanide
9. Mercury
10. Ethylene
11. PAN
12. Herbicides (sprays of weed killers)
13. Smog

Effect of some specific air pollutants on plants

Pollutant	Dose	Effect
1. Sulphur dioxide	Mild	Interveinal chlorotic bleaching of leaves
	sever	Necrosis in interveinal areas and skeletonised leaves
2. Ozone (O_3)	Mild	Flecks on upper surfaces, premature aging and suppressed growth

	sever	Collapse of leaf, necrosis and bleaching
3. Fluorides	Cumulative effect	Necrosis at leaf tip
4. nitrogen dioxide	mild	Suppressed growth, leaf bleaching
5. ethylene (CH ₂)	mild	Epinasty, leaf abscission
6. PAN	mild	Bronzing of lower leaf surface, suppressed growth. Young leaves are more susceptible.
7. Chlorine (Cl ₂)	0.10 ppm for at least 2 hours	The epidermis and mesophyll of plants will be affected by bleaching between veins, tip and margin burn and leaf abscission.
8. Hydrogen chloride	50 ppm	Browning of tips of grasses
	5 ppm	Interveinal bronzing of tomato leaves
	-	Leaf burning of broad leaf plants, bleaching and necrosis
9. Mercury (Hg)	-	Greenhouse crops and floral parts of all vegetation are affected; abscission and growth reduction occur in most of the plants
10. Pesticides and herbicides	-	Defoliation, dwarfing, curling, twisting, growth reduction and killing of plants may occur. If necessary precautions are not taken taste and flavour of plants and cotton also are affected.
11. Particulates	-	Affects quality of plants, reduces vigor & hardness and interferes with photosynthesis due to plugging of leaf stomata and blocking of light.

Kinds of injury to plants

Acute injury –

It results from short time exposure to relatively high concentrations. The effects are noted within a few hours to a few days and may result in visible markings on the leaves due to a collapse or death of cells. This leads to necrotic patterns i.e., areas of dead tissues.

Chronic injury –

It results from long-term low level exposure and usually causes chlorosis or leaf abscission.

Growth or yield retardation –

Here the injury is in the form of an effect on growth without visible markings (invisible injury). Usually a suppression of growth or yield occurs.

Effects of air pollution on materials

Air pollution damage to the property is a very important economic aspect of pollution. Air pollution damage to property covers a wide range – corrosion of metals, soiling and eroding of building surfaces, fading of dyed materials, rubber cracking. Following are the processes which account for the effects of air pollution on materials.

Mechanism of deterioration by air pollutants

1. Abrasion: solid particles of considerable size travelling with higher speeds can cause abrasive action. Large sharp edged particles embedded in fabrics can accelerate wear.

2. Chemical action: Some pollutants react directly and irreversibly with materials to cause deterioration. SO₂ bleaches marble, hydrogen sulphide tarnishes silver and acidic mists cause etching of metallic surfaces.
3. Absorption (Indirect chemical action) – Some materials absorb pollutants and get damaged when the pollutants undergo chemical action. SO₂ absorbed by leather will be converted to sulphuric acid which deteriorates the leather.
4. Corrosion: Action of air pollutants in the presence of moisture causes corrosion. The atmospheric deterioration of ferrous metal is due to corrosion by an electrochemical process.
5. Deposition and removal: Solid and liquid particles deposited on a surface may damage the material by spoiling its appearance. The removal of these particles may cause deterioration as in the case of washing of soiled clothes i.e., it needs rough rubbing action to clean the clothes which spoils its appearance.

Factors influencing the effect on materials

1. **Temperature** affects the rate of a chemical reaction and consequently it affects the rate of deterioration. Most of the chemical reactions are accelerated at higher temperatures.
2. The presence of **moisture** in the atmosphere greatly helps in the process of corrosion. Without moisture in the atmosphere, there would be little atmospheric corrosion, if any, even in the most severely polluted environments. Rate of corrosion of metals will increase as the **relative humidity (moisture)** in the air increases.
3. **Sunlight** may directly damage materials as in case of fading of dyes and cracking of rubber. Moisture present on the materials becomes the host of several organisms like algae and fungi in the presence of light. **Sunlight** is indirectly responsible for damage of materials as many secondary pollutants like PAN and O₃ are formed in the atmosphere in the presence of sunlight.
4. **Precipitation** in the form of fog may fill the pores of materials, especially building materials and later may freeze and expand. Due to this or due to alternate wetting and drying, the materials may be damaged.
5. **Wind direction** plays a very important role as it drives the air pollutants from the sources. Damage to the crops in the vicinity of the factories is caused by **air movement** only. Wind speed is also an important factor in determining the impact of air pollutants on materials pollutants present in the wind travelling at high speeds will cause more abrasive effects.
6. **Stability of atmosphere-** In highly **stable** atmospheres pollutant dispersion is restricted, leading to very high ground level concentrations. **Unstable** atmospheres are favourable for dispersion, causing less damage to the materials.
7. **Concentration and duration-** Material damage is directly related to **concentration of the pollutants and exposure time**. For example, the effect of 260µg/m³ of particulates on a material for 24hours may be the same as the effect of 75µg/m³ for one year. Usually the **concentration of pollutants** changes from time to time depending upon the meteorological conditions.

Effect of Air Pollutants on Materials

Sl. No.	Material	Air Pollutants	Influencing Parameter	Effects
1	Metals and alloys	SO ₂ , NO ₂ , acid gases.	Moisture and temperature	Tarnishing of surfaces, corrosion of metals
	Silver	Cl ₂ , H ₂ S, Chromium, HCl	Particulates	H ₂ S tarnishes silver.
	Ferrous metals, zinc, aluminium, copper and glass	SO ₂ , acids, CO ₂ , NO _x , P	Moisture	Etching of surfaces by acid mists, Etching of glass by H ₂ S, loss of metal and loss of strength due to reaction of acids formed by SO _x , CO ₂ , phosphorous etc.
2	Building materials	SO ₂ , acids & gases	Moisture, wind, sea sprays and oily particles	Soiling discolouration and damage due to abrasion, alternate wetting and drying.
	Bricks and stones	CO ₂		Deterioration by carbonic acid formed due to (CO ₂ + moisture)
	Limestone, sand stone, marble, roofing slate, mortar, statues.	SO _x , NO _x	Moisture	Indirect chemical action, Formation of loose surfaces that flake off.
3	Wood, fibre glass, rubber, PVC.	NH ₃	Moisture and temperature	Softening; stress corrosion of carbon steel due to NH ₃ .
	Textiles	SO ₂ , acids, gases,	Moisture and sunlight	Soiling, reduction in life due to abrasive action during washing,
		O ₃ , NO ₂ , NH ₃ , chromium, iron and manganese		Loss of tensile strength in cotton curtains and nylon drapes, oxidation of dyes turning white fabrics into yellow.
4	Paints and waxes			Staining due to formation of their oxides.
		SO ₃ , H ₂ S and particulates, Iron, NH ₃ , Cl ₂ , chromium,	Moisture, fungus,	Microbial attack on organic constituents of paints, discolouration, deposition of particulate matter.

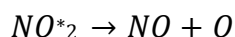
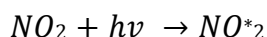
		microorganisms		
5	Paper	SO ₂ , acidic gases, Chromium	Sunlight	Embrittlement and discolouration, Decrease in folding resistance of the paper.
6	Plastics, elastomers (rubbers), tyres, insulators	Oxidants like O ₃ , NH ₃ , NO ₂ , PAN	Sunlight, weather inversions	Cracking of rubber by O ₃ attack, Decrease in molecular weight and increase in rigidity of polymers making them more brittle and less resilient.
7	Backery and other food products	Biological aerosols	Moisture	Saprophytic bacteria and fungi cause food spoilation
8	Leather products	SO ₂ , microorganisms	Temperature, humidity	Embrittlement, Bacteriological degradation

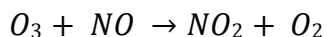
Photochemical smog

It was first observed in Los angeles, USA in 1940s and now has been detected as a common phenomenon in most of the metropolitan cities. Photochemical air pollution occurs in highly motorized areas and when inversion conditions occur in the atmosphere. The formation of photochemical smog is due to action of sunlight on the two pollutants- Hydrocarbons and oxides of nitrogen. The major source of these two pollutants is the exhaust gases from automobiles. The conditions for the formation of photochemical smog are air stagnation, abundant sunlight and high concentrations of hydrocarbons and NO_x in the atmosphere. Due to complex photochemical reactions secondary pollutants such as ozone, aldehydes, ketones and PAN are formed.

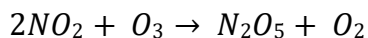
It has been found that photochemical smog normally occurs in the morning and evening time. The conditions which prevail for this are lower temperatures in the morning and evening, presence of sunlight, occurrence of natural fog in the morning and evening.

In the beginning, light energy is absorbed by NO₂. The highly energized molecule (NO₂^{*}) then decomposes into nitric oxide and atomic oxygen. The atomic oxygen reacts quickly with molecular oxygen to form ozone. A stable ozone molecule is formed when a third body (X) is present otherwise ozone decomposes rapidly. If nitric oxide is present, it reacts with ozone to form NO₂ and an oxygen molecule.

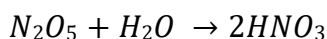




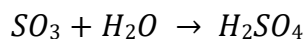
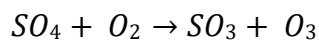
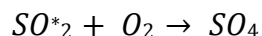
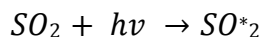
If ozone is present in excess, then



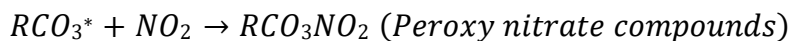
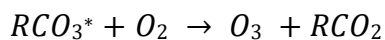
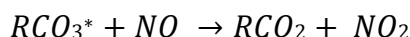
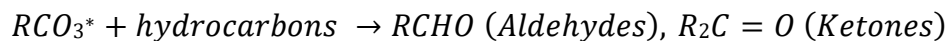
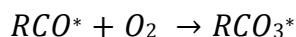
In presence of water vapour,



Ozone may be formed in the atmosphere as a byproduct during the photochemical oxidation of sulphur dioxide to sulphuric acid. The reaction takes place as follows,



Further in the presence of certain hydrocarbons, other reactions take place. Some of the atomic oxygen, ozone and nitric oxide react with hydrocarbons to form a variety of compounds.



With the other reactions, RCO_3NO_2 may be

$CH_3(CO)O_2NO_2$ – Peroxy acetyl nitrate (PAN)

$H(CO)O_2NO_2$ – Peroxy formyl nitrate (PFN)

$C_6H_5(CO)O_2NO_2$ – Peroxy benzyl nitrate (PBzN)

In presence of sunlight aldehydes produce organic free radicals.

Effects of Photochemical smog

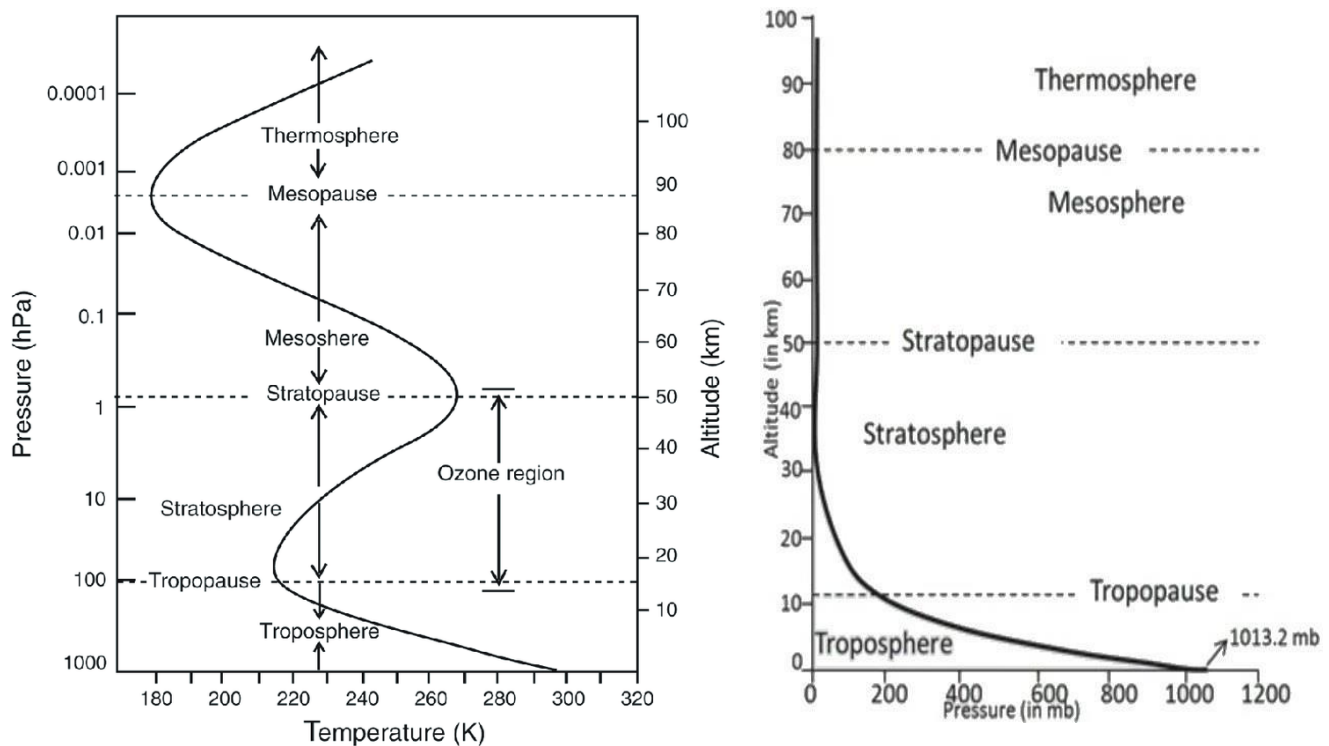
1. The compounds of formaldehyde, acrolein, PAN, and PBzN are highly irritant to eyes.
 2. O₃, NO₂, PAN present in the photochemical smog cause necrosis and silvering or bronzing of the upper side of the leaves. Vegetation is badly affected by photochemical smog.
 3. Carbon, sulphur and halides present in the smog cause visibility problems. The usual size of the aerosols present is about 0.3 μ.
 4. Ozone present in the smog is responsible for cracking of rubber, if anti-ozonants are not used in production of rubber materials.
 5. Fading of dyes is also another important economic effect of photochemical smog.
-

METEOROLOGY

(Temperature lapse rate & stability, wind velocity & turbulence, plume behaviour, measurement of meteorological variables, wind rose diagrams, plume rise, estimation of effective stack height and mixing depths. Development of air quality models – Gaussian dispersion model)

2.1 Structure of the atmosphere

The gaseous layer surrounding the earth up to a height of about 700km is called atmosphere. As we go higher and higher, the characteristics and composition of the atmosphere changes. On the basis of altitude, the atmosphere is divided into 4 important spheres and 3 pauses. They are 1. Troposphere with tropopause 2. Stratosphere with stratopause 3. Mesosphere with mesopause and Ionosphere or thermosphere. The different zones of the atmosphere with variations in temperature and pressure are shown in figures below.



Troposphere: this is the lowest gaseous layer of the atmosphere and extends to a height about 10 to 20km from the earth's surface. It contains nearly 2/3rd mass of the atmosphere and this is the zone of rapid weather changes and clouds. In this region, temperature decreases with increase in altitude. The higher we go, cooler it is.

Tropopause joins the troposphere with the upper stratosphere.

Stratosphere: it is a 30km thick layer that lies above the tropopause. This layer is free from violent weather changes. In the stratosphere, temperature rises as the altitude increases. This is due to the presence of ozone layer at a height of 25-30km above the earth's surface. Ozone absorbs the UV radiation from the sun and converts it into heat and chemical energy. Due to this temperature rises significantly.

Stratopause joins the stratosphere with the upper mesopause.

Mesosphere: it is a relatively quite region where few energy releasing reactions occur. Here again the temperature decreases with the altitude. This layer and zones above have no significance in the air pollution studies.

Ionosphere: it is also known as thermosphere because of the very high temperatures – as much as 870 °C to 1430 °C. almost all the atoms in this region are ionised. Large number of free electrons flash about in this area. It is the highest and vastest zone of the atmosphere starting from 115km above the earth up to 700km. The region above 700km is termed as exosphere and as yet very little known about it. It is believed to be a low-density, high temperature region.

2.2 Meteorology and Air Pollution

Air pollutants emitted from a source must first be transported and diluted in the atmosphere before these undergo various physical, photochemical transformations and at last reach their receptors. Otherwise, the pollutant concentrations reach dangerous levels near the source of emission. Hence, it is important that to understand the natural processes that are responsible for their dispersion. Effective dispersion of pollutants in the atmosphere depends primarily on the degree of stability of the atmosphere and on its turbulent structure. In the broadest sense, dispersion is controlled by **meteorological conditions** prevailing in the atmosphere. Thus, even if the emissions are same in different places, it is the weather that can lead it to an air pollution episode in a place.

The important meteorological parameters that influence air pollution can be classified into primary and secondary parameters.

Primary parameters are,

1. Wind direction, speed and turbulence
2. Temperature
3. Atmospheric stability
4. Mixing height

Secondary parameters are,

1. Precipitation
2. Humidity
3. Solar radiation
4. Visibility



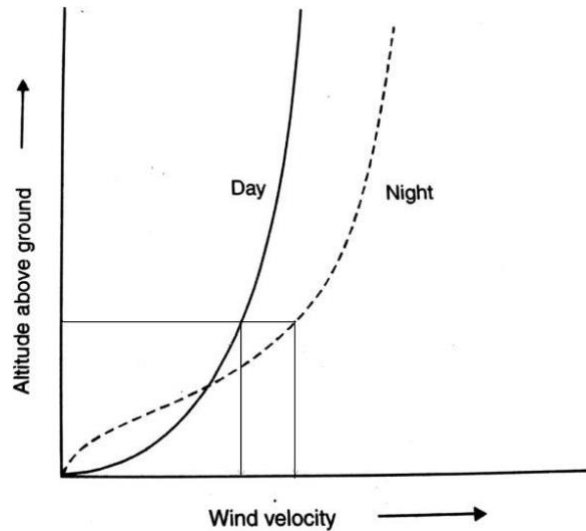
2.2.1 Wind Direction, Speed and Turbulence

The moving air is known as wind. Such a movement in the air is caused by the unequal distribution of atmospheric temperature and pressure over the earth's surface and is largely influenced by the rotation of the earth. The **direction of winds** is always from higher pressure areas to low pressure areas. Regional and local, geographical and topographical features may also affect the direction and speed of the winds.

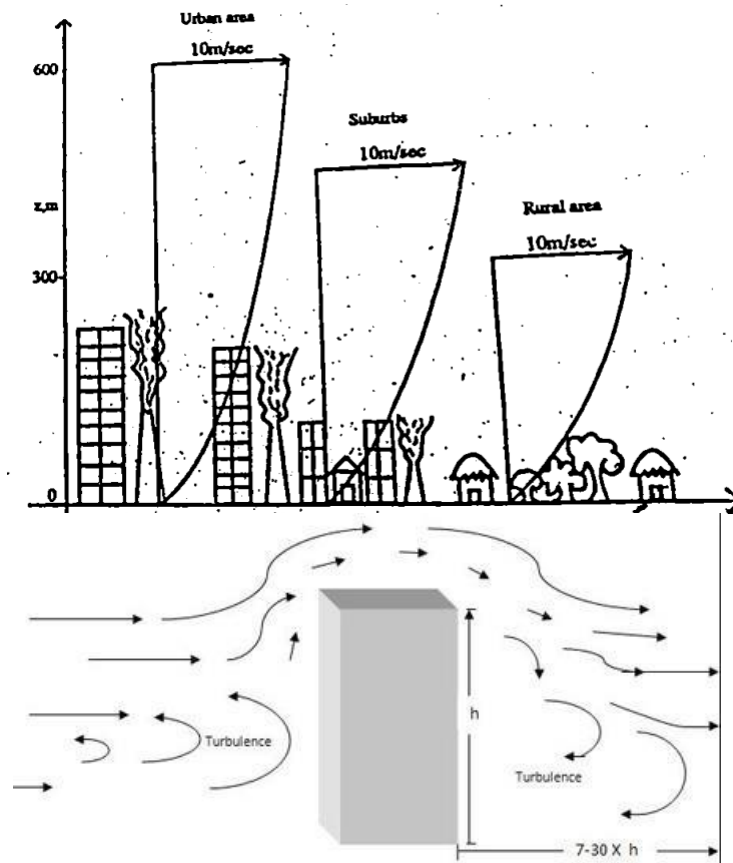
The direction and speed of the surface winds govern the drift and diffusion of air pollutants discharged near the ground level. The higher the wind speed at or near the point of discharge of pollution, the more rapidly are the pollutants carried far away from the source. The pollutants so dispersed will not exist at the same concentration but will rapidly be diluted with greater and greater volumes of air. On the other hand, when wind speeds are low, pollutants tend to be concentrated near the area of discharge and longer the periods of such light winds, greater will be the concentration of pollutants.

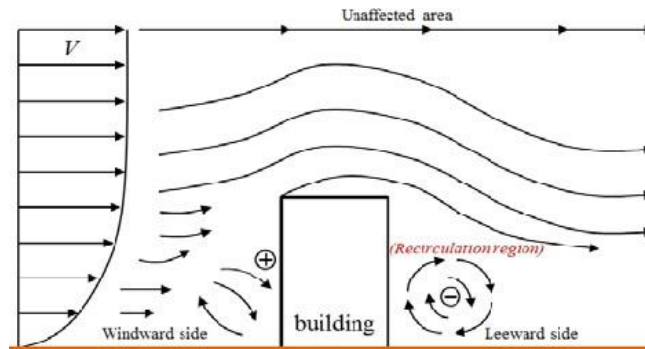
Differential solar heating of the earth's surface produces pressure and temperature gradients. As a result, the atmosphere is practically in continuous motion with air movement, being always turbulent. The motion of the air near the earth's surface is retarded by friction which varies with surface roughness. Again this adds up some amount of the turbulence in it. This friction can affect the wind up to 1 km above the surface (in planetary boundary layer).

It is also influenced by time of the day. During the day time, solar heating causes **thermal turbulence**, it sets up **convective currents** because of which turbulent mixing is increased. This results in a steeper velocity profile in the day than that at night. The typical velocity profiles are shown in the figure. Thermal turbulence also depends upon the thermal stability of the atmosphere. It is maximum on a clear sunny day in the afternoon and minimum at night or in the early morning.



The second type of turbulence is the **mechanical turbulence** which is produced by shearing stress generated by air movement over the earth's surface – the greater the surface roughness, the greater will be the turbulence. The effect of terrain on the wind velocity profiles is shown in the figure. For smooth surfaces, the air velocity profile becomes very steep near the ground. For rougher surfaces such as those in urban areas, more mechanical turbulence is generated and the velocity profile becomes less steep and reaches deeper into the atmosphere.





2.2.2 Temperature Lapse Rate and Atmospheric Stability

In the troposphere, the temperature of the ambient (surrounding) air normally decreases with an increase in the altitude (height). This rate of change of temperature with altitude is called **Lapse rate**. This rate will differ from place to place, and from time to time even at the same place.

“The normal rate of decrease of temperature with altitude in the stationary atmosphere at a given time and location is called as **Environmental Lapse rate (ELR)** (Normal or natural)”. That is the natural change in temperature of the local environment at different heights. In the troposphere, the value of normal or environmental Lapse rate is averaged to about 6.5 °C/km.

Under normal environmental conditions, when a parcel of air which is hotter and lighter than the surrounding air is released, then naturally it tends to rise up, until of course, it reaches to a level at which its own temperature and density becomes equal to that of surrounding air. Hence, when a pocket of artificially heated air (eg. from an industrial stack) is emitted in the environment, it rises up and expands in the broad atmosphere and gets cooled **without exchange of heat**. The rate at which temperature of this parcel of air decreases is somewhat different from natural lapse rate. This internal decrease of temperature with height which occurs in the rising parcel of air, can be theoretically calculated, by assuming the cooling process to be adiabatic. In other words, as the air parcel moves up its temperature decreases as its own heat energy is expanded due to increase in the volume of air parcel as shown in figure. This rate of decrease of temperature with height is called **adiabatic lapse rate (ALR)**. “Adiabatic lapse rate is the rate of change of temperature of an air parcel as it moves upwards through the atmosphere **rapidly**”.

$$\text{Mathematically, } \gamma = \frac{-dT}{dz}$$

If the **dry air** is expanding and cooling adiabatically (normally cools @ 9.8 °C/km), it is called as the **Dry adiabatic lapse rate (DALR)**. In saturated (**wet**) air, this rate is calculated to be 6 °C/km, and is known as **Wet adiabatic lapse rate (WALR)**.

On a comparison, depending upon the relative positions of the ELR and DALR lines on the graph sheet, the stability of the environment is determined.

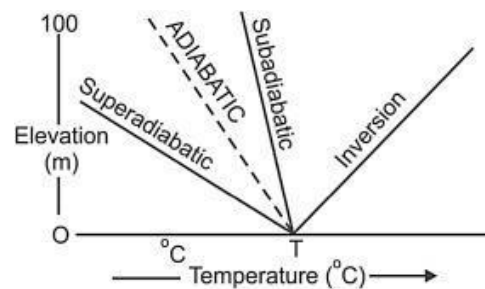
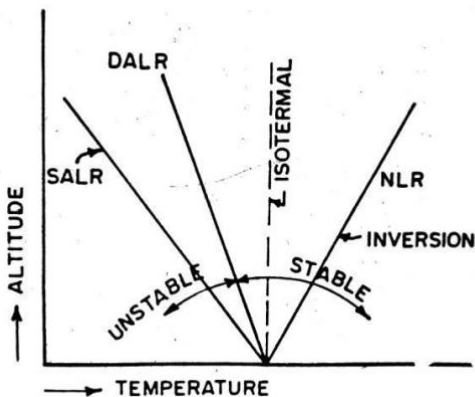
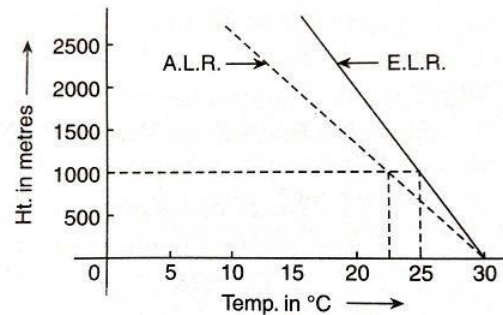
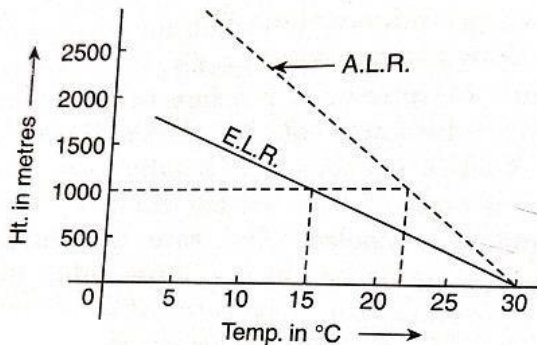
- When ELR is greater than the DALR (For example, from the below figure, the ELR is 15 °C/km and DALR is 8 °C/km), the lapse rate of the local atmosphere is said to be **Super adiabatic lapse rate (SALR)**. On a clear sunny day, rapid heating of the earth by the sun warms the air near the surface, to the point where lapse rate is super adiabatic. Under this condition the atmosphere is said to be in unstable equilibrium, and vertical mixing of the air results. This is a condition in which pollutants are dispersed rapidly.
- In reverse case, when ELR is less than the ALR, as shown in below figure, the environment is said to be stable, and this lapse rate of the local atmosphere is called as **Sub-adiabatic lapse rate**.
- The third case would be the one, when ELR equals the ALR, and both the lines coincide. The environment in such a case is said **Neutral** (may be 1 °C/km).

Lapse- Gradual change

Adiabatic – A process occurring without the addition of outside heat or loss of its own internal heat. (Not by exchanging)

Rapid condition means that the air parcel moves fast enough that there is no considerable exchange of heat with the surrounding air.

The change in temperature is due to the fact that as you move upwards through the atmosphere, the atmospheric pressure decreases, causing the air parcel to expand. Since this expansion is adiabatic, the work required for expansion is taken from the internal energy of the air parcel, causing it to cool down.



Negative lapse rate or Inversion

In an unusual case, when the temperature of the environment (i.e., ambient air) increases with altitude, then the lapse rate becomes inverted or negative from its normal state. Negative lapse rate curve would be of the type as shown in the below figure.

When the reverse or negative lapse rate occurs, a cold layer of the air at ground level gets covered by a warmer air layer at higher levels.

“A phenomenon in the atmosphere, when the reverse or negative lapse rate occurs, in which a dense cold stratum of the air at ground level gets covered by a lighter warmer air at higher level is known as **inversion**.” During inversion, vertical air movement is stopped and the pollutants will be concentrated beneath the inversion layer (i.e. the dispersion of pollutants is retarded). This condition of the atmosphere is said to be **stable** as very little turbulence or mixing takes place. Inversion is a frequent occurrence in the autumn and winter months.

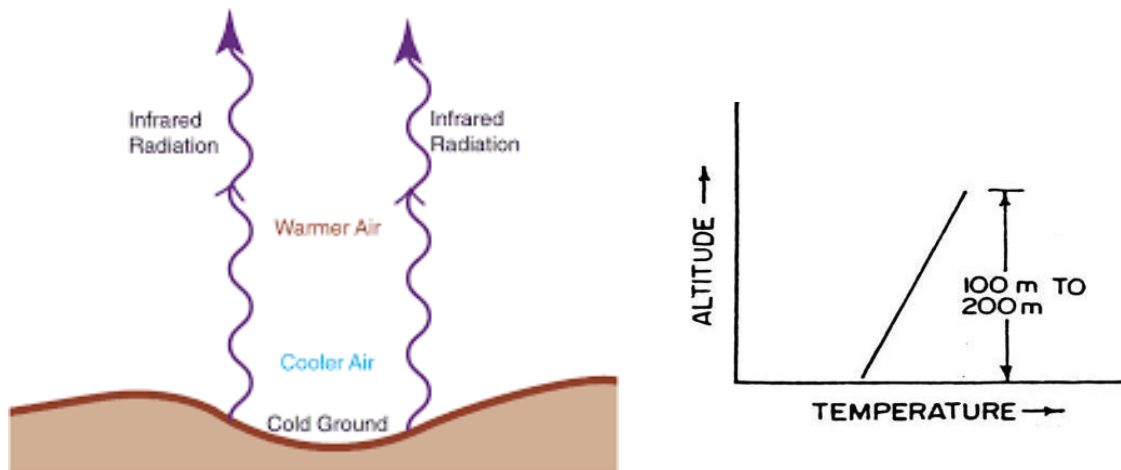
During the inversion, the accumulation of smoke and other contaminants further increases the pollution level by preventing the sun's rays from warming the ground and the adjacent air. Fog is commonly associated with inversions. At the time of inversions, visibility is greatly reduced and contaminants are at a maximum.

Inversions may be of the following types,

- 1) Radiation inversion
- 2) Subsidence inversion
- 3) Double inversion

Radiation inversion

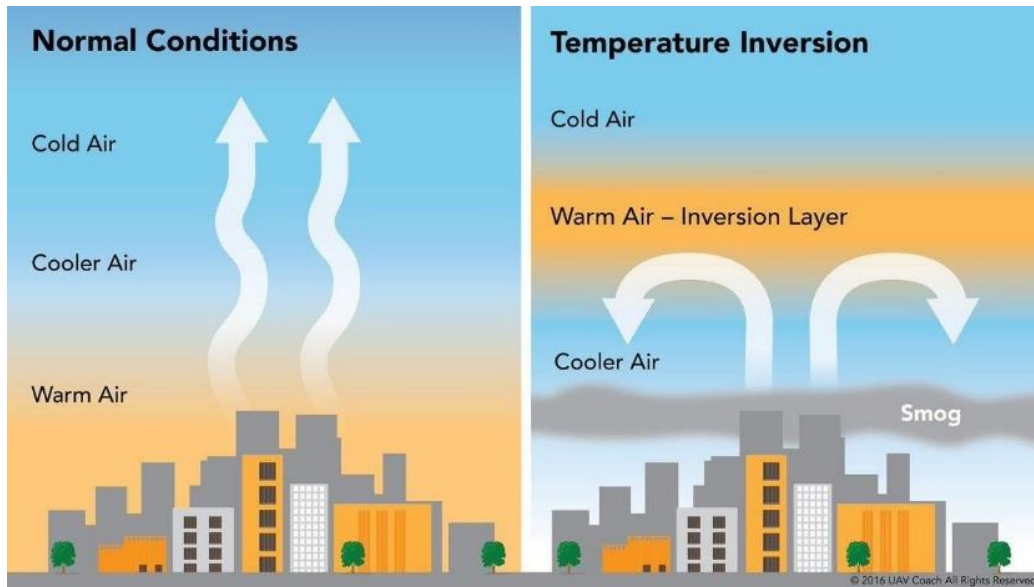
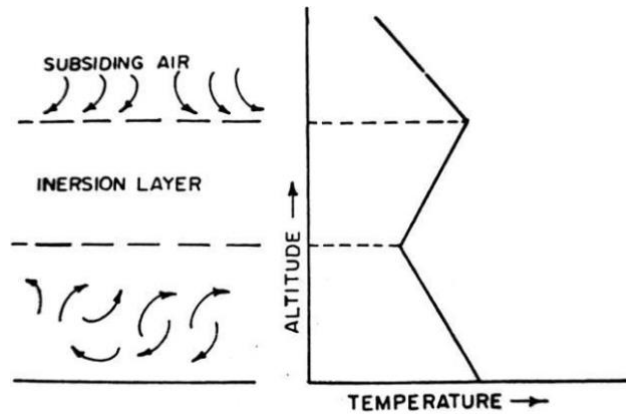
This type of inversion usually occurs in the night as the earth loses its heat and cools the air layer which is in contact with it. After sunset, the ground is cooled by losing its heat **by radiation**, thus the air in contact with it cools down. Then the cool air stratum is covered by the warmer air layer restricting the vertical movement of the air. This formation will continue until the sun warms the lower air, next morning. If the air is moist and its temperature is below the dew point, **fog** will be formed.



Radiation inversion is more common in the winter season than in summer, because of longer nights. In the valley area, this type of inversion occurs more frequently because of restriction in the horizontal air movement by high level ground in the surrounding. In India, because of intense solar heating of the ground, inversions are broken within few hours after sunrise. However, simultaneous occurrence of fog or mist increases the duration of inversion by blocking the sunlight reaching the ground.

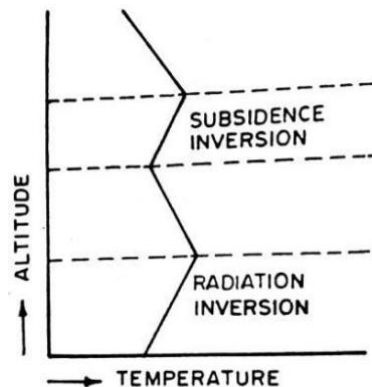
Subsidence inversion

It is one of the most common types which occurs at modest altitudes and often remains for several days. It is caused by sinking or subsiding of air in anticyclones (high pressure areas surrounded by low pressure areas). The air circulating around the area descends slowly at the rate of about 1000m per day. As the air sinks, it is compressed and gets heated to form a warm layer hotter than the air present at ground level. This acts as a lid which stops the upward movement of contaminants. The inversion height may vary from ground surface to 1600m. When this drops to less than 200m, extreme pollution occurs.



Double inversion

Radiation and subsidence inversions both may occur simultaneously, some times. Such a phenomenon is known as double inversion.



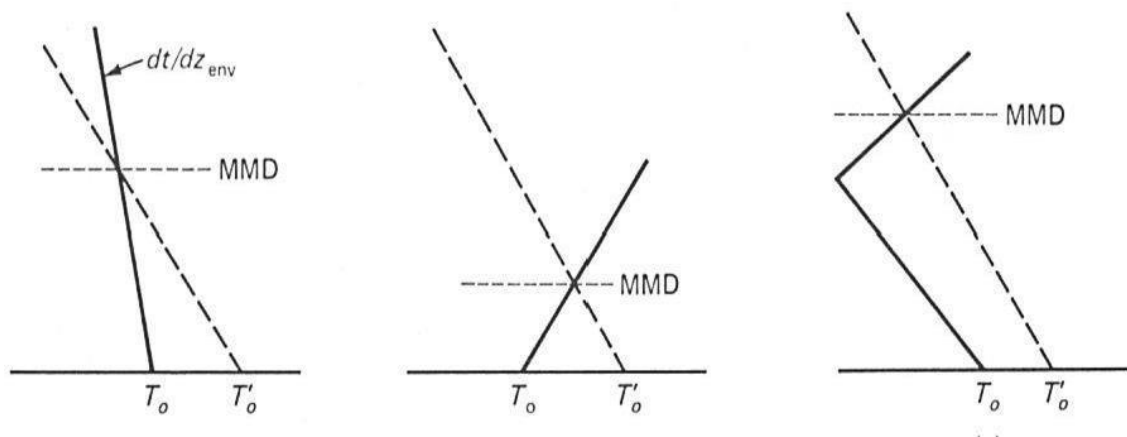
2.2.3 Mixing Height or Maximum Mixing Depth (MMD)

The fourth primary meteorological parameter is the mixing height.

It is defined as, that height above the earth's surface to which pollutants will rise in the atmosphere, primarily by the action of atmospheric turbulence. It is importantly dependent upon the three factors: wind

direction, wind speed and wind turbulence. The vertical extent to which the mixing takes place varies diurnally (from day to day), seasonally (from season to season), and it is also affected by topographical features. The greater the vertical extent, larger will be the volume of atmosphere available to dilute the pollutants.

In practice, MMD is determined with the help of temperature profile of the actual atmosphere for several kilometres above the earth's surface. Mean MMD value for a location is found for period of 1 month. The values of the MMD are usually lower at night and higher during the day time. If inversion occurs at ground level then MMD value will be zero. And in the day time, the MMD values may vary from 2000m to 5000m. On a seasonal basis, the average MMD will be minimum in winter season and maximum in the summer season.



2.2.4 Precipitation

Rainfall or precipitation has a two-fold cleansing action on the pollutants discharged into the atmosphere. It accelerates removal of the particulate matter from the atmosphere and hence its deposition on the ground. It also helps to remove the concentration of the gaseous pollutants which are soluble in water. The washout of air-borne radioactive wastes by precipitation is a matter of particular concern.

2.2.5 Humidity

Humidity is a measure of water vapour in the atmosphere. The moisture content of the atmosphere influences the corrosive action of the air pollutants. If the air is moist and its temperature is below the dew point, **fog** will be formed and visibility is reduced. Moisture indicates the potentiality for fog formation. The relative humidity is most frequently used in air pollution studies.

2.2.6 Solar radiation

The solar radiation has a pronounced effect on the type and rate of chemical reactions in the atmosphere. Earth's surface is the prime absorber of solar heat energy. Thus the air stratum near to the earth gets warmed by the transfer of heat energy. And it leads to temperature variations with the altitude which has a great influence on the dilution and dispersion of the pollutants once they are released.

2.2.7 Visibility

Just as the weather affects the severity of air pollution, air pollution may in turn affect the weather conditions. Air pollution may influence the weather in several ways. Once the fog is formed, the incoming solar radiation may be decreased and the pollutants will be concentrated. The visibility is greatly reduced. Therefore duration of the fog and its frequency will be increased.

Plume behaviour

Plume is defined as the path taken by continuous discharge of gaseous pollutants emitted from a stack or chimney. The behavior of the plume emitted from any stack depends on local air stability. The different forms are generally seen at lower atmosphere (<300m above ground). The shape of the path or concentration distribution of the plumes depends upon diurnal (day-to-day) and seasonal (season to season) variations in the atmospheric stability.

The behavior or travel of air pollutants in the atmosphere once they are released is very important aspect to understand the atmospheric stability and to design the industrial stack heights. Diffusion of pollutants into the atmosphere is governed by ELR as well as ALR. By comparing these two lapse rates, it is possible to predict as to what will happen to gases emitted from a stack. Once they are emitted, how do they travel in the atmosphere, in what direction, what will be the shape of their path of travel, this all depends upon stability of the atmosphere, wind direction, wind speed and turbulence.

Seven types of plumes are usually detected in the different environmental conditions, characterized by different relative positions of ELR and ALR lines, are explained below. The spread of the plume is directly related to the vertical temperature gradient as shown on the left hand side of the figure.

- 1) **Looping plume:** This is the common type of plume behavior which occurs under super adiabatic lapse rate (SALR) (when $ELR > ALR$) conditions with turbulent air in warm seasons with clear skies. The plume has wave type behavior since it occurs in a highly unstable atmosphere. High turbulence helps in rapid dispersion of the plume, but high concentrations may occur near the stack if the plume touches the ground.
- 2) **Neutral plume:** It is the upward vertical rise of the plume from the stack as shown in figure, which occurs when the ELR is equal to or very near to ALR, and under light winds and clear skies. The upward lifting of the plume will continue till it reaches an air of density similar to that of the plume itself.
- 3) **Coning plume:** It is a type of plume which is shaped like a cone (roughly 10° with a horizontal axis). This occurs when wind velocity is greater than 32km/h, under sub-adiabatic or slightly stable (or say near neutral atmosphere) conditions. This occurs under wet and cloudy climate. There is limited vertical mixing, thereby increasing the probability of air pollution in the area. However the plume reaches the ground at greater distance from the stack as compared to looping.
- 4) **Fanning plume:** A fanning plume occurs under a large inversion condition, in the presence of light winds with very little turbulence. This usually occurs at night and in the early morning condition when earth is cooled by outgoing radiations. This type of plume may appear as a narrow horizontal fan without any vertical spreading for several kilometers downwind. In some cases, If the plume is extremely hot, it rises vertically a little and then drifts horizontally. The dispersion of the plume is very slow.
- 5) **Lofting:** Lofting occurs when there is a strong SALR above a surface inversion. In such conditions, downward motion and mixing is prevented by surface inversion, thus the plume is rapidly dispersed in the upward direction. Lofting occurs in the evening time with clear skies and under moderate winds. In these conditions, emission will not reach the ground surface, thus lofting is a favourable plume.
- 6) **Fumigation:** when an inversion layer occurs above the top of the stack, and super adiabatic conditions exist below the stack, then plume is said to be fumigating. In such a case, the plume will not escape above the stack because of presence of inversion layer, but it will be brought down to the ground surface. This represents quite a bad case of atmospheric conditions for dispersion. Fumigation occurs usually under clear skies and light winds in the morning times of summer season.
- 7) **Trapping plume:** This is achieved when the plume is caught between two inversion layers. Hence the emitted plume neither can go up nor down and will be trapped in between. It occurs in a stable

atmosphere, both above and below the stack height, with unstable atmosphere trapped in between both. It may occur at any time of the day in any season.

Plume rise and Height of the stack

The dilution of pollutants from heightened stacks is considered to occur in two stages, namely, plume rise and dispersion. In the first stage, the hot plume from the stacks goes up to a certain height above stack exit due to buoyancy and momentum. Subsequently in second stage, the plume spreads both vertically and horizontally by the dispersion process. The second stage is described by the mathematics of diffusion.

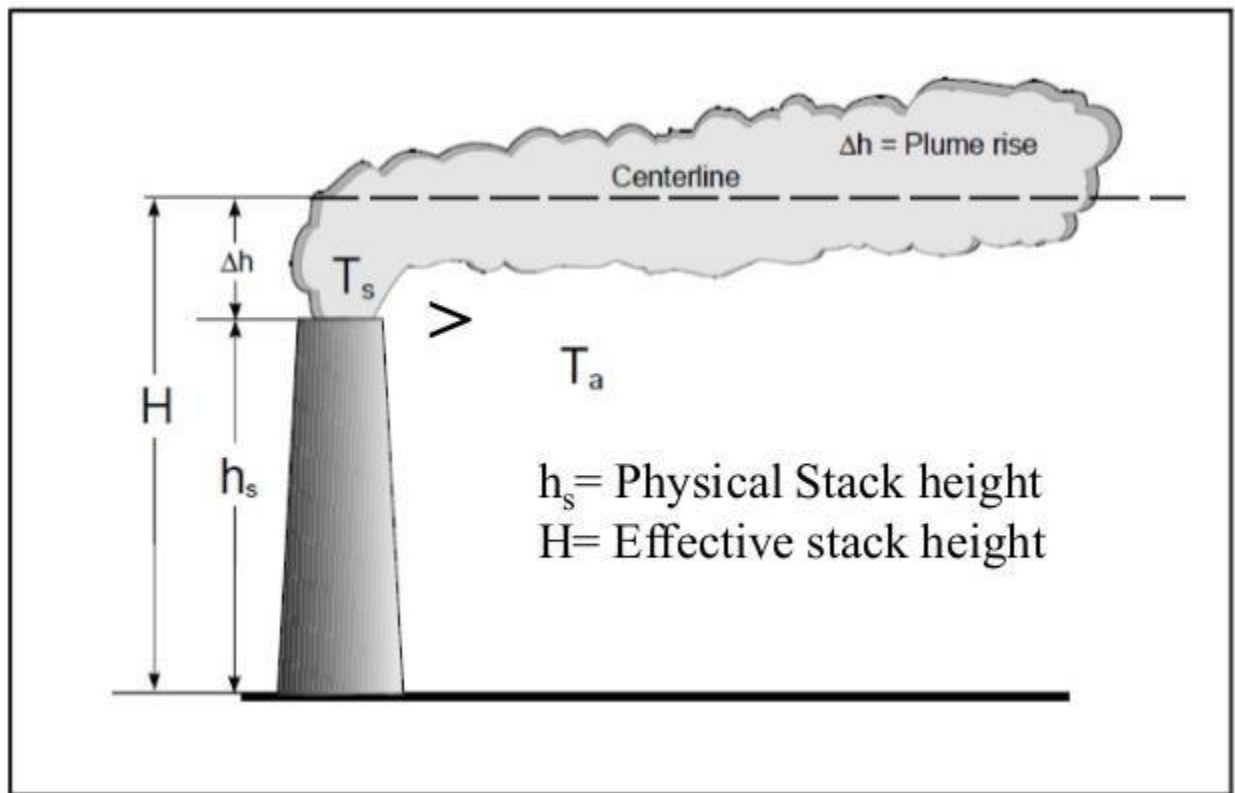
The height of the stack and the plume rise play a major role in the ground level concentrations expected on the downwind side. The plume rise typically increases the H by a factor of 2 to 10 times and can reduce maximum ground level concentration of pollutants by a factor of as much as 100.

Because of momentum and buoyancy, the plume released from the stack rises vertically up to a certain height and then gets dispersed by the wind. This height is called as the plume rise (Δh).

$$\text{Total plume rise } (\Delta h) = \Delta h_{\text{buoyancy}} + \Delta h_{\text{momentum}}$$

The height of the stack is an important factor in determining the level of pollution at a given location. The effective height of the stack (H) is the sum total of actual height (h) of the stack and plume rise (Δh) as shown in the figure.

The plume rise Δh depends upon many factors such as stack gas exit velocity, wind speed, diameter of stack, temperature of plume, lapse rate in the area etc. the several empirical formulae are there to predict it.



(i) General equation

In general, plume rise can be given by,

$$\Delta h = K \frac{Q_H^a}{u^Q}$$

Where, Q_H = heat emission rate

u = average wind velocity

α , β and K are constants, and according to Canadian combustion research laboratory formula of the above form, their values be $\alpha=0.25$, $\beta=1$ and $K=66.4$ when Q is expressed in kcal/s and u in m/s.

(ii) Moses and Carson's equation

$$\Delta h = C_1 \cdot \frac{V_s \cdot d}{u} + C_2 \cdot \frac{Q_H^{1/2}}{u}$$

Where, V_s = Stack gas exit velocity (m/s)

u = wind speed (m/s)

d = diameter of the stack (m)

Q_H = heat emission rate (kcal/s)

C_1 and C_2 = plume rise regression coefficients which depend on atmospheric stability

As per the above equations, Δh is inversely proportional to wind speed u , in the sense, higher the wind speed lower will be the plume rise, and Δh is directly proportional with stack gas velocity and heat release, in the sense, higher the stack gas velocity and its temperature higher will be the plume rise.

(iii) Holland's equation

$$\Delta h = \frac{V_s \cdot d}{u} [1.5 + (2.68 \times 10^{-3}) \cdot p \cdot d \left(\frac{T_s - T_a}{T_s} \right)]$$

Where, p = atmospheric pressure in millibars (mbars)

T_s = stack gas temperature (K)

T_a = air temperature (K)

This equation is applicable for neutral conditions.

For unstable conditions, the above value of Δh should be increased by 10 – 20%.

For stable conditions, Δh should be decreased by 20-10%.

(iv) Davidson and Bryant's equation

$$\Delta h = d \cdot \left(\frac{V_s}{u} \right)^{1.4} \left(1 + \frac{T_s - T_a}{T_s} \right)$$

(v) Brigg's formulae recommended by ISI

The bureau of Indian standards has suggested the use of Brigg's formulae (IS: 8829-1978).

a) For hot effluents (with heat release of order of 10^6 cal/s or more)

$$\Delta h = 0.84 (12.4 + 0.09h) \frac{Q_H^{1/4}}{u}$$

Where, Q_H = heat emission rate (cal/s)

h = height of the stack (m)

u = wind speed (m/s)

b) For not very hot releases (momentum is only the dominant factor here)

$$\Delta h = \frac{3 \cdot V_0 \cdot d}{u}$$

Where, V_o is afflux velocity (m/s)

Design of stack height

The basic function of a stack is to provide natural draft for the gases released from combustion process. Stacks are designed to fulfill two additional requirements (i) that the pollutants should be sufficiently dispersed and (ii) that the smoke should not re-enter the industrial plant under adverse wind conditions.

The ratio of stack gas exit velocity to wind velocity (V_s/u) should be greater than 1.5 to allow the effluent to get exit cleanly from the stack. For design purposes, maximum local wind velocities should be determined and stack gas exit velocities should be set according to that in proportions.

Higher the stack gas velocity higher will be the plume rise. Thus, to obtain same H, one can reduce h and increase Δh keeping higher exit velocities. This may reduce the initial cost for installment of stack. But to maintain such higher velocities, high capacity blowers are needed, that increases the running costs. And also if any buildings are present near to the stack, it may cause mechanical turbulence and may bring down all the pollutants. Hence the stack height should be at least 2 – 2.5 times the height of the surrounding building.

The diameter of the stack at exit end can be determined on the basics of stack gas flow rate and on the exit velocity required.

If h is more, H will also be more and better dispersion is possible. Smaller stacks may lead to higher ground level concentrations. The maximum concentration is usually inversely proportional to the square of the effective stack height. Central pollution control board (CPCB) has given the following recommendations for the minimum height of the chimney.

a) For chimney emitting particulate matter

$$h_{\min} = 74 (Q_p)^{0.27}$$

where Q_p is the PM emission rate (tones/hour)

b) For chimney emitting SO_2

$$h_{\min} = 14 (Q_s)^{1/3}$$

where Q_s is the SO_2 emission rate (kg/hour)

In India, the concentrations of other gases like NO_x , HC, CO etc. are generally very much less than the concentration of SO_2 and PM from various industries. Hence, CPCB has made only SO_2 and PM as the criterion for the design.

c) Minimum values

For any industry (except thermal power plants): $h_{\min} = 30m$

For thermal power plants of 200MW-500MW capacity: $h_{\min} = 220m$

For thermal power plants above 500MW capacity: $h_{\min} = 275m$

Problem 2.1: Determine the effective height of a stack, with the following given data:

Physical stack is 180m tall with 0.95m inside diameter, wind velocity is 2.75m/s, air temperature is $20^\circ C$, barometric pressure is 1000mbars, stack gas velocity is 11.12m/s, stack gas temperature is $160^\circ C$.

Soln: Given $h = 180m$, $D = 0.95m$, $u = 2.75m/s$, $T_a = 20^\circ C = 20 + 273 = 293 K$.

$p = 1000mbars$, $V_s = 11.12m/s$, $T_s = 160^\circ C = 160 + 273 = 433 K$.

$$\Delta h = \frac{V_s \cdot d}{u} [1.5 + (2.68 \times 10^{-3}) \cdot p \cdot d \left(\frac{T_s - T_a}{T_s} \right)]$$

$$\Delta h = \frac{11.12 \times 0.95}{2.75} [1.5 + (2.68 \times 10^{-3} \times 1000 \times 0.95 (\frac{433-293}{433}))]$$

$$\Delta h = 8.92m$$

Effective height of the stack $H = h + \Delta h$

$$H = 180 + 8.92 = 188.92m$$

Problem 2.2: An industry burns 0.3ML of oil fuel per month. The quantities of various pollutants emitted are given as: PM = 2.9t/ML/yr, SO₂ = 60t/ML/yr, NO_x = 8t/ML/yr, HC = 0.4t/ML/yr, CO = 0.5t/ML/yr. Calculate the height of the chimney required to be provided for safe dispersion of the pollutants.

Soln:

Industry is burning the oil 0.3ML/month.

Fuel burnt per year $0.3 \times 12months = 3.6$ ML

PM that may be emitted if 1ML/yr oil is burnt = 2.9tonnes,

$$\text{Then } Q_p \text{ (for burning 3.6ML/yr)} = 3.6 \times 2.9 = 10.44 \text{ t/yr} = \frac{10.44}{300 \times 24} = 1.45 \times 10^{-3} \text{ t/hr}$$

(Assuming 300 working days)

SO₂ that may be emitted if 1ML/yr oil is burnt = 60tonnes,

$$\text{Then } Q_s \text{ (for burning 3.6ML/yr)} = 3.6 \times 60 = 216 \text{ t/yr} = \frac{216 \times 1000}{300 \times 24} = 30 \text{ kg/hr}$$

a) Height of the chimney on the basis of PM emission

$$\begin{aligned} h_{min} &= 74 (Q_p)^{0.27} \\ h_{min} &= 74 \times (1.45 \times 10^{-3})^{0.27} \\ h_{min} &= 12.67m \end{aligned}$$

b) Height of the chimney on the basis of SO₂ emission

$$\begin{aligned} h_{min} &= 14 (Q_s)^{1/3} \\ h_{min} &= 14 \times 30^{1/3} = 43.45m \end{aligned}$$

Since 43.45m is more than minimum requirement (i.e., 30m)

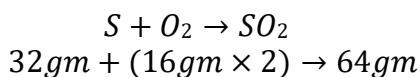
$h = 43.5m$ approx.

Problem 2.3: A thermal power plant daily burns 100tonnes of coal with 5.5% sulphur content. Calculate minimum stack height required. The particulate concentration in flue gases is 8000mg/m³ and the gas flow rate is 20m³/sec.

Soln:

Coal burnt = 100tonnes/day

Means Sulphur content of 100 tonnes coal is 5.5 tonnes/day



Since every 32gm of sulphur releases 64gm of SO₂,

$$\text{SO}_2 \text{ emission rate} = 5.5 \times \frac{64}{32} = 11 \text{ t/day} = 11000 \text{ kg/day} = \frac{11000}{24} = 458.33 \text{ kg/hr}$$

{Use this simple formula ($\text{SO}_2 = S \times \frac{64}{32}$), where S is sulphur content}

Height of the chimney on the basis of SO_2 emission,

$$h_{\min} = 14 (Q_s)^{1/3}$$

$$h_{\min} = 14 \times 458.33^{1/3} = 107.94 \text{ m} = 108 \text{ m}$$

Height of the chimney on the basis of PM emission,

PM concentration = 8000 mg for 1 m^3 volume = 8 g/m^3

Discharge rate is $20 \text{ m}^3/\text{s}$

PM emitted for $20 \text{ m}^3/\text{s}$ discharge = $8 \times 20 = 160 \text{ g/s} = 160 \times 3600 = 576000 \text{ g/hr} = 0.576 \text{ t/hr}$

$$h_{\min} = 74 (Q_p)^{0.27}$$

$$h_{\min} = 74 \times 0.576^{0.27}$$

$$h_{\min} = 63.76 \text{ m}$$

The minimum stack height to be provided is the maximum of 30m, 108m and 63.76m.

Thus, $h = 108 \text{ m}$

Air quality modeling

Pollutants emitted in to the atmosphere are mixed thoroughly with the surrounding air and diluted in the atmosphere. This dispersion is primarily due to turbulent diffusion and bulk air flow with high velocities. This understanding of dispersion theory of air pollutants is needed to know the concentration of pollutants at any point in the atmosphere after they are discharged.

This quantitative information of the pollutants at any point is essential for installing the control measures so that good air quality could be maintained.

Mathematical modeling – prediction of any parameter by using mathematical approach

“It is the mathematical simulation technique used to predict the dispersion and concentration of air pollutants in the atmosphere.”

“Air pollution modeling is the term used to describe using mathematical theory to understand or predict the way pollutants behave in the atmosphere.”

“It is the mathematical relationship between emissions and air quality that incorporates the transport, dispersion and transformation of compounds emitted into the air”

Mathematical approach has been applied for understanding the dispersion of pollutants into the atmosphere, and this dispersion is considered generally in three directions i.e., x, y and z.

For this, dispersion models are developed based on **Fick's law of molecular diffusion**. Using such mathematical relationships we can predict or determine the pollutant concentration at any distance in x, y and z directions i.e., horizontal downwind direction, horizontal cross wind direction and vertical direction respectively.

For continuous point source, the dispersion models are based on plume behavior, turbulent diffusion, wind speed, amount of dilution etc. because the continuous emission of pollutants results in a plume which is carried by the wind speed and spreads by the turbulence of wind.

Based on stability classification in the field of atmospheric diffusion the three well known models in use are,

1. Pasquill model

2. ASME model (American society of mechanical engineers model)
3. McElroy model

The variety of existing models may be classified according to the different attributes of a model as,

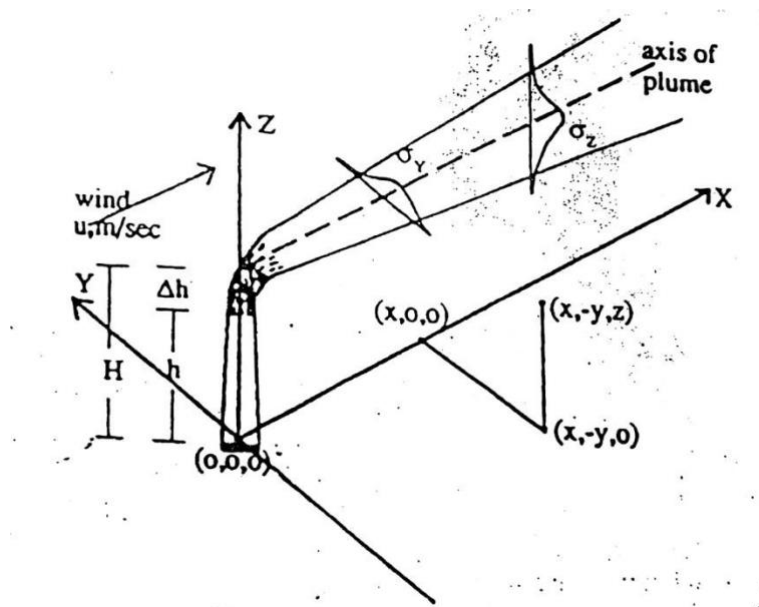
1. Eulerian grid model
2. Lagrangian trajectory model
3. Gaussian plume model

Gaussian plume model

Consider a point source somewhere in the air where a pollutant is released at a constant rate Q (g/s). The wind is blowing continuously in a direction x (measured in metres from the source) with a speed u (m/s). The plume spreads as it moves in the x direction such that the local concentrations $C(x,y,z)$ (g/m³) at any point in space form distributions which have shapes that are “Gaussian” or “normal” in planes normal to the x direction. As it moves in the x direction, on the centre line of the plume, concentration will be maximum, and it decreases because of lateral dispersion along y axis and z axis (on left side & right side as well as upside & downside of the center line of plume). This type of curve is known as Gaussian curve (shown in following figures).

The parameters σ_y and σ_z (m) are the standard deviations of these Gaussian distributions, which indicate the spread of the plume in the y and z directions, respectively. They increase with the distance x from the source.

This distribution measures y and z normally from the x -axis (the x -axis may also be considered to be the direction of the centre-line of the plume).



Gaussian developed following simple statistical equation to compute turbulent transport of plume,

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

$C_{x,y,z}$ = concentration of pollutant at any point (x,y,z) in space (g/m³)

Q = pollutant emission rate (g/s)

u = wind speed at stack height (m/s)

H = effective stack height (m)

If only concentrations at **ground level** are required (for example in assessing the exposure of crops or humans to the pollutant) then we can simplify the equation by setting $z=0$. This gives

$$C_{x,y,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

If only concentrations at ground level on the centre-line of the plume (along the x-axis direction) are required then the equation is simplified further since both $z=0$ and $y=0$. This gives

$$C_{x,0,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

Using the basic equation, if we know the rate of emission from the source (Q), the prevailing wind speed (U) and direction (x) and the height of the centre-line of the plume above ground (H), we can determine the concentration (C) at any point (x,y,z). Values for σ_y and σ_z are obtained with respect to x value from the graphs given below.

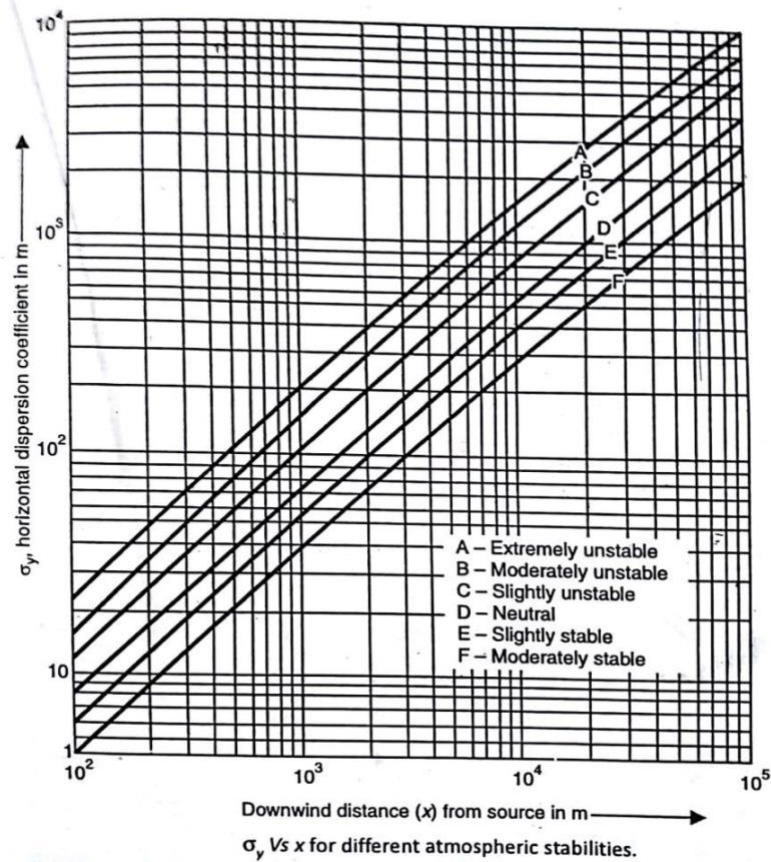
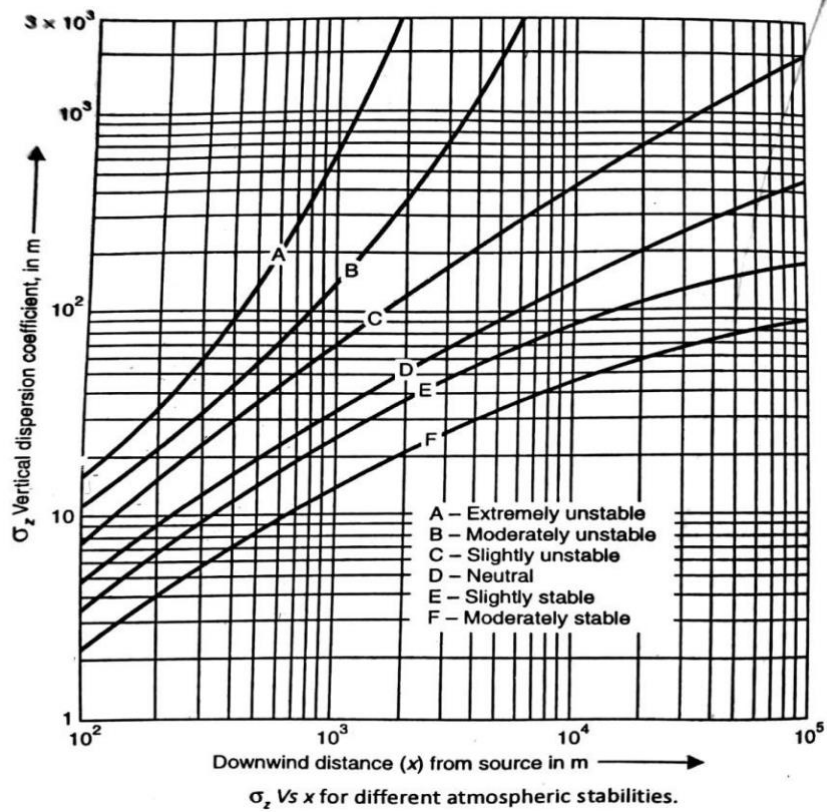
Maximum ground level concentration C_{max} should be substantially below the requirement of the ambient air quality standards and the stack height should be increased if this is not so.

It should be noted that the maximum ground level concentration occurs where $\sigma_z = \frac{H}{\sqrt{2}}$

σ_z / σ_y is constant with downwind distance x.

$$C_{max} = \frac{2Q}{\pi u e H^2} \cdot \frac{\sigma_z}{\sigma_y}$$

Pasquill-Gifford stability classes	
Class	Definition
A	Extremely unstable
B	Moderately unstable
C	Slightly unstable
D	Neutral
E	Slightly stable
F	Moderately stable



Assumptions of Gaussian model

1. The plume has Gaussian distribution in both horizontal and vertical planes with σ_y and σ_z as the standard deviations of the concentrations of the plume in crosswind and vertical directions respectively.
2. u is the wind speed at the stack exit which uniform all the time.
3. Uniform and continuous emission of Q (g/s) of pollutants takes place.
4. Diffusion of pollutant in x direction is negligible compared to diffusion in cross-wind direction. This is true if emission continuous and if wind speed is more than 1m/s.
5. Parameters governing the diffusion of pollutants do not change in space and time i.e., steady – state conditions prevail.
6. The terrain underlying the plume is flat.

Limitations

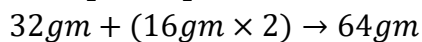
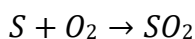
1. It does not consider the various stability layers at different heights in the atmosphere.
2. It does not consider the change in stability with time.
3. It does not consider the terrain characteristics such as terrain roughness, existence of mountains, valleys, distribution of lands and water masses.
4. It does not consider the strong wind shears like change of wind directions and wind speed.
5. It can be applied only for shorter distances and of shorter travel time.

Guidelines for determining Pasquill-Gifford stability classes					
Surface wind speed (ms^{-1})	Day with insolation			Night	
	Strong	Moderate	Slight	Overcast or $\geq 4/8$ low	$\leq 3/8$
				low cloud	cloud
2	A	A-B	B	–	–
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

Problem 2.4: A thermal power plant burns coal at the rate of 8tonnes per hour and discharges the flue gases through a chimney having effective height of 90m. The coal has a sulphur content of 4.5%. The wind velocity at stack exit is 7.5m/s. The atmospheric conditions are slightly unstable. Determine the maximum ground level concentration of SO_2 and the distance from the stack at which this occurs

Soln: Coal burnt per hour = 8tonnes= 8000kg

Sulphur content of 8tonnes coal = $8000 \times 0.045 = 360\text{kg}$



$$SO_2 = S \times \frac{64}{32} = 360 \times 64/32 = 720\text{kg } SO_2 \text{ produced per hour}$$

$$\text{Thus, } SO_2 \text{ emission rate} = \frac{720 \times 1000}{3600} = 200g/s$$

Maximum ground level concentration occurs at a point where $\sigma_z = \frac{H}{\sqrt{2}} = 0.707H$

$$\sigma_z = \frac{90}{\sqrt{2}} = 63.64m$$

For slightly unstable condition, we have stability class C.

From graph σ_z Vs x , for $\sigma_z = 63.64m$ we can obtain $x_{max} = 900m$

From graph σ_y Vs x , for $x = 900m$ we can obtain $\sigma_y = 100m$ for C class stability.

Now,

$$C_{max} = \frac{2Q}{\pi u e H^2} \cdot \frac{\sigma_z}{\sigma_y}$$

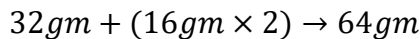
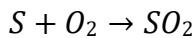
$$C_{max} = \frac{2 \times 200}{\pi \times 7.5 \times 2.7183 \times 90^2} \times \frac{63.64}{100}$$

$$C_{max} = 4.9 \times 10^{-4} \text{ g/m}^3$$

Problem 2.5: A thermal power plant burns coal at the rate of 8tonnes per hour and discharges the flue gases through a chimney having effective height of 90m. The coal has a sulphur content of 4.5%. The wind velocity at stack exit is 7.5m/s. The atmospheric conditions are slightly unstable. Determine GLC at a distance 2000m downwind at a) centre line of the plume and b) at a cross wind distance of 400m on either side of the centre line.

Soln: Coal burnt per hour = 8tonnes= 8000kg

Sulphur content of 8tonnes coal = 8000 x 0.045= 360kg



$$SO_2 = S \times \frac{64}{32} = 360 \times 64/32 = 720kg \text{ SO}_2 \text{ produced per hour}$$

$$\text{Thus, SO}_2 \text{ emission rate} = \frac{720 \times 1000}{3600} = 200g/s$$

we have $x = 2000m$

Then $\sigma_z = 130m$

$\sigma_y = 210m$ for C class stability

a) GLC at a distance 2000m downwind at centre line of the plume

$$C_{x,0,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

$$C_{2000,0,0} = \frac{200}{\pi \times 7.5 \times 130 \times 210} \cdot e^{-\frac{1}{2} \left(\frac{90}{130} \right)^2}$$

$$C_{2000,0,0} = 2.45 \times 10^{-4} \text{ g/m}^3$$

b) GLC at a distance 2000m downwind and at a cross wind distance of 400m

$$C_{x,y,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

$$C_{2000,400,0} = \frac{200}{\pi \times 7.5 \times 210 \times 130} \cdot e^{-\frac{1}{2} \left(\frac{400}{210} \right)^2} \cdot e^{-\frac{1}{2} \left(\frac{90}{130} \right)^2}$$

$$C_{2000,400,0} = 0.4 \times 10^{-4} \text{ g/m}^3$$

Problem 2.6: For the data given in above problem, compute the concentration at x = 1000m, y = 100m and z = 20m.

Soln:

we have x = 1000m

Then $\sigma_z = 68\text{m}$

$\sigma_y = 115\text{m}$ for C class stability

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

$$C_{1000,100,20} = \frac{200}{2\pi \times 7.5 \times 115 \times 68} \cdot e^{-\frac{1}{2} \left(\frac{100}{115} \right)^2} \left[e^{-\frac{1}{2} \left(\frac{20-90}{68} \right)^2} + e^{-\frac{1}{2} \left(\frac{20+90}{68} \right)^2} \right]$$

$$C_{1000,100,20} = 0.59 \times 10^{-4} \text{ g/m}^3$$

Problem 2.7: Find the effective stack height if a 40m stack releases SPM at a rate of 1.25g/s. The atmospheric pressure is 1.08kg/cm². The temperatures of ambient air and gas are 27°C and 400°C. The stack diameter is 2.3m. Stack gas velocity is 6.0m/s and the wind velocity is 1.8m/s. Also find GLC at 1km, 5km distances in the direction of wind.

Soln: Given h= 40m, d=2.3m, u=1.8m/s, Ta=27°C=27+273=300 K.

p = 1.08kg/cm² = 1.059bars (1bar = 1.0198kg/cm²) then p = 1059mbars

Vs = 6.0m/s, Ts = 400°C = 400+273 = 673 K.

$$\Delta h = \frac{V_s \cdot d}{1.8} \left[1.5 + (2.68 \times 10^{-3}) \cdot p \cdot d \left(\frac{T_s - T_a}{673} \right) \right]$$

$$\Delta h = \frac{6 \times 2.3}{1.8} \left[1.5 + (2.68 \times 10^{-3} \times 1059 \times 2.3 \left(\frac{673-300}{673} \right)) \right]$$

$$\Delta h = 39.78\text{m}$$

Effective stack height H = h + Δh = 40 + 39.78 = 79.78m

Assuming conditions for poor dispersion, moderately stable atmosphere (F class stability)

x	1km=1000m	5km=5000m
σy, m	38	160
σz, m	15	33

At

1km

downwind,

$$C_{x,0,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

$$C_{1,0,0} = \frac{1.25}{\pi \times 1.8 \times 38 \times 15} \cdot e^{-\frac{1}{2} \left(\frac{79.78}{15} \right)^2} = 2.796 \times 10^{-10} \text{ g/m}^3$$

At 5km downwind,

$$C_{x,0,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

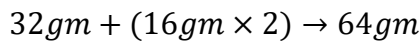
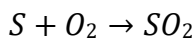
$$C_{5,0,0} = \frac{1.25}{\pi \times 1.8 \times 160 \times 33} \cdot e^{-\frac{1}{2} \left(\frac{79.78}{33} \right)^2} = 2.25 \times 10^{-6} \text{ g/m}^3$$

Problem 2.8: A thermal power plant burns 5.45 tonnes with 4.2% sulphur per hour and discharges through a stack of effective height 75m. The average wind speed at top of stack is 6m/s. The atmosphere is slightly unstable. Find a) maximum G.L.C and the corresponding distance b) G.L.C. at 3km downwind and 0.4km cross wind distance.

Soln:

Coal burnt = 5.45tonnes/hour

Sulphur content of 5.45 tonnes = $\frac{4.2}{100} \times 5.45 = 0.2289 \text{ tonnes} \cong 229 \text{ kg}$



$$SO_2 = S \times \frac{64}{32} = 229 \times 64/32 = 458 \text{ kg } SO_2 \text{ produced per hour}$$

$$\text{Thus, } SO_2 \text{ emission rate} = \frac{458 \times 1000}{3600} = 127.22 \text{ g/s}$$

a) maximum G.L.C and the distance at which it occurs

$$\text{Max. GLC occurs at a point where } \sigma_z = \frac{H}{\sqrt{2}} = 0.707H$$

$$\sigma_z = \frac{75}{\sqrt{2}} = 53 \text{ m}$$

Considering slightly unstable condition, we have stability class C.

From graph σ_z Vs x , for $\sigma_z = 53 \text{ m}$ we can obtain $x_{\max} = 700 \text{ m}$

From graph σ_y Vs x , for $x = 700 \text{ m}$ we can obtain $\sigma_y = 78 \text{ m}$ for C class stability.

$$C_{\max} = \frac{2Q}{\pi u e H^2} \cdot \frac{\sigma_z}{\sigma_y}$$

$$C_{\max} = \frac{2 \times 127}{\pi \times 6 \times 2.7183 \times 75^2} \times \frac{53}{78}$$

$$C_{\max} = 5.98 \times 10^{-4} \text{ g/m}^3$$

b) G.L.C. at 3km downwind and 0.4km cross wind distance.

1) GLC at 3km downwind

we have $x = 3000 \text{ m}$

Then $\sigma_z = 170 \text{ m}$

$\sigma_y = 280 \text{ m}$ for C class stability

$$C_{x,0,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

$$C_{3,0,0} = \frac{127}{\pi \times 6 \times 280 \times 170} \cdot e^{-\frac{1}{2} \left(\frac{75}{170} \right)^2} = 1.28 \times 10^{-4} \text{ g/m}^3$$

2) At 0.4km cross wind distance

For same x = 3000m

We have $\sigma_z = 170\text{m}$ $\sigma_y = 280\text{m}$ for C class stability

$$C_{x,y,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \cdot e^{-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2} \cdot e^{-\frac{1}{2} \left(\frac{H}{\sigma_z} \right)^2}$$

$$C_{3,0.4,0} = \frac{127}{\pi \times 6 \times 280 \times 170} \cdot e^{-\frac{1}{2} \left(\frac{400}{280} \right)^2} \cdot e^{-\frac{1}{2} \left(\frac{75}{170} \right)^2}$$

$$C_{3,0.4,0} = 4.62 \times 10^{-5} \text{ g/m}^3$$

Measurement of meteorological parameters

A meteorological instrument should have an acceptable degree of accuracy and sensitivity. Also it should be simple and durable. In our country the National environmental engineering research institute (NEERI) has developed some devices for measuring meteorological parameters.

(i) *Wind direction recorders*

a) *Windsocks*

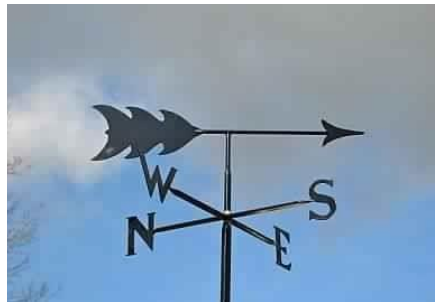
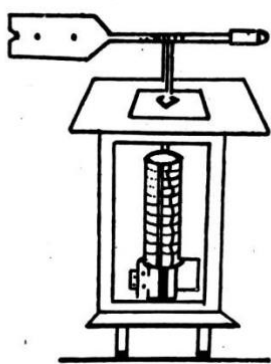
windsocks are very basic devices that measure wind direction and provide a rough idea of the wind's intensity. They comprise a tubular piece of fabric or thin, flexible fabric attached to a pole. In windless conditions, the fabric hangs vertically from the attached pole. When wind begins to blow, it fills the windsack and causes the sides to expand away from each other. This results in the windsack's rounded, cylindrical appearance and also causes the windsack to rise up to a horizontal position. Either the pole or the harness attached to the windsack can rotate when the wind changes direction, so the direction of the windsack will indicate that of the wind.



b) Wind vanes

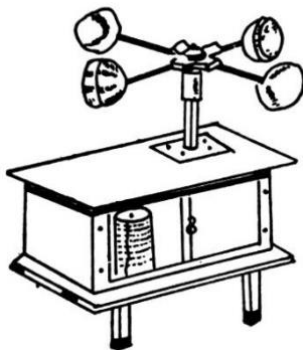
This instrument has been developed by NEERI for measuring wind direction, which is simple one, which employs the conventional wind vane to sense the direction. It is automatic and operated mechanically without any power supply. The instrument continuously records on an attached chart the direction of the wind with time.

A weather vane / wind vane works similarly to a windsock. Instead of a tubular sock, this instrument consists of a horizontal pole placed atop a vertical one. The poles are joined together so that the horizontal pole can move independently of the structure's base. The horizontal pole has a flattened, vertical end that reacts to wind. This flattened end may be any broad, flat shape, such as the traditional rooster shape. When wind blows on the broad side of this end, it pushes it, causing the pole to rotate. When the pole has rotated to a position parallel to the wind's direction, the flattened end also sits parallel, and air moves by it on either side without having any further effect on the pole's position.



(ii) Wind speed recorder

Instruments for measuring wind speed are called anemometers. If they are recording instruments they are known as anemographs. The most common type is cup anemometer. The rate of rotation of the shaft to which the cups are attached indicates the wind speed and this is transmitted to a recorder or an indicating panel by either mechanical, optical or electrical means. The Neeri has developed a wind speed recorder. In the instrument a 4 cup rotor is employed to sense the wind. The motion of the cup is transferred after reducing its speed by a gear system, to the pen which makes a continuous rise and fall impression on the chart paper. This rate of rise or fall is proportional to the wind speed. The instrument gives a 24 hour record in one setting. Wind speed at a particular time and average wind speed can be found out from this record.



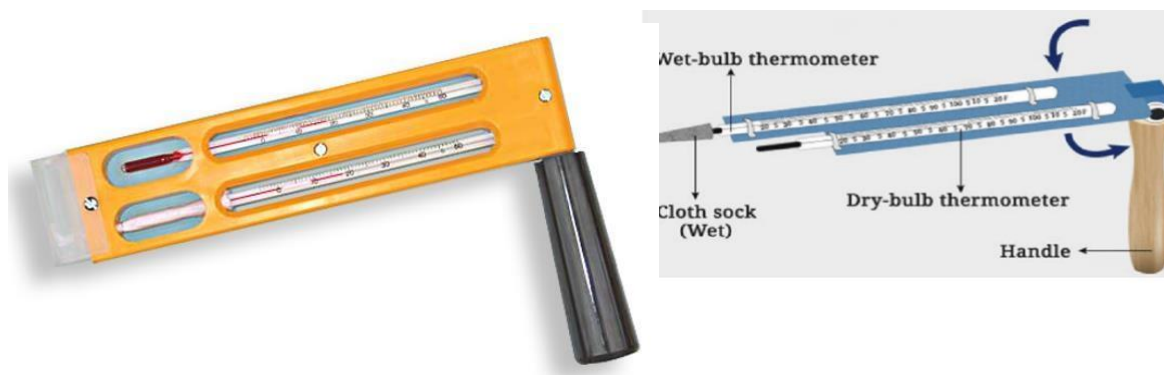
THE ROBINSON ANEMOMETER.



(iii) *Humidity measurement*

One of the simplest and most reliable instruments is the whirling psychrometer. Other instruments that can be used are 1) Hair hygrometer 2) Infra-red hygrometer.

The whirling psychrometer consists of two thermometers mounted on a frame that can be whirled in the air by hand. The bulb of one thermometer is covered with a tight-fitting muslin sack and wetted with water. This thermometer is known as the wet-bulb thermometer. The other is the dry-bulb thermometer. The psychrometer is whirled to force air past the bulbs. The dry bulb indicates the temperature of the air. The wet bulb helps determine the relative humidity. When the psychrometer whirls through the air, water from the muslin evaporates. The evaporating water cools the wet bulb. The amount of cooling that occurs depends on the relative humidity. The lower the humidity, the faster the water in the muslin will evaporate, and the more the bulb will cool. High humidity will cause less evaporation, slowing the cooling process. From the difference in temperatures of wet and dry bulb thermometers, the relative humidity can be found by referring to a special chart (psychrometric table).



Wind roses

For better understanding of dispersion of pollutants in the atmosphere, a knowledge of usual/frequent wind direction as well as wind speed is essential. This type of information varies significantly from city to city and varies in a particular city from month to month. The wind data (i.e., wind direction, wind duration, intensity (speed)) are graphically represented by a diagram called wind rose.

“Wind rose is defined as any one of a class of diagrams designed to show the distribution of wind direction experienced at a given location, over a considerable period.”

The wind data should usually be collected for a period of at least 5 years and preferably of 10 years, so as to obtain an average data with sufficient accuracy.

The most common form of wind rose consists of a circle and data are usually reported at eight primary and eight secondary directions of the compass by lines. The length of each line denotes the frequency of wind from that direction and frequency of calm conditions is entered in the centre. There are many variations in construction of wind roses, some indicate wind speeds along with specific wind directions, some indicate any other meteorological parameter along with wind direction.

From the data obtained over a given time period such as a particular month or season or a year, the construction of wind roses may be done. In constructing or interpreting wind roses, wind direction refers to the direction from which wind is blowing. For example, a line/bar extending to the south of the wind rose indicates the frequency of winds blowing from the south. The wind rose diagram is prepared using an appropriate scale to represent percentage frequencies of wind directions and appropriate index shades, lines, colours, textures etc. to represent various wind speeds.

Some times, special wind roses are constructed called ‘Pollution roses’ like

- 1) particulate wind rose
- 2) smoke wind rose
- 3) sulphur dioxide wind rose
- 4) hydrocarbon wind rose etc.

These are constructed by the parameters of particulate matter, smoke, SO₂, hydrocarbons, particulates etc. instead of wind speed.

Wind rose diagrams can be plotted in two types as follows.

Type 1 wind rose: In this type of wind rose, the radial lines indicate the wind direction and each circle represents the duration of wind. The observed values of the total percentage of time in a month or a year during which wind blows are plotted along the corresponding directions. All the plotted points are then joined by straight lines. The maximum wind blowing direction is usually along the direction of the longest line on the wind rose. This type of wind rose does not account for the effect of cross wind component.

Type 2 wind rose: In this type of wind rose, the wind intensity is represented by each circle to some scale. The values entered in each segment represent the percentage of time in a month or a year during which the wind, having particular intensity, blows from the respective direction.

Problem2.9: Draw the TYPE – 1 wind rose diagram for the following data

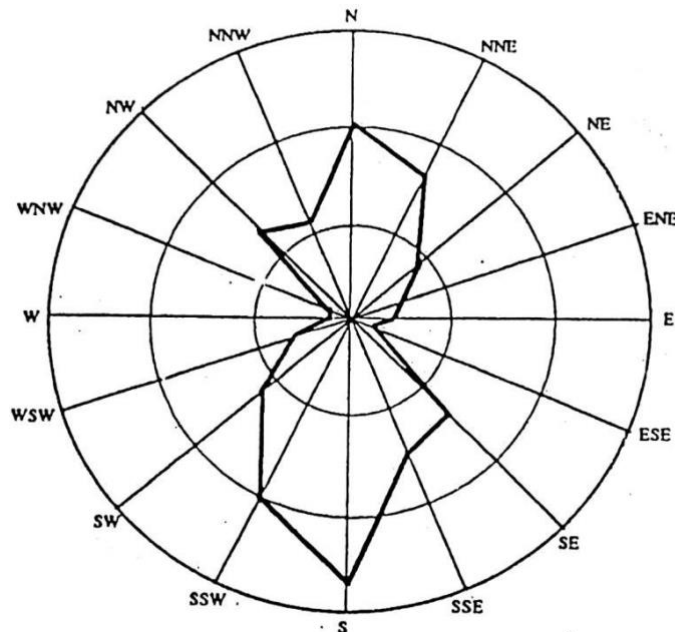
Wind direction	Duration of the wind, percent		
	6.4 -25 kmph	25-40 kmph	40-60 kmph
N	7.4	2.7	0.2
NN	5.7	2.1	0.3
E			
NE	2.4	0.9	0.6
ENE	1.2	0.4	0.2
E	0.8	0.2	0.0
ESE	0.3	0.1	0.0
SE	4.3	2.8	0.0
SSE	5.5	3.2	0.0
S	9.7	4.6	0.0
SS	6.3	3.2	0.5
W			
SW	3.6	1.8	0.3
WSW	1.0	0.5	0.1
W	0.4	0.1	0.0
WNW	0.2	0.1	0.0
NW	5.3	1.9	0.0
NNW	4.0	1.3	0.3

Soln:

Wind direction	Duration of the wind, percent			Total wind duration in a particular direction (%)
	6.5 -25 kmph	25-40 kmph	40-60 kmph	
N	7.4	2.7	0.2	10.3
NNE	5.7	2.1	0.3	8.1
NE	2.4	0.9	0.6	3.9
ENE	1.2	0.4	0.2	1.8
E	0.8	0.2	0.0	1.0
ESE	0.3	0.1	0.0	0.4
SE	4.3	2.8	0.0	7.1
SSE	5.5	3.2	0.0	8.7
S	9.7	4.6	0.0	14.3
SSW	6.3	3.2	0.5	10.0
SW	3.6	1.8	0.3	5.7
WSW	1.0	0.5	0.1	1.6
W	0.4	0.1	0.0	0.5
WNW	0.2	0.1	0.0	0.3
NW	5.3	1.9	0.0	7.2
NNW	4.0	1.3	0.3	5.6
The gross total of wind duration				86.5%

Therefore the percentage of time during which wind speed is less than 6.4kmph is $100-86.5 = 13.5\%$
Therefore calm period is 13.5%

In figure the radial lines indicate the wind direction and each circle represents the duration of wind. The total percentage of time in a year during which the wind blows from north direction is 10.3%. This value is plotted along the north direction. Similarly, other values are also plotted along the respective directions. All plotted points are then joined by straight lines as shown in figure.



Problem 2.10: Draw the TYPE – 1 and TYPE – 2 wind rose diagrams for the following data.

Wind	Duration of the wind, %		
direction	1-5 kmph	5-10 kmph	>10 kmph
N	10	10	8
NE	7	6	6
E	5	3	2
SE	4	2	0
S	2	1	1
SW	3	0	3
W	5	4	3
NW	5	5	5

CONTROL TECHNIQUES

(Control of Particulate matter & Gaseous pollutants – settling chambers, cyclone separators, scrubbers, filters and ESP)

4.1 Introduction

Everyday about half-a-million tonne of particulates (of sizes 100 μ m down to 0.1 μ m and even less) are released into the atmosphere by anthropogenic sources. Micro-scale particles may cause severe effects on man, material and vegetation.

Basically, there are 4 ways available for the control of industrial effluent discharges into atmosphere and thereby controlling the atmospheric pollution.

1. Reduction of pollutants discharge at the source by the application of control equipment
2. Reduction at the source through raw material changes, industrial operational changes or modifications, or replacement of process equipment (for ex., replacing older equipments with newer ones)
3. Dilution of the source discharge by installing taller stacks
4. Dispersion of source locations by adopting proper planning and zoning of industrial areas.

But the most effective ways are reduction at the source by application of control equipment and process control. To remove particulate matter from gases, various types of control equipments are available.

Factors to be considered for the selection of particular equipment -

1. Quantity of gas to be cleaned and its variation with time
2. Chemical, physical nature and concentration of the particulate matter to be removed
3. Temperature and pressure of the gas stream
4. Nature of the gas (for solubility and corrosive effects)
5. Desired/Required quality of the cleaned gas

Objectives of using control equipments –

1. Prevention of nuisance
2. Prevention of physical damage to the property
3. Elimination of the health hazards to plant employees and to the population living near the plant
4. Recovery of valuable waste products
5. Minimisation of economic losses through the reduction of plant maintenance
6. Improvement of product quality

4.2 Settling Chambers

The gravitational settling chambers are the simplest of all control equipments. Settling chamber is almost the cheapest device to construct, operate and maintain and serves as a pre-cleaner.

There are two primary types of settling chambers: the expansion chamber and multiple-tray chamber. In the expansion chamber, the velocity of the gas stream is reduced as the gas expands in a large chamber. Reduction in velocity allows larger particles to settle down.

Settling chamber serves as a preliminary screening device usually. Where the mass of larger particles is more, the settling chamber can remove much of the mass of particulate matter, otherwise other control devices would be choked up and their operation will be impaired, leading to frequent cleaning. Thus in majority of particulate control devices, the first unit is a gravity settling chamber.

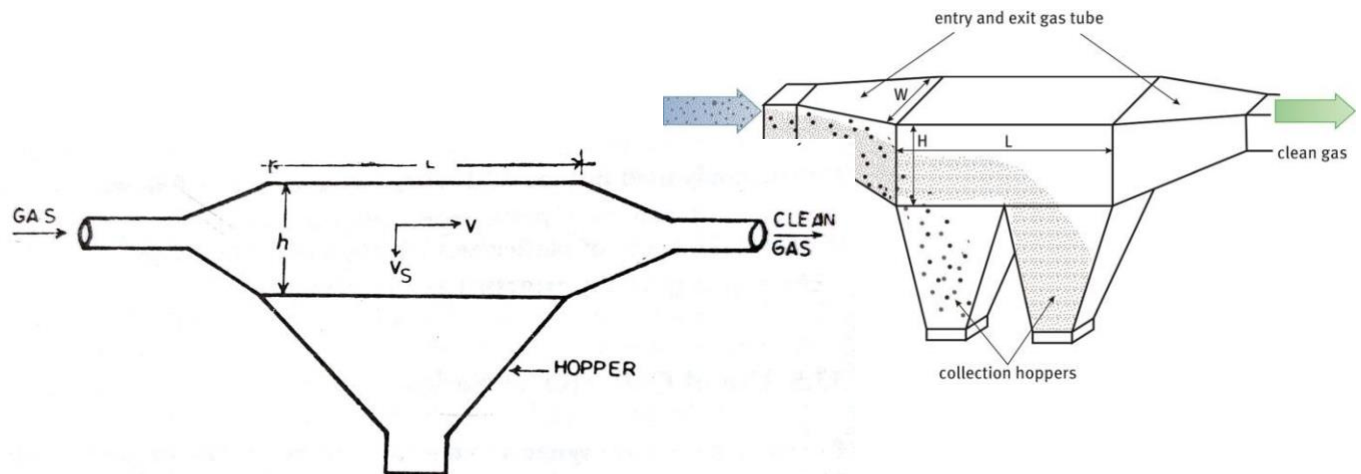
4.2.1 Principle, Construction and Working of settling chambers

Principle:

Gravitational force may be employed to remove particulates in settling chambers. Carrier gas velocity is reduced to induce the action of gravity on the particles. For settling operations, Stoke's law is applied. Gravity settling chambers are provided with enlarged areas to minimise horizontal velocities and allow time for the vertical velocity to carry the particulate to the bottom of the tank. Settling chambers are effective for large and/or dense particles.

Construction:

The most common type of settling chamber consists of a long box like structure, with an inlet at one end and an outlet at the other end, set horizontally, often on the ground. It can be constructed from brick and concrete. A hopper is provided at the bottom to collect the particulates.



Working:

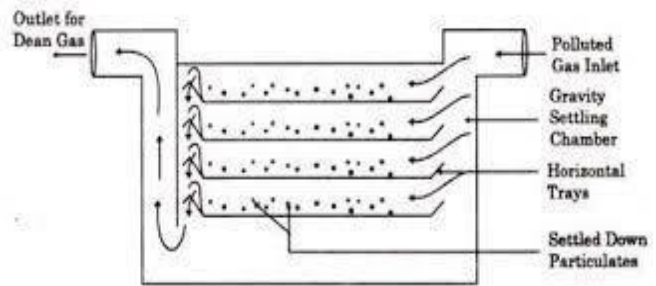
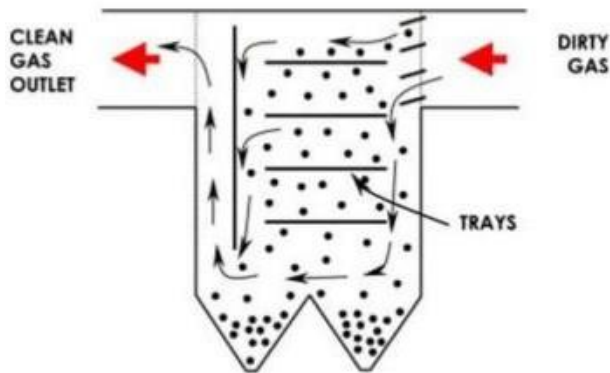
The carrier gas is made to pass inside the chamber through inlet provided at one end, with lower velocities. The solid particulates having higher density than the surrounding gas, settle due to action of gravity on the base of the chamber. The cleaned gas will come out through the outlet provided at another end. The settled out particulates are then collected from the hopper for disposal.

The gas velocity must be sufficiently low (less than about 3m/s to prevent particle re-entrainment, less than 0.5m/s for better results). To minimise turbulence and maintain uniform velocity, curtains, rods and wire mesh screens may be provided in the chamber.

4.2.2 Howard's settling chamber

A multiple-tray settling chamber is referred to as Howard's chamber. A multiple-tray settling chamber consists of a number of thin trays closely spaced within the chamber, which causes the gas flow horizontally between them. Usually the trays are fitted at 1-3cm spacing. The collection efficiency generally improves because the particles have much shorter height to fall down. Efficiency can be improved if the height to be travelled by the particle is reduced. Particles of size 10-15 μ can be removed by this modified settling chamber. But the use of this modified Howard's chamber is limited due to difficulty in cleaning the closely spaced trays.

TRAY ARRANGEMENTS



4.2.3 Design considerations

Generally, settling chamber design based on laminar flow requires either a large size or large number of trays. Practically, the flow is turbulent rather than laminar.

Consider a settling chamber having dimensions $L \times W \times H$ and containing 'n' number of trays including bottom surface, assuming laminar conditions.

The criterion for laminar flow is that Reynold's number, which is based on hydraulic diameter, should be less than 2300. The hydraulic diameter for flow passage between the trays is given by

$$D_h = \frac{2W \Delta H}{W + \Delta H} \quad \text{----- 4.1}$$

The Reynold's number, $Re = \frac{VD_h \rho}{\mu} \quad \text{----- 4.2}$

Velocity inside the chamber can be given by, $V = \frac{Q}{nW \Delta H} \quad \text{----- 4.3}$

Substituting eq. 4.1 & 4.3 in eq. 4.2,

$$Re = \frac{2Q\rho}{n\mu(W + \Delta H)} \quad \text{----- 4.4}$$

If thickness of the thin trays is neglected, the space between the trays is $\Delta H = \frac{H}{n}$

Then eq. 4.4 becomes

$$Re = \frac{2Q\rho}{\mu(nW + H)} \quad \text{----- 4.5}$$

A particle entering the chamber at the top will be collected by the chamber, if its settling time is the same (or less than) the time the gas takes to pass through the chamber (from inlet to outlet).

For laminar conditions ($Re < 2300$) within the trays, particles of size d_p will settle to a height of h with settling velocity V_s in time t . Thus $t = \text{distance/velocity} = h/V_s$

During the same time the particles are transported horizontally a distance L , with horizontal velocity of the gas stream V . Thus $t = L/V$.

Equating these two, $\frac{h}{V_s} = \frac{L}{V}$

$$V_s = \frac{hV}{L} \quad \text{----- 4.6}$$

Height through which the particulates travel before settling down, $h = \frac{V_s \cdot L}{V}$

$$\text{Efficiency, } \eta = \frac{h}{\Delta H} = \frac{L V_s}{V H} = \frac{L V_s n}{V H} = \frac{n W L V_s}{Q} \quad \text{--- 4.7}$$

The V_s can be calculated using Stoke's law

$$V_s = \frac{g \cdot (d_p)^2 \cdot (\rho_p - \rho)}{18\mu} \quad \text{--- 4.8}$$

Where, d_p = diameter of the particle

g = acceleration due to gravity

ρ_p = density of the particles

ρ = density of the gas

μ = viscosity of the gas

From eq. 4.6 and 4.7,

$$dp = \sqrt{\frac{18Vh\mu}{Lg(\rho_p - \rho)}} \quad \text{--- 4.9}$$

$$\text{And also } dp = \sqrt{\frac{18\mu Q}{WLg(\rho_p - \rho)}} \quad \text{--- 4.10 (another formula)}$$

If the flow is turbulent, the collection efficiency can be given by

$$\eta = 1 - e^{-\left[\frac{nLV_s}{Q}\right]} \text{----- 4.11}$$

4.2.4 Advantages and disadvantages of settling chambers

Advantages

1. Low initial costs
2. Simple construction, no moving parts
3. Low maintenance costs
4. Low pressure drop
5. Dry and continuous disposal of solid particles
6. Excellent reliability
7. It can be constructed out of almost any material

Disadvantages

1. Large space requirements
2. Unable to handle sticky and tacky particles
3. Trays in Howards chamber may warp during high temperature operations
4. Only larger particulates can be collected ($>40\mu$)

4.3 Cyclone Separators

Cyclone separators are the most common separating devices called as centrifugal or inertial separators because of the use of centrifugal force or action for the separation process. A cyclone collector can be defined as “a structure without any moving parts in which the velocity of an inlet gas stream is transformed into a confined vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body”.

It depends upon centrifugal force instead of gravity to separate the particles from the gas stream. Because the centrifugal force generated can be several times greater than the gravitational force, particles that can be removed in centrifugal collectors are much smaller than those that can be removed in gravity settling chambers.

During cyclonic separation, carrier gas rotational velocity (velocity of vortex flow inside cyclone) may exceed several times the average inlet velocity.

4.3.1 Principle, Construction and Working of Cyclone Separators

Principle:

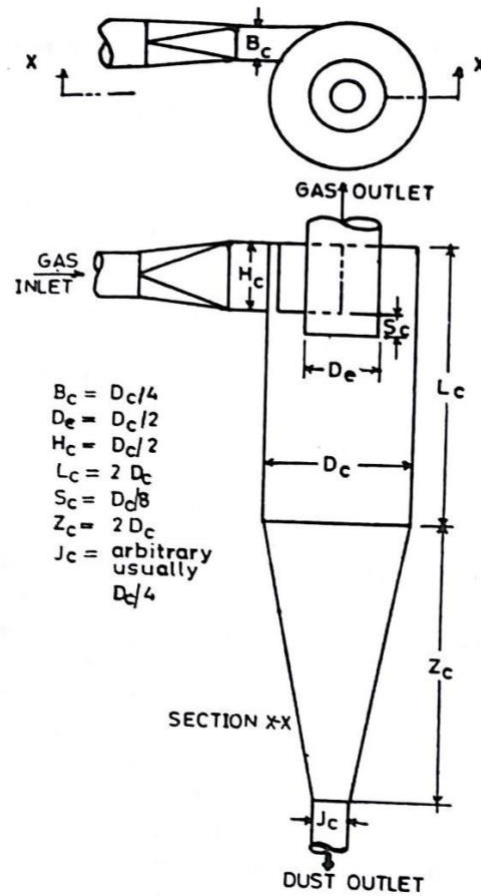
Centrifugal force separates the particulates from the gas stream instead of gravitational force. Velocity of an inlet gas stream is transformed into a confined vortex from which centrifugal forces tend to drive the suspended particles to the wall of the cyclone body.

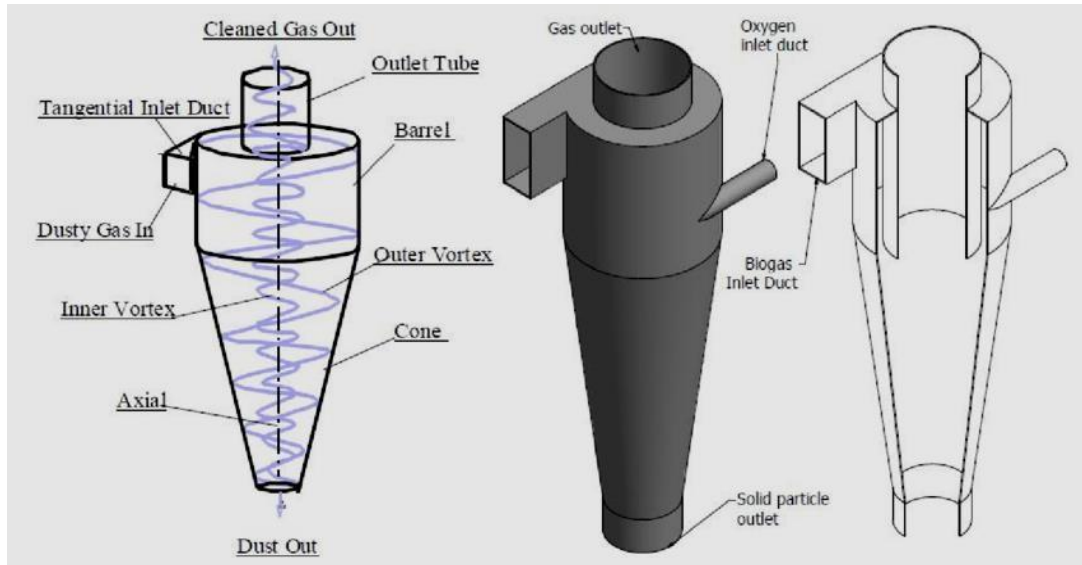
Construction:

Generally a cyclone separator consists of a vertically placed cylinder, an inverted conical base attached to the bottom of the cylinder, a dust hopper too collect the dust and an inlet from where the dirty gas enters the cyclone. Outlet for clean gas is provided in the centre at the top. All the parts of the cyclone are designed as per the standard set of dimensions as shown in the figure.

Working:

The dirty gas consisting of particulates is made to enter the cyclone with higher velocities through inlet, tangentially to the cylinder. The gas path generally follows a double vortex. First, the gas spirals downwards along the wall of the cylinder and continues through conical portion and reaches the bottom. Then, second, the gas stream moves upwards in a narrower inner spiral, concentric with the first and comes out from the cyclone through the outlet pipe. Due to the rapid spiralling movement of the gas, the particles are thrown to the wall by the centrifugal force and then they fall to the bottom of the body by gravity. They are collected in a storage hopper.





4.3.2 Design considerations:

1. A set of sizes of various parts of the cyclone

Diameter of the cyclone cylinder = D_c , Diameter of the gas exit $D_e = D_c/2$, Length of cylinder $L_c = 2 D_c$, Length of the cone $Z_c = 2 D_c$, Height of the entrance/inlet $H_c = D_c/2$, Width of the entrance/inlet $B_c = D_c/4$, Diameter of dust exit $J_c = D_c/4$

2. Separation factor

In a cyclone, the initial separating force is the radial component of the centrifugal force and is a function of tangential velocity. The centrifugal force F_c is given by,

$$F_c = \frac{m V_0^2}{R}$$

$$\text{Separation factor } S = \frac{V_0^2}{g R}$$

Higher the separation factor, the better is the performance of the cyclone.

3. Efficiency

$$\eta = \frac{1}{d_p^2}$$

$$1 + \left(\frac{PC}{d_p} \right)$$

4. Cut size

Cut size (d_{PC}) is the size of those particles that are collected with 50% efficiency. Collection efficiency will be greater than 50% for the particles larger than d_{PC} . Collection efficiency will be less for smaller particles.

The extremely smaller particles than d_{PC} may be collected in very less quantity or they may not be collected. Thus d_{PC} is the diameter of the smallest particle which can be theoretically completely separated from the gas stream.

$$d_{PC} = \sqrt{\frac{9 \mu B_c}{2\pi V_i N_t (\rho_p - \rho)}}$$

5. Number of cyclones

If Q is total volumetric flow, then $Q = VA$

A is total area of cyclone including of all cyclones

V is inlet velocity

Then $Q = VA = V_i B_c H_c n$

$$\text{Number of cyclones (n)} = \frac{Q}{V_i B_c H_c}$$

6. Number of turns

Number of turns made by inlet gas in main outer vortex inside the cyclone

$$N_t = 1.5 \times \frac{L_c}{H_c}$$

Or

$$N_t = \frac{1}{H_c} \left[L_c + \frac{Z_c}{2} \right]$$

4.3.3 Operating Problems

There are 3 important operating problems associated with cyclones. They are erosion, corrosion and material build-up.

Erosion: Heavy, hard, sharp-edged particles, in a high concentration, moving at high velocity in the cyclone, continuously scrape against the wall and can erode the metallic surface. Therefore suitable body material is used.

Corrosion: This problem occurs if the cyclone operates at lower temperatures and when reactive gases are present. The best solution to any corrosion problem in a cyclone is to maintain the temperature above the dew point. If the gas and dust are corrosive at low temperatures then perhaps the only alternative is to use a stainless alloy.

Build-up of dust cake: It occurs most frequently on the cyclone walls. It can be removed periodically and scrapped.

4.3.4 Advantages and Disadvantages of Cyclone separators

Advantages

1. Low initial cost
2. Simple construction and operation
3. Low pressure drop
4. Low maintenance requirements
5. It has no moving parts
6. Continuous disposal of solid particulates
7. They can be constructed of any material

Disadvantages

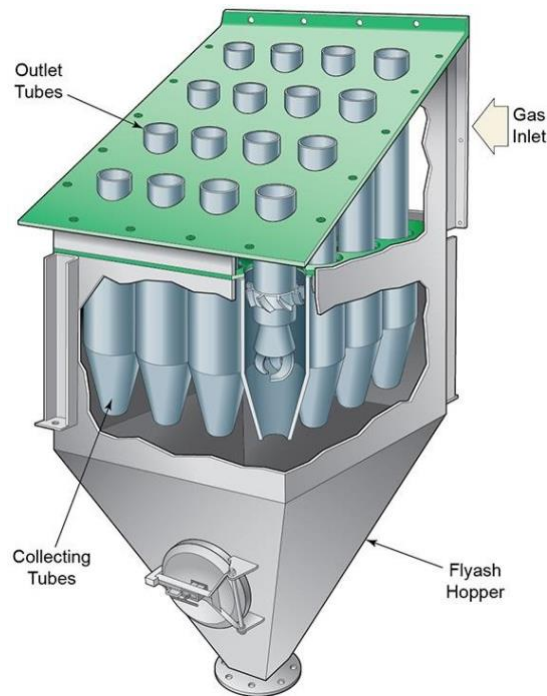
1. Low collection efficiency for particulates below 5-10 μ
2. Equipment is subject to severe abrasive deterioration
3. Decreasing collection efficiency for decreasing particulate concentration.

4.3.5 Applications

Cyclones are used widely for control of particulates in industrial operations such as cement manufacture, feed & grain processing, food and beverage processing, mineral processing, paper and textile industry, and wood working industries.

Cyclones are also used to separate dust in disintegration operations, such as rock crushing, ore handling and sand conditioning in industries. They are also used in the recovery of catalyst dusts in the petroleum industry, and in the reduction of fly ash emissions.

Multiple cyclone separator unit



4.4 Fabric Filters

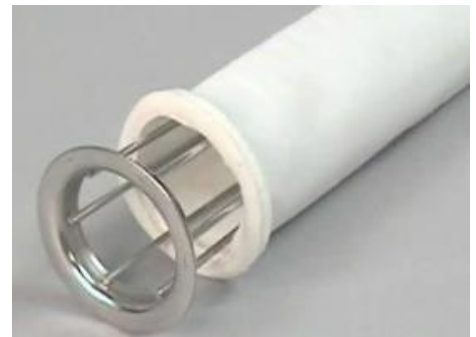
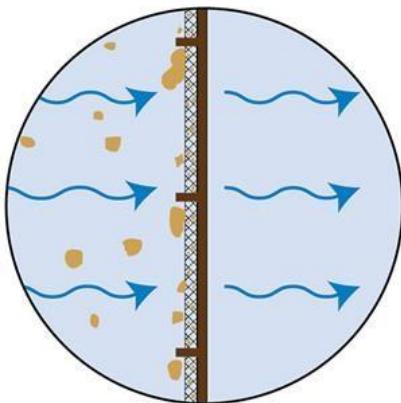
One of the oldest and most widely used methods of separating particulates from carrier gas is 'Filtration'. A filter is generally a porous structure composed of granular or fibrous material which tends to retain the particulates and allows the gas to pass through the voids of the filter. The filter is constructed of any material compatible with the carrier gas and particulates and may be arranged in 1) fabric or cloth filters 2) fibrous or deep bed filters.

In fabric/cloth filters, the filter is made of cloth material arranged in the form of tubular bags or cloth envelopes and is suitable for dust content of the order of 1g/m^3 . They are capable of removing dust particles as small as 0.5μ . In case of deep bed filters, the filter is made of fibrous material like mats of wool, cellulose etc. Deep bed filters have large void spaces of 97-99% of total volume and collection of particulates takes place in the interstices of the bed, and is suitable for light dust contents of the order of 1mg/m^3 .

4.4.1 Principle, construction and working of Fabric filter or Bag house filter

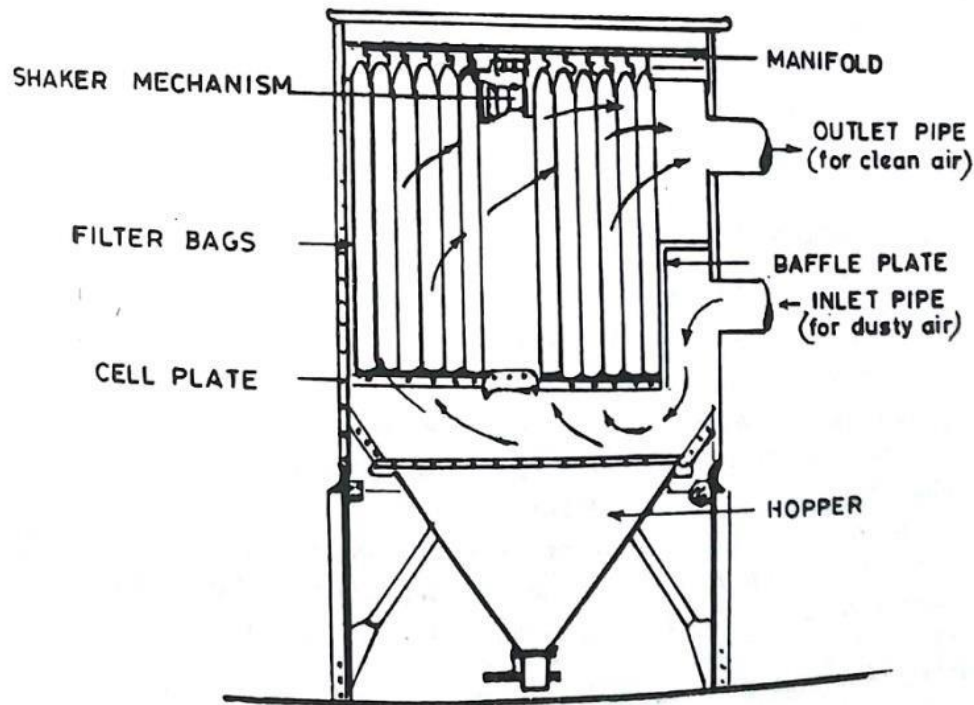
Principal

Separation of particulates from carrier gas stream is simply like sieving as the small pores of the fabrics retain the larger particles and allow only gas to pass through them. Basically, initial deposition of the particulates on the filter media takes place through interception and impingement of the particles on the fabric fibres. A pre-coat or the dust cake will be formed on the filter media within a minute or two. This dust cake/dust layer/pre-coat becomes itself a filtering media to retain more number of particles. The fabric fibres just act like matrix to support the dust cake/pre-coat. Efficiency will be comparatively low during the formation of pre-coat but efficiency increases after the formation of pre-coat.



Construction:

The most common type of fabric filter consists of tube shaped fabric bags. A bag house consists of numerous vertical bags of 120-400mm diameter and 2-10m long. The upper ends are closed and lower ends are open. The bags are suspended and attached to a manifold/shaking mechanism. The hopper at the bottom serves as a collector for the dust. A baffle plate is provided in front of the inlet.



Working:

The gas entering the house through inlet pipe strikes the baffle plate which causes the large particles to fall into a hopper due to gravity. The carrier gas then flows upward into the tubes with velocity of 0.4-1m/min and passes outward through the fabric leaving the particulate matter as a dust cake on inside walls of the bags. Efficiency during the formation of pre-coat is low, but efficiency increases after the formation of pre-coat. Once the pre-coat is formed, it acts as a filtering media which helps in further removal particulates. The clean gas comes out through the outlet.

The accumulation of dust on inside of the bags, increases air resistance therefore filter bags have to be cleaned periodically.

4.4.2 Factors affecting efficiency

1. **Excessive filter ratios** – ‘Filter ratio’ is defined as the ratio of the carrier gas volume to gross filter area, per minute flow of the gas. Excessive filter ratio lowers the removal efficiency and results in bag wear. Therefore low filter ratios are recommended for high concentration of particulate matter.

Filter ratio = Gas volume per minute flow/ Gross filter area

Gas volume per minute of flow = Volume/Time = Discharge (Q)

And we know that Discharge (Q) = c/s Area (A) x Velocity (V)

Thus Filter ratio = AV/Gross filter area

Here filter ratio is directly proportional to velocity. If the velocity increases, filter ratio increases. High velocities cause escaping of particulates through pores of filter media that decreases the efficiency. Thus low filter ratios are recommended.

2. **Improper selection of filter media** leads to lower removal efficiency and higher maintenance costs. While selecting filter media for bag house, we must consider the characteristics and

properties of carrier gas and dust particles such as temperature resistance of the material, resistance to chemical attack, abrasion resistance, carrier gas temperature, carrier gas composition, gas flow rate, size & shape of the dust particles and its concentration.

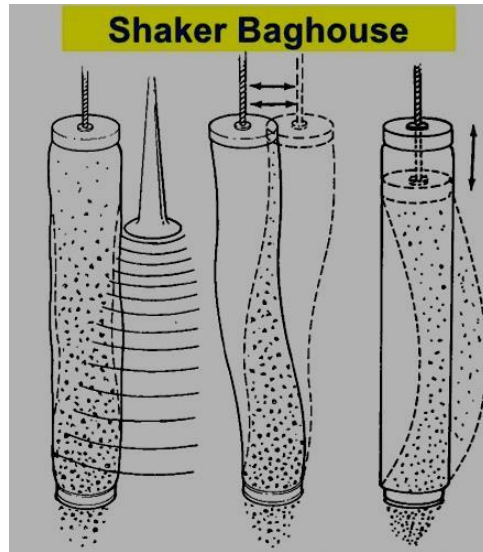
4.4.3 Operating problems in fabric filters

1. **Cleaning:** Periodic cleaning of bags is an important problem. After few hours of operation, the formation of heavy dust layer blocks the passage of air. Thus the carrier gas no longer pass through the bag. Then the bags have to be cleaned by rapping, shaking, by reverse air flow or by pulse jet.
2. **Rupture of cloth:** While cleaning the filter, the greatest problem that may be seen in cloth filters is rupture of cloth. It is often difficult to find out the ruptures and it leads to replacement of the cloth.
3. **Temperature:** Fabric filters will not perform properly if temperature overload occurs. Generally, the filters are designed for about 250°C to 300°C. The temperature related problem occurs when carrier gas contains a reactive gas such as SO₂ which can form an acid if the temperature in the bag house falls below the dew point. This can be prevented having the bag house fairly insulated. Sometimes an auxiliary heater is used in winter season so that temperature does not fall below dew point.
4. **Bleeding:** Bleeding is the escape of fine particles through fabric. Bleeding occurs if fabric weave is too open or if the superficial filtration velocity (Filter ratio) is too high. Generally, only very fine particles may escape through fabrics and they only cause human health hazards. The solution to bleeding is to use double layered thick woven fabrics.
5. **Humidity:** Humidity control is a common and an important problem especially if a hygroscopic dust is involved. Hygroscopic dusts are those readily attract water from its surroundings through either absorption or adsorption. Cleaning will become difficult in such cases. This problem can be overcome by taking suitable precautions.
6. **Chemical attack:** Another problem associated with fabric filters is possibility of chemical attack due to corrosive chemicals such as SO₂ present in the carrier gas. Acid/alkali resistant filter cloths are to be used in such cases.

4.4.4 Filter cleaning methods

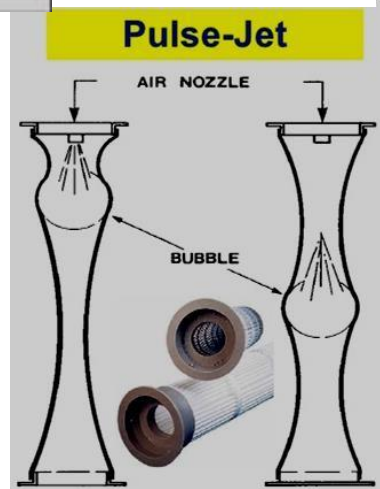
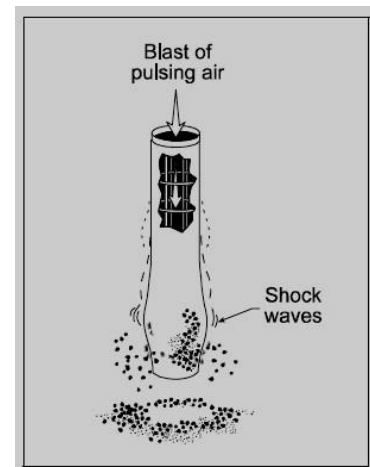
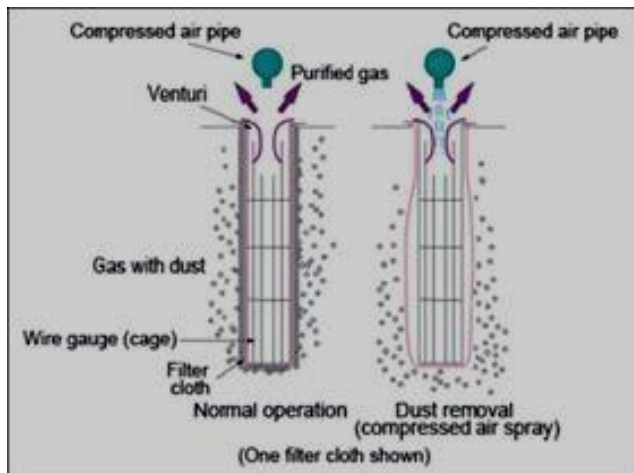
Filter cleaning can be done by the following methods.

1. **Shaking:** The shaking mechanism is the oldest one, the number of bags suspended in the bag house and attached to a shaking manifold are shaken manually or mechanically. Shaker cleaners hold the top of the bag still and shake the entire tube sheath, vibrations produced by the shaker loosens the dust cake. The dust will fall down into the hopper at the bottom. This method is not used for sticky dusts because the forces needed to remove the collected dust would cause tearing and ripping in the bags quickly. For cleaning by this method, the filtration process has to be stopped for some time and specified duration should be provided for cleaning.
2. **Reverse air flow:** The filter is cleaned by a high velocity air jet which is discharged in reverse to normal flow direction to the filter. Blow rings around the each bag are used to pass the air jet. As the blow ring traverses outside of the filter tube, the air jet passes through the fabric in backward direction and removes dust cake continuously from the filter surface. The main advantage of this method are 1) No need of shutting down of filtration process blow rings are a continuous cleaning mechanism 2) The cloth resistance can be maintained. But the disadvantage is that blow rings are mechanical linkages and are individual attachments for each bag, resulting in increased maintenance costs.

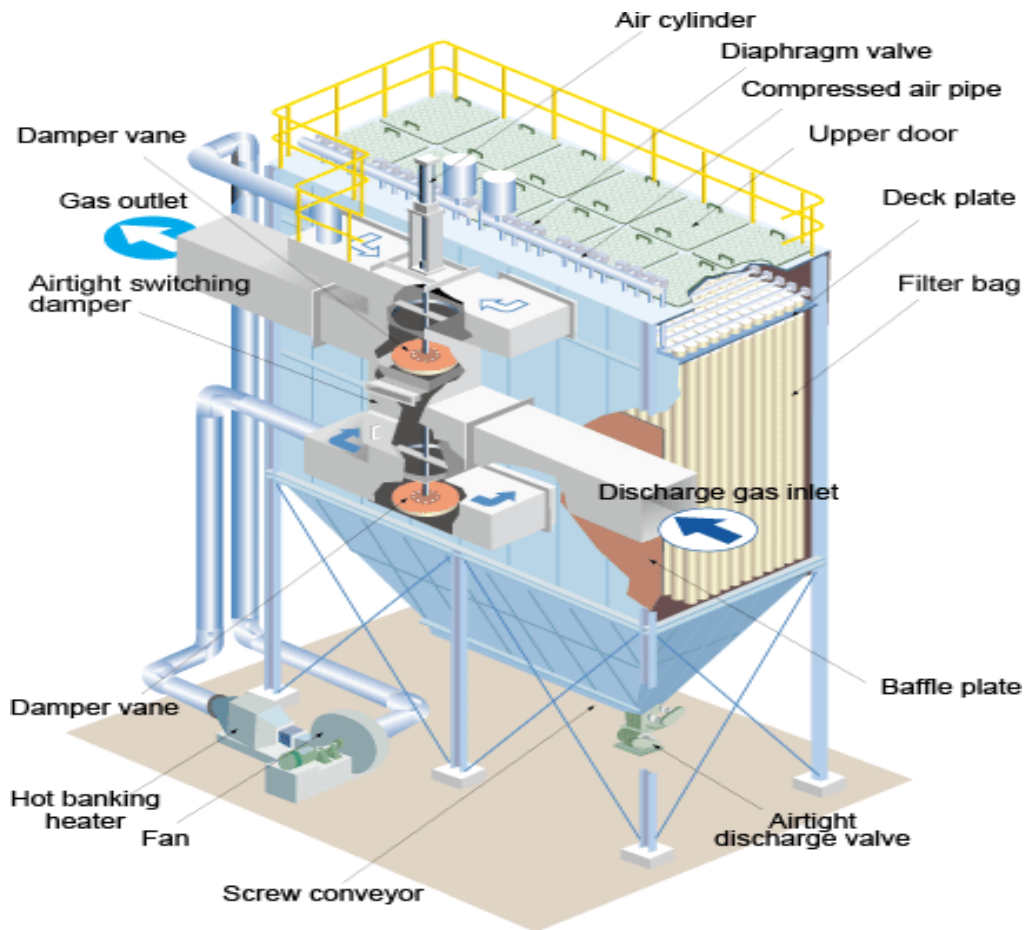


3. **Pulse jet:** Here, a jet of high pressure air is blasted inside periodically. When the compressed high pressure air is blasted, the bag will be inflated (swelled out or stretched out). This inflation of bag causes the dust cake to loosen from the surface and then the dust cake falls down. The advantage of this method is, there are no moving parts and also duration of cleaning is not important.

In general, while selecting particular cleaning method, we have to consider the cleaning mechanism, frequency of cleaning required, duration of cleaning and any undesirable effects on the bags.



An industrial unit of Bag House



4.4.5 Advantages and Disadvantages of fabric filters

Advantages

1. High collection efficiency for particulates of all sizes.
2. Simple construction and operation
3. Nominal power consumption
4. Dry disposal of collected material

Disadvantages

1. Operation limits are induced if carrier gas temperature and humidity are high.
 2. High maintenance and fabric replacement costs
 3. Large size of the equipment
 4. Problems in handling dusts which may abrade, corrode, or blind the cloths.
-

4.5 Scrubbers/Wet collectors

We know that nature cleanses herself up to considerable extent. Just consider that in an atmosphere, the particulate matter is suspended in the air. When it rains in that atmosphere, what happens?

When it rains, all the dust particulates will be washed away from the atmosphere and they are carried along with the rain water. Every water droplet of the rain hits the dust particle and it tends the particle to settle down. That's why we all experience the fresh air sensation after every rain. The same principle is used in the scrubbers.

Scrubbers are the devices which utilize a liquid to assist in removal of particulates from the carrier gas stream. Generally water is used as the scrubbing liquid. The scrubbers are basically cheap to install but costly to operate. The particles larger than 0.2μ can be collected from high efficient scrubbers.

4.5.1 Collection Mechanism

The four major steps are involved in collecting particles by wet collectors.

- 1) Transport – the particles must be moved to the vicinity of the water droplets which are usually 10-1000 times larger than particulates.
- 2) Collision- the particles must collide with the droplet.
- 3) Adhesion – when the particles collide with the droplets, they will be adhered (stuck) to the water droplets.

Interception - when they hit the droplets, the water droplets act as baffles/barriers which disallow the particles to move further, thus particles will experience a loss of velocity and then can be collected separately.

Condensation – Condensation of the liquid medium vapours on the particulates increases the size and weight of particles. Thus, it helps in easy removal of the particulate matter.

- 4) Precipitation – the particles are precipitated to the bottom of the scrubber containing dust particles. It means removal of the droplets containing the dust particle from the gas phase.

4.5.2 Types of scrubbers

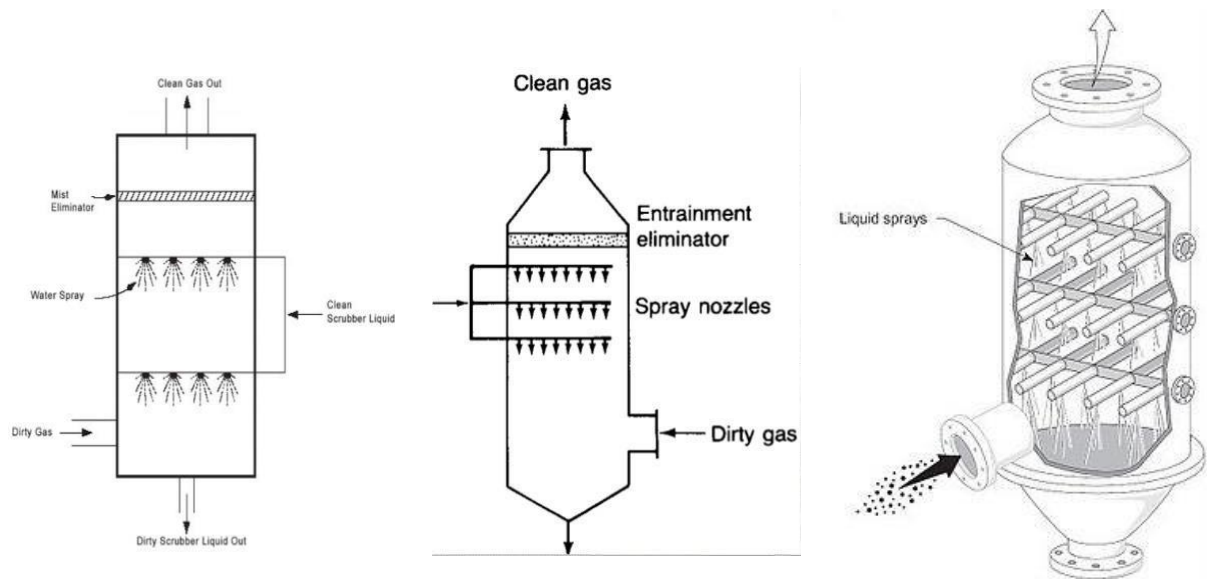
Following are the most commonly used types of scrubbers.

- 1) Spray towers
- 2) Venturi scrubber
- 3) Cyclone scrubber
- 4) Packed scrubber
- 5) Mechanical scrubber

4.5.2.1 Spray Towers

A Spray tower is the simplest type of wet scrubber into which water is introduced by means of spray nozzles. A simple spray tower is shown in figure. A spray tower can be either round or rectangular, in which gas is passed, counter-current to falling liquid drops from spray nozzles. The particle collection can be done by the mechanism of adhesion and interception.

Spray towers cause very little pressure loss (energy) and can handle large volume of gases. The towers effectively remove particles $>10\mu\text{m}$. The maximum efficiency occurs if droplets have a diameter of $800\mu\text{m}$ (0.8mm). The efficiency of a spray tower depends upon the droplet size, flow velocity of the gases, velocity of liquids etc. Effectiveness of the spray tower varies with the size of particles. It is 94% for $5\mu\text{m}$ particles to 99% for $25\mu\text{m}$ particles.

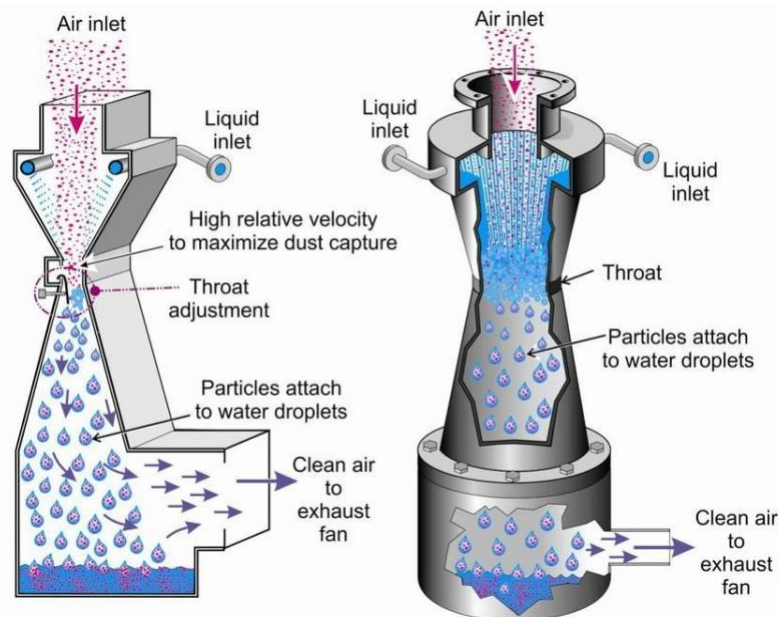
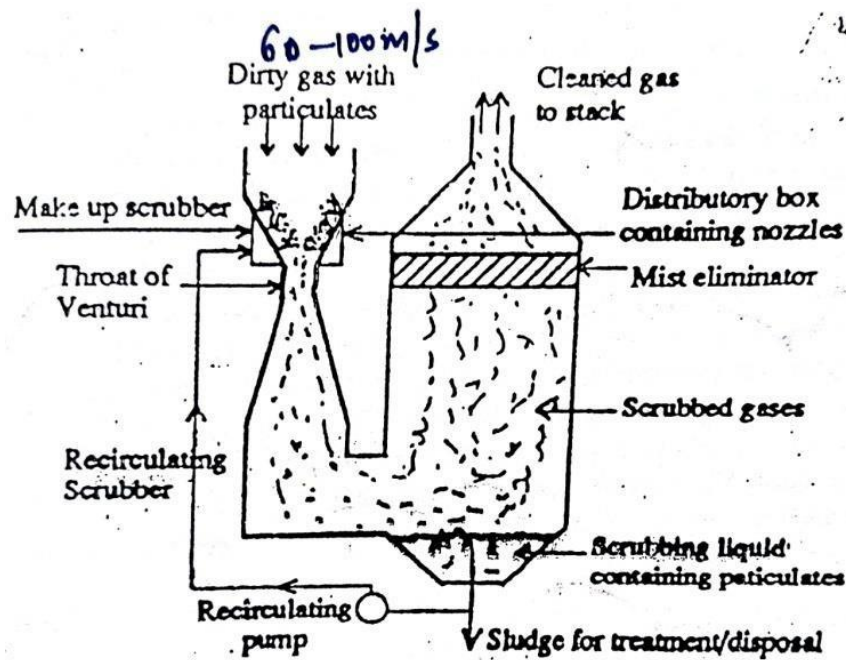


4.5.2.2 Venturi scrubbers

Venturi scrubbers are called as high performance scrubbers. These are high energy wet scrubbers with high efficiency collection of particles ($0.5\text{--}5\mu\text{m}$). These are suitable for submicron particulates associated with smoke, fume and also highly corrosive matter. Venturi scrubbers have converging and diverging sections. The high performance of the venturi scrubber is achieved by accelerating the gas stream to very high velocities ($60\text{--}100\text{m/s}$). Due to high speed action, the feed liquid is atomised (i.e., liquid layers broken into number of droplets) with uniform fashion in the throat of the venturi. In the throat section, several low pressure spray nozzles are mounted as shown in the figure.

The droplets accelerate in the throat section and due to the velocity difference between the particles and the droplets the particles are impacted against the slow moving droplets. Slurry is sent to the collection tank and the cleaned gas is continuously passed out. The principle collection mechanism is inertial impaction (collision and adhesion).

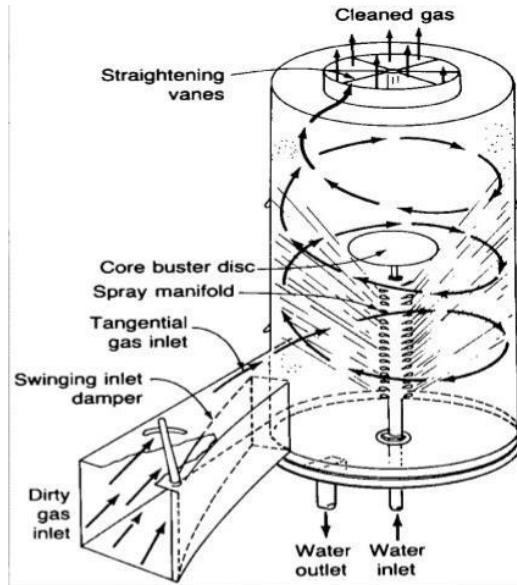
The application of venturi scrubber is more oftenly used in Kraft mill furnaces, metallurgical furnaces, sulphuric acid concentrators etc for removing mists and dusts from gases.



4.5.2.3 Cyclone scrubbers

This is just a modification of dry cyclone by the addition of liquid phase. In cyclone scrubbers, the gas is tangentially swirled around, as same as in the dry cyclone. Water sprays are introduced in the centre of the cyclone. Scrubbing liquid is sprayed from the centre to the wall of the cyclone. These sprays help in the collection of particles preventing re-entrainment. Impingement and inertial separation are the primary collection mechanisms.

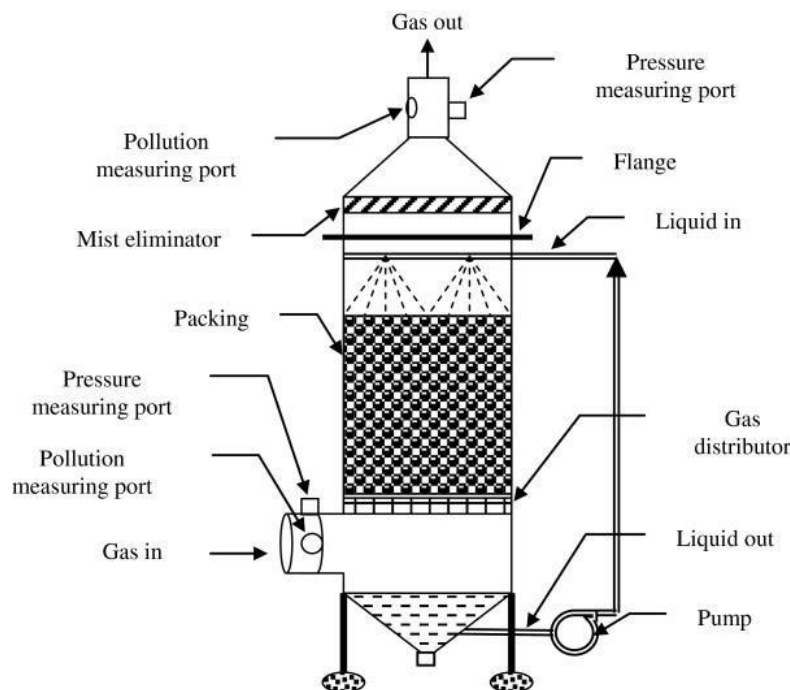
For droplets of 100 μ m, efficiency may reach 100%. And 90-98% efficiency may be reached for droplets of 5-50 μ m. Generally efficiencies slightly higher than those with the spray tower and dry cyclone.

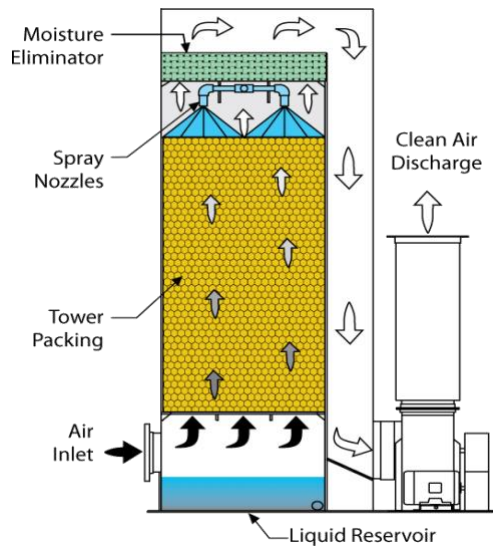


4.5.2.4 Packed scrubbers

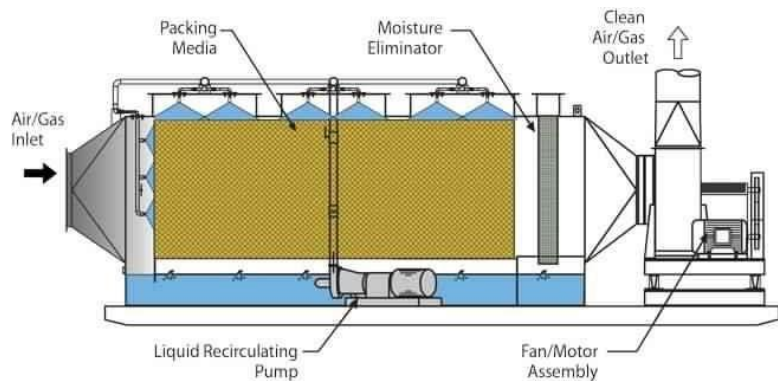
In packed scrubbers, a bed of material is packed inside. Usually fibre glass fine filaments, coke or broken stone are used as the packing bed material. The polluted gas stream moves upward in a counter current flow packed scrubber. And scrubbing liquid stream flows downward over the packed bed. The gas stream and scrubbing liquid are passed through pore spaces of packed bed, particles present in the gas are captured by the liquid. The primary collection mechanism is collision and adhesion. Smaller packing increases the efficiency. Sometimes packing towers encounter plugging problems, which can be reduced by employing sprays to wash the packed bed or by using low density spheres.

Packed towers can also be co-current or cross-flow type design (as shown in the figure) depending on the direction of liquid flow with respect to the direction of gas flow.





Counter current packed scrubber



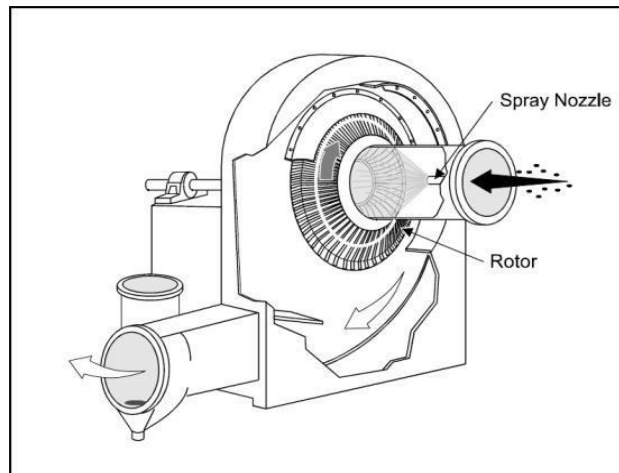
Cross flow packed scrubber

4.5.2.5 Mechanical scrubbers

This is a mechanically aided scrubber, has a rotating mechanical part for breaking up the liquid layers into smaller droplets and simultaneously creating turbulence. These are high energy scrubbers.

Here, the liquid-particles contact is achieved by the simultaneous introduction of scrubbing liquid and gas stream on the rotating discs, blades or perforated plates. The scrubbing liquid falls down on the rotating part and violently disintegrated into fine droplets that are thrown out radially by centrifugal force and are removed quite easily.

These scrubbers have high initial cost, high operating cost and require considerable maintenance. The water use rate is also high.



4.5.3 Advantages and disadvantages of Wet collectors or Scrubbers:

Advantages:

1. Low initial cost
2. Moderately high collection efficiency for even submicron particles

3. Applicable for high temperature installations
4. They can simultaneously remove particulates and gases
5. Valuable byproducts can be obtained.

For example, if Sulfur dioxide is present in the gas, $SO_2 + H_2O \rightarrow H_2SO_3/H_2SO_4$ here, H_2O is scrubbing liquid and sulfuric acid is valuable byproduct.

If the ammonia is present in the gas, $2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$ here sulfuric acid is scrubbing liquid and ammonium sulfate is a valuable byproduct.

Disadvantages:

1. High power consumption for higher efficiency
2. High maintenance costs because of corrosion and abrasion
3. Wet disposal of the collected material

4.6 Electrostatic Precipitators

Electrostatic precipitation is a method of dust collection that uses electrostatic forces. They have been successfully used for removal of fine dusts from all kinds of waste gases with very high efficiencies (98-99%). Particles as small as 0.1μ can be removed.

Basically, an ESP consists of six major components,

1. A source of high voltage
2. Discharge electrodes and collecting electrodes
3. Inlet and outlet for the gases
4. A hopper for disposal of collected material
5. An electronic cleaning system
6. An outer casing form an enclosure around the electrodes (precipitator shell)

4.6.1 Principle:

Electrostatic precipitators (ESP) are particulate collection devices that utilise electrical energy directly to assist in the removal of the particulate matter. In an ESP, the gas containing aerosols is passed between two electrodes. Out of the two electrodes, one is a discharging electrode (anodic) and the other a collecting electrode (cathodic). Electric potentials as high as 40-60 KV are used. Because of such high voltage, a powerful ionising field is formed. This ionisation creates an active glow zone (blue electric discharge) called 'corona'. As the particulates in the carrier gas pass through this field, they get charged and migrate to the oppositely charged collecting electrode. The particles once deposited on the collecting electrode, they are removed mechanically by rapping, vibration or washing and collected in the hopper at the bottom.

Thus four steps in the process involved are,

- 1) Gas ionisation – charging of particulates
- 2) Migration of particles to the collector
- 3) Neutralisation of the charge at collector
- 4) Removal of collected particles

4.6.2 Types of ESPs:

ESPs can be grouped, or classified according to a number of different features in their design.

- Based on the structural design and operation of the discharge electrodes (Ex: rigid-frame, wires or plate) and collection electrodes (Ex: pipe or plate type ESP)

- Based on the method of charging (Ex: single-stage or two-stage)
- Based on the method of particle removal from collection surfaces (Ex: wet or dry ESP)

These categories are not mutually exclusive. For example, an ESP can be a rigid-frame, single-stage, plate-type ESP as described below.

Single stage and two stage ESPs:

ESPs are classified by the number of stages used to charge and remove particles from a gas stream.

A **single-stage** precipitator uses high voltage to charge the particles, which are then collected within the same chamber on collection surfaces of opposite charge.

In a **two-stage** precipitator, particles are charged by low voltage in one chamber, and then collected by oppositely charged surfaces in a second chamber.

Almost all industrial precipitators are of single stage design. Usually two stage precipitator is used for lightly concentrated gases and single stage for more heavily concentrated industrial gas streams.

Single-stage ESPs use very high voltage (50 to 70 kV) to charge particles. After being charged, particles move in a direction perpendicular to the gas flow through the ESP, and migrate to an oppositely charged collection surface, usually a plate or pipe. Particle charging and collection occurs in the same stage and same chamber. Thus, the precipitators are called single-stage ESPs.

The two-stage precipitator differs from the single-stage precipitator in both design and amount of voltage applied. The two-stage ESP has separate particle charging and collection stages as shown in the figure. The ionizing stage consists of a series of small, **positively** charged wires equally spaced 2.5 to 5.1 cm from parallel grounded tubes/pipes. A corona discharge between each wire and a corresponding tube charges the particles suspended in the air flow as they pass through the ionizer. The direct-current potential applied to the wires is approximately 12 to 13 kV. The second stage consists of parallel metal plates less than 2.5 cm apart. The particles receive a positive charge in the ionizer stage (first chamber) and are collected at the collector plates in the second stage (second chamber).

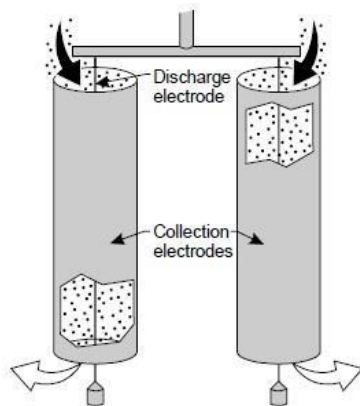


Figure: Single - stage Pipe type ESP

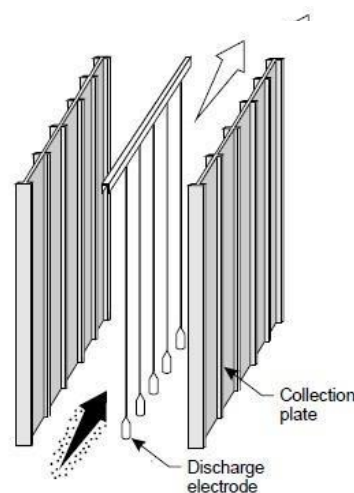


Figure : Single - stage Plate type ESP

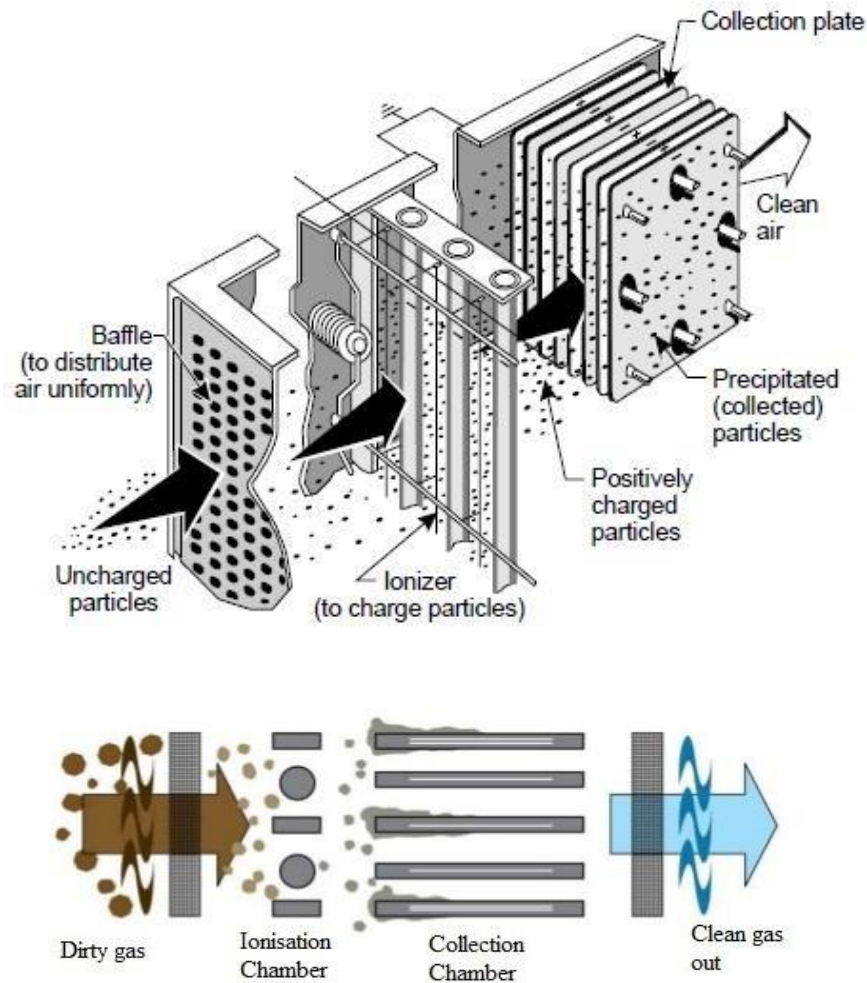


Figure: Two – stage ESP

Tubular and Plate ESPs:

Tubular or pipe type precipitators consist of cylindrical collection electrodes (tubes) with discharge electrodes (wires with small radius of curvature) located in the center of the cylinder (figure). The wires/discharge electrodes must be weighted to keep them straight and in the center of cylinders. Dirty gas flows into the tubes, where the particles are charged. The charged particles are then collected on the inside walls of the tubes. Collected particles are removed by rapping of pipes or washing the pipes with water sprays located directly above the tubes. The tubes may be formed as a circular, square, or hexagonal honeycomb with gas flowing upward or downward. A tubular ESP is tightly sealed to minimize leaks of collected material. Tube diameters typically vary from 0.15 to 0.31m, with lengths usually varying from 2 to 5m. Spacing between discharge electrode and collection electrode ranges from 8 to 20cm.

Tubular precipitators are generally used for collecting mists or fogs, and are most commonly used when collecting particles that are wet or sticky. Tubular ESPs have been used to control particulate emissions from sulfuric acid plants, coke oven byproduct gas cleaning (tar removal), and iron and steel sinter plants.

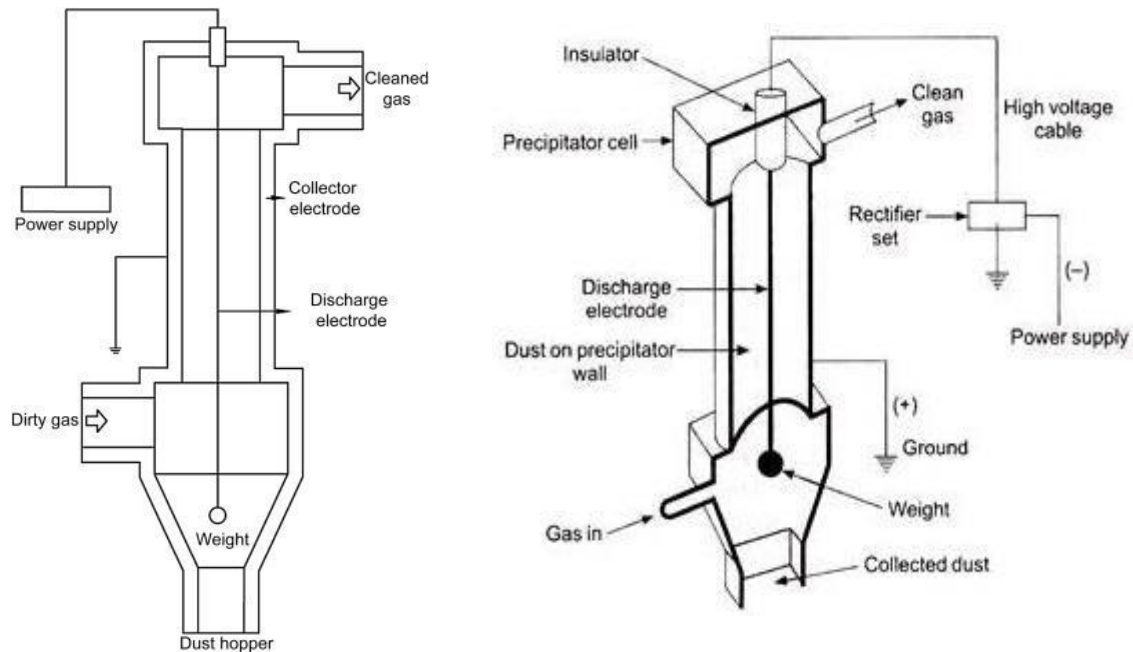
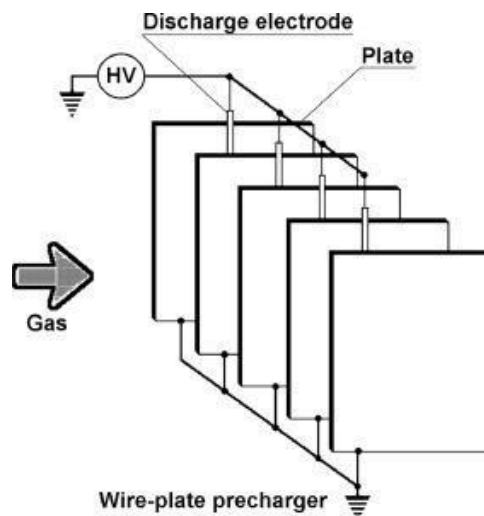


Figure : Diagrams showing Tubular or pipe type ESP

Plate electrostatic precipitators primarily collect dry particles and are used more often than tubular precipitators. Plate ESPs can have wire, rigid-frame, or occasionally, plate discharge electrodes. Figure shows a plate ESP with wire discharge electrodes. Dirty gas flows into a chamber consisting of a series of discharge electrodes that are equally spaced along the center line between adjacent collection plates. Charged particles are collected on the plates as dust, which is periodically removed by rapping or water sprays. Discharge wire electrodes are approximately 0.13 to 0.38cm in diameter. Collection plates are usually between 3 and 6m high. For ESPs with wire discharge electrodes, the plates are usually spaced from 15 to 35cm apart. For ESPs with rigid-frame or plate discharge electrodes, plates are typically spaced 30 to 38cm apart and 8 to 12m in height. Plate ESPs are typically used for collecting fly ash from industrial and utility boilers as well as in many other industries including cement kilns, glass plants and pulp and paper mills.



4.6.3 Advantages and disadvantages of ESPs:

Advantages of ESPs:

1. High collection efficiency
2. Particles as small as 0.1μ can be removed.
3. Low maintenance and operating costs
4. Low pressure drop
5. Satisfactory handling of large quantities of high temperature gases
6. Treatment time is negligible
7. Cleaning is easy

Disadvantages of ESPs:

1. High initial cost
2. Space requirement is more because of the larger size of the equipment
3. Possible explosion hazards
4. Precautions are necessary to maintain safety during operation.
5. Poisonous gas 'Ozone' is produced during gas ionization.

4.6.4 Applications of ESPs:

The important applications of ESP are listed in the table below.

Sl. No.	Industry	Application
1	Cement factories	Cleaning of flue gas from cement kilns, recovery of cement dust from kilns.
2	Pulp and paper	Soda-Fume recovery in Kraft pulp mills
3	Steel plants	Cleaning blast furnace gas, removing tars from coke over gases, cleaning open hearth and electric furnace gases.
4	Chemical Industries	Collection of Sox. Phosphoric Acid mist, cleaning various types of gases i.e., hydrogen, CO ₂ , SO ₂ , Removing dust from elemental phosphorus in the vapor state
5	Petroleum industry	Recovery of catalyst
6	Carbon black industry	Agglomeration and collection of carbon black
7	Thermal Power plants	Collecting Fly ash from coal fired boilers.

4.6.5 Design considerations of ESP

1. The efficiency of the ESP is given by

$$\eta = 1 - e^{\frac{(-V_p \cdot A_c)}{Q}}$$

Where,

Q= Gas flow rate

V_p= Drift velocity or migration velocity

Note: A_c= Total collection area if Q is total gas flow rate.

And also A_c = Area of the one collecting electrode if Q is considered as gas flow rate in each channel.

2. Gas flow rate is calculated by

$$Q = \frac{\pi D^2}{4} \times V_g \quad \text{For pipe or tubular ESP}$$

$$Q = HS \times V_g \quad \text{For parallel plate ESP}$$

Where ,

D= Diameter of the cylinder (0.1 to 0.5m)

H= height of the collecting electrode (2 to 6m)

S= Spacing between the plates

3. Area of collecting electrode is calculated by

$$A_c = \pi DL \quad \text{For pipe type ESP}$$

$$A_c = 2HL \quad \text{For plate type ESP}$$

Where,

L= length of the collecting electrode

If many number of channels are there, then total collection area $A_c = 2HL \times n$
Where n is the number of channels.

4. Migration / Drift velocity is the velocity of particles migrating towards attractive collection electrodes after being charged in the corona field. It depends upon different operational quantities like electric field strength, particle size, viscosity of gas and dielectric & resistivity properties of the dust. V_p normally ranges from 0.05 to 0.2m/s.
The drift velocity is given by

$$V_p = a \times d_p$$

d_p = diameter of the particles

a = constant and is a function of voltage applied
