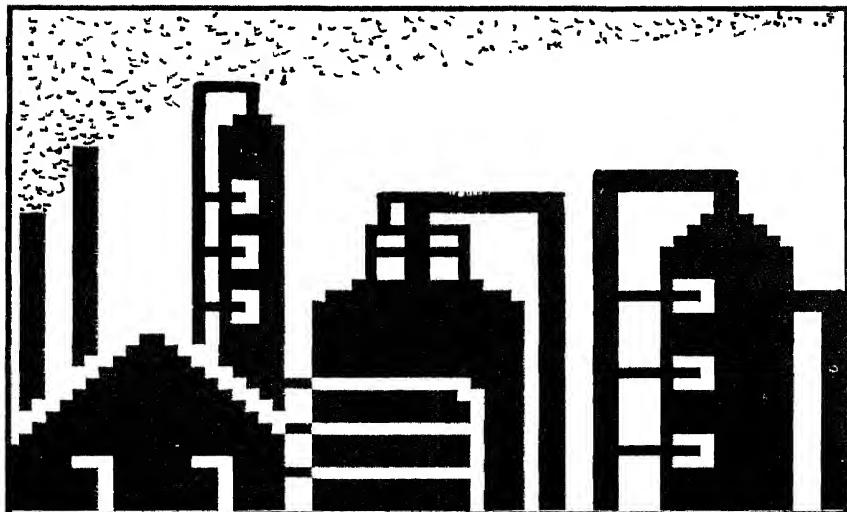


AIR POLLUTION AND CONTROL



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**AIR POLLUTION
AND CONTROL
K.V.S.G. Murali Krishna**

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To my parents

Kadiyala Janaki

and

Ramakrishna Sastry

PREFACE

Man's quest for progress is eternal. In his zeal to achieve scientific and technological advancement, which he hopes would make his life happier, man is unwittingly endangering the surroundings and tilting the ecological balance. Some of these are a result of unimaginative planning and reckless execution. The wanton destruction of vegetation with gay abandon and the prolific construction of concrete jungles in its place, coupled with the unconscionable disposal of even toxic industrial wastes into the air threaten the very survival of the humankind. 'Man will thus kill himself if he thoughtlessly and violently upsets the delicate web of environment of which he is a part'. Everyone is crying hoarse from house tops about the need to protect environment. But it is only a few like Sundarlal Bahuguna and Medha Patkar that have been making a valiant effort, even risking their lives, to bring awareness among the public in this regard. Even scientists and engineers confine their protests merely to paying lip sympathy. This is due to a total lack of understanding of the deleterious effects of environmental pollution.

It is with a view to educating these elite sections of the society that a humble attempt is made by this author in highlighting the probable causes of air pollution suggesting remedial measures for minimising it. Every effort has been made to make the subject matter easily understandable even by a layman, in the fond hope that everyone would make his contribution towards providing a safer and cleaner environment.

The reproduction of some of the material from the publications of the Bureau of Indian Standards is acknowledged. Extensive reference has been made to contributions by various authors, which is also gratefully acknowledged. The help rendered directly or indirectly, by several friends and well-wishers, in bringing out this book in its present form is also placed on record with appreciation and a sense of gratitude.

As mentioned earlier, this is a humble attempt and the first by the author. Any suggestion for the improvement of this book to make it a more effective and useful tool in disseminating the knowledge on this most important subject of air pollution is wholeheartedly welcome.

The author

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CHAPTER - I

INTRODUCTION

1.1 MAN AND ENVIRONMENT

Man is the most beautiful of all God's creation. Shakespeare, the Bard of Avon, grew eloquent in singing about the beauty of man.

"What a piece of work is man,
How noble in reason
How infinite in faculties
In form and moving, how express
In action how like an angel
In apprehension how like a god
The beauty of the world
The paragon of animals"

Man is created to enjoy the bountiful nature bestowed on him by God.

Environment means the surroundings in which we live. It is a life-sustaining system in which various living beings like animals, including man, birds, insects, micro organisms like algae, fungi, protozoa, amoeba and non-living beings like air, water and soil are inter-related. Like man, his environment too is beautiful. The earth is a wonderful planet that has perennial sources

of water to quench his thirst with their sweet water. Its atmosphere supplies pure air for him to breathe and has a natural ozone umbrella that protects him from sun's dangerous ultraviolet rays. It has a green carpet to utilize the carbondioxide that we exhale to recycle it into oxygen essential to sustain life on this planet. It has number of attractions like the rainbow to wonder at.

The atmosphere, the lithosphere and the hydrosphere form the biosphere in which life-be it man, animal or plant exists. The biosphere is not only a source of life sustaining elements but also a sink into which all waste products are dumped. From time immemorial, the biosphere is discharging faithfully its duty of recycling waste products to make good the loss so that every generation finds it the same as the one before it. But this self-cleaning and equilibrium maintenance of the biosphere is disastrously disturbed if waste products released into it exceed its capacity to purify herself. Of late, this is what is happening. We are loading it with enormous amounts of waste products that the biosphere is becoming more and more poisonous and soon a day will be reached when it becomes inhabitable.

Primitive man ate uncooked food available from plants, birds or animals within his reach. He ate the raw meat. He drank the water from the rivers. He lived in caves or huts made of mud, wood and leaves of some trees. This sort of living never polluted the environment. When Promethenes stole fire, man's travails began. He used it not only to cook food but also as a weapon to destroy the neighbour. With fire smoke issuing out was polluting the atmosphere; there was stink. It was in the beginning of the first century that the Roman Philosopher Seneca complained about air pollution. This went on increasing until in the 20th century the Ganges has become a death bed for all aquatic animals and the series of air pollution disasters affected millions all over the world.

1.2 IMPACT OF MAN ON ENVIRONMENT

As human population is increasing by leaps and bounds, there is need for more production in all spheres. So more industries and more vehicles are coming up polluting more and more that leaves the biosphere foul unless properly treated. Take for example manufacturing of cookers. Cookers are made of aluminium with copper bottom and plastic handles. This involves first ore dressing, extraction of metals, purification and then reshaping. All these involve machines which while working leave by-products that cannot be easily assimilated by biosphere. The list can be lengthened by adding manufacturing of plastics etc. Thus as man ascends rung by rung the ladder of civilisation, his needs grow in arithmetic progression and the corresponding pollution grows in geometric progression. So the modern

huge population with a thrust on being more civilized is imposing a great concern for environmentalist.

As long as man was contended with what he had, when he was not subdued by greed he lived a happy healthy life. But when he wanted to control nature, when he wanted to reign supreme in this universe, when pampering of the flesh and starvation of the soul began he started defining his environment! In the name of civilization, he built giant industries to belch out huge quantities of smoke which contain harmful particulates. In his attempt to fly like a bird, he invented the aeroplane which while soaring high produces thundering sound to deafen man. At the dusk of the 20th century, he has sufficiently polluted the air we breathe, the water we drink, and the food we eat. He was ignorant of the consequences of his meddling too much with nature. Wordsworth cautioned us "Our meddling intellect, mishaps the beauteous forms of things, we murder to dissect". Ignoring him man went ahead. But when he saw before him men and women falling dead like flies before a burner when the 'Little Boy' and 'Fat Man' were dropped on Nagasaki and Hiroshima and the Chernobyl and Bhopal tragedies, he realised his folly and wanted to make amends. Better late than never.

The early examples of pollution is a mere warning to the threatening problem we have to face at the dawn of the 21st century. As man has become more and more civilized he is not content with the three primary requisites food, shelter and clothing. Men now have more needs - more entertainment and more comfort. Where they could walk, they needed a means of transport, where they found natural food sufficient they went for processed food. These acquired needs had a major thrust on industry because most of them are met by items requiring processing, refinement, large scale production and then transport. All these involve machines which leave by products. The pesticides, the insecticides and the fertilizers used for rich yield and tests of some materials cause air pollution leading to diseases such as cancer. In 1958 Paul Muller was awarded Nobel prize for his discovery of DDT. Malaria was eradicated but at the same time DDT traces are found in almost all living organisms and its use is banned because it is a cumulative toxin. The series of ecological and environmental disasters made man realize that he will kill himself if he thoughtlessly and violently upsets the delicate web of environment of which he is a part. The earth song of Emerson is a trenchant indictment for the avaricious bipeds who deem to control nature.

"They called me theirs
Who so controlled me
Yet everyone

Wished to stay and is gone
 How am I theirs
 If they cannot hold me
 But I hold them!"

1.3 IMPORTANCE OF AIR POLLUTION CONTROL

Of all the problems man is facing today at the dusk of the twentieth century, the most intriguing is Air Pollution.

Man can survive for 5 weeks without food, 5 days without water and less than 5 minutes without air. This is attributed to the fact that he breathes, on an average, 25000 times a day at a rate of 1-2 litres of air per breath. The consumption of air by man conditioned by the circumstances is as follows:

Activity	Consumption of Air	
	m ³ /day	kg/day
1. Resting	10	12
2. Light work	40	50
3. Heavy hardwork	60	75

Compared to the consumption of water of about 2 litres a day (2 kg/day) man consumes about 20,000 times more of air by volume and 25 times more by weight. Thus man requires enormous quantities of air for his survival. In addition, the air he breathes goes into direct contact with the most sensitive organs of the human body - the respiratory tract and the lungs. Thus the quality of air he breathes has a direct bearing on his health and well being. That is the reason why the concentrations of pollutants should be very small in air when compared to the corresponding concentrations in water. A concentration of more than 0.3 ppm i.e. 0.3 mg/l or 3,00,000 µg/m³, of lead in water is considered harmful to man but a concentration of 1.5 µg/m³ of lead in air is deadly harmful. Majority of air pollutants like sulphur dioxide, nitrogen peroxide, ozone, ammonia etc. have a direct effect on man, material and vegetation. The air pollutants can affect the environment on a global scale. Carbon dioxide as a greenhouse gas causes global warming, increases mean sea level, submerges millions of hectares of fertile land and brings famine thus leading eventually to destruction of life on this planet. Sulphur dioxide and nitrogen peroxide can bring acid rains which can completely upset the delicate balance between the various biotic and abiotic components of the biosphere. CFCs, the chlorofluorocarbons can destroy the ozone layer, man's protecting umbrella, and spread incurable diseases among human

beings and other animals. PAN (Paroxy Acetyl Nitrate) and other oxidants can completely destroy vegetation. These pollutants one way or other, have already damaged the art treasures and cultural heritage of man. The Parthenon of Athens, the Statue of Liberty in New York, our Tajmahal withstood the ravages and plunders of the fury of nature for centuries but are showing signs of decay due to atmospheric pollution in this century. It is no hyperbole to say that if man continues his activities of discharging thousands of millions of tonnes of a variety of pollutants into the atmosphere he would one day extinguish himself or need a sanctuary to protect him! A proper place for a sanctuary also will be beyond his reach.

1.4 AIR POLLUTION CONTROL

Air pollution is a major threat at the dawn of 21st century. Every man must fight against it on a war-front, instead of wringing his hands in despair or joining the carping crowds demanding a halt to our technological advances. Air pollution is woven throughout the fabric of modern life. Man has polluted air so much that clean air has become more than a luxury for him today. Man sees filth everywhere. He dislikes it but reconciles with it. Primitive man had no desires. His first desire was for intoxication and probably the last desire is for cleanliness. He should change his out of sight is out of mind concept and must wholeheartedly participate in the environmental quality improvement programmes. The public must be educated to keep their surroundings clean. The environmental engineers and scientists must find out ways and means to convert by-products into useful materials and minimise waste to as small an amount as possible. He must copy nature, that is he must observe what processes are going on in nature to assimilate foreign material and use the same methods to destroy harmful pollutants arriving into the atmosphere from industrial concerns. If every citizen realizes that it is his primary duty to leave this world a better place than he had found it, the problem will be automatically solved.

Thus the only solution to mitigate the menace of air pollution is that every citizen must take a oath to protect our beautiful environment from pollution and seek methods to control it. If each man contributes his mite by planting a tree or by reducing the effluents from his own vehicle or by educating another person on how to fight against pollution, we will go a long way to leave a cleaner world for our future generations. "Think globally, work locally". Let us not forget:

"Little drops of water
Little grains of sand
Make the mighty ocean
And the pleasant land".

1.5 DEFINITION OF AIR POLLUTION

Engineers Joint Council of U.S.A. defines air pollution as "the 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 duration 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 the Bureau of Indian Standards, IS - 4167 (1966) air pollution is "the presence in ambient atmospheres of substances, generally resulting from the activity of man, in sufficient concentration, present for a sufficient time and under circumstances such as to interfere with comfort, health or welfare of persons or with reasonable use or enjoyment of property. According to 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 property".

Thus, if the concentration of any substance or element in air is more than a certain value, it may affect man and his property, directly or indirectly and may be termed as an air pollutant. According to the definition, the study of air pollution is limited only to outdoors i.e. ambient air. But, unfortunately most of the people spend more than 90 % of their time indoors - in their homes, educational institutions, offices or theatres. Thus fumes in kitchens, smoking in closed office rooms, malodorous emissions in an auditorium etc. are not covered under the definition of air pollution.

1.6 DEFINITIONS OF AIR - POLLUTANTS

AEROSOL : Finely divided solid or liquid particles of microscopic size suspended and dispersed in a gas or in atmosphere as in the case of dust, mist, fog, haze or smoke. The term is applied to the system of dispersed phase and dispersing medium together, while particles alone are called 'aerosol particles'. They range from 0.1 to 100 microns in size. The typical size ranges in microns are: cement 150 - 10; flyash : 80 - 3; spores : 30- 10; bacteria : 15 - 1 and pollens : 6 - 20 μ .

DROPLET: A small liquid particle of such size and density that it falls under still conditions but may remain suspended under turbulent conditions.

DUSTS : They are small solid particles generated by crushing, grinding, blasting, processing or handling of materials such as coal, cement or grains eg. sawing of wood, sand blasting, cement manufacturing . Their size ranges from 1 to 200 microns. They remain in suspension and do not diffuse. Particles of size above 75 microns would come into the category of grit. If

the particle size is less than 0.1 micron, they are affected by Brownian motion. They collide with the surrounding particles, coagulate, flocculate and then settle down finally. Most of the dusts settle on ground as dust-fall but particles less than 5 μ in size become stable substances in the atmosphere.

FLY ASH: Non - combustible particles contained in flue gases. They are released when organic portion of coal is burnt. Like dust, its size is 1 to 200 microns; like smoke it results from burning and like fumes it consists of inorganic metallic or mineral substances.

FOG : Atmospheric obscuration caused by mists. In meteorological terms, fog implies reduction of visibility to less than 1 km.

FUMES : Very fine solid or liquid particles, 0.001 to one micron 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, calcination or molten metal processes. Like dusts they may flocculate, coalesce and settle out. The word fumes is commonly used to imply unpleasant and smelling airborne effluents.

GASES : One of the three states of matter having no independent shape and expanding continuously till its volume equals that of the container.

MISTS: Liquid particles formed by condensation of vapour (as in distillation) or dispersion of a liquid (as in foaming or splashing of water) or a chemical reaction (as in the formation of H_2SO_4). Usually applied to water droplets in air where visibility has a value of 1 km or more. Natural mists may be aggravated by air pollutants. If their concentration is high and decreases visibility to less than 1 km, it is called fog.

PARTICLE : A small discrete mass of solid or liquid matter.

SMOG : Term derived from smoke and fog (smoke + fog = smog).

SMOKE : Finely divided gas borne aerosol particles of size range 0.001 to 1 micron, resulting from incomplete combustion of fuels. It mainly consists of carbon and other combustible material.

SOOT : Small agglomerations of carbonaceous particles impregnated with tar formed by the incomplete combustion of carbonaceous material, particularly bituminous coal. They tend to adhere to the inside of the chimney or the exposed surfaces.

VAPOUR : The gaseous phase of matter which normally exists in a liquid or solid state (eg. gasoline, steam)

1.7 MEASUREMENT OF AIR POLLUTION

Air pollutants like water pollutants, are expressed in ppm or micrograms per cubic meter ($\mu\text{g}/\text{m}^3$). For water, 1 ppm = 1 part of pollutant in 1 million parts of water i.e. 1 mg per 10^6 mg i.e. 1 mg/l. However, for air it is not so. One gram - mole of any gas at STP conditions occupies the same volume of 22.4 litres. Thus 64 gms. of SO_2 or 30 gms. of NO or 46 grams of NO_2 or 48 grams of O_3 ,.... all these occupy the same volume of 22.4 litres at 0°C temperature and 760mm of Hg pressure. The volume occupied is 24.5 litres at 25°C and 760mm Hg. pressure.

\therefore If M is the molecular weight of a gas, then, M grams of it occupies $22.4 \times 10^{-3} \text{ m}^3$ at 0°C and $24.5 \times 10^{-3} \text{ m}^3$ at 25°C .

$$\begin{aligned} 1 \text{ ppm} &= \frac{1 \text{ part of gas}}{10^6 \text{ parts of air}} = \frac{1 \text{ m}^3 \text{ of gas}}{10^6 \text{ m}^3 \text{ of air}} \\ &= \frac{M/(22.4 \times 10^{-3})}{10^6 \text{ m}^3} \text{ grams} = \frac{M}{22.4} \times 1000 \mu\text{g}/\text{m}^3 \text{ at } 0^\circ\text{ C.} \\ &\quad = \frac{M}{24.5} \times 1000 \mu\text{g}/\text{m}^3 \text{ at } 25^\circ\text{ C.} \end{aligned}$$

The conversion factor may be written in a general form as follows:

$$1 \text{ ppm} = 44.64 M \times \frac{273}{273 + T} \times \frac{P_2}{P_1} \mu\text{g}/\text{m}^3 \text{ where}$$

M = Molecular weight of the pollutant (gas)

T = Temperature of gas in $^\circ\text{C}$

P_1 = Pressure at STP conditions and P_2 = Pressure of gas (air)

The ppm - $\mu\text{g}/\text{m}^3$ conversion factor for different gases is given in table.

Pollutant	Molecular Weight, M	ppm - $\mu\text{g}/\text{m}^3$ conversion factor	
		$0^\circ\text{C}, 760 \text{ mm}$	$25^\circ\text{C}, 760 \text{ mm}$
O_3	48	2142	1960
SO_2	64	2860	2620
CO	28	1250	1145
CO_2	44	1964	1796
HC (as CH_4)	16	715	655
NO	30	1343	1230
NO_2	46	2054	1880
$\text{CH}_3(\text{CO})\text{O}_2$	121	5348	4945
NO_2 (PAN)			

1.8 GLOSSARY OF TERMS RELATING TO AIR POLLUTION

AAQS: Ambient Air Quality Standards

Abatement : Reduction or lessening (of pollution) or doing away with (a nuisance)

Absorption: (a) The taking up usually of a liquid or gas into the body of another material (the absorbent). Thus an air pollutant may be removed by absorption in a suitable absorbent. (b) The taking up of radiation by a material it encounters or passes through. This can be the basis of measuring concentration of a number of substances.

Accretion: A phenomenon consisting of the increase in size of particles by the process of external additions; for example, water to salt particles.

Actionograph : An instrument for recording the incoming solar radiation.

Acute Toxicity: Used in relation to the effects of certain concentrations of air pollutants to describe a response coming rapidly to a climax. Poisonous effect within 24-96 hours causing severe biological harm and often death.

Adsorption: The phenomenon in which molecules of a substance (the adsorbate) are taken up and held on the surface of another material (the adsorbent).

Advection: The process of transfer of an atmospheric property (for example, heat, moisture, pollution) by horizontal motion of the air.

Afterburner : A device fitted after the main point of fuel combustion in a stationary plant or a vehicle to produce nearly complete combustion of the exhaust gases. It may be a burner fitted to incinerate polluted process gas.

Agglomeration: The clustering or adhering together of a number of small particles to form a body or structure (an agglomerate) which then acts as a larger single particle.

Air Pollution Index: An arbitrarily derived mathematical combination of air pollutants which gives a single number trying to describe the ambient air quality.

Air, Primary : The air supplied to the fuel in its early stages of combustion.

Air Quality : The term usually refers to the concentration in air of one or more pollutants. For many pollutants the air quality is expressed as a concentration over a certain period of time, for example, $\mu\text{g}/\text{m}^3$ - 24 hours.

Air , Secondary: Air introduced above or beyond the bed of burning fuel

to promote complete combustion of volatile material produced in the first stage of combustion.

Air Shed: A region that shares a common air supply.

Aitken Nuclei: Particles ranging in size from $0.05 \mu\text{m}$ to $0.1 \mu\text{m}$ with or without electrical charge.

Albedo: The ratio of the amount of electromagnetic radiation reflected by a body or a surface to the amount incident upon it .

Allergy: The abnormal reaction of a living body to physical, chemical or biological agents to which certain body cells are supersensitive. The final effect may be redness, itching, inflammation, tissue damage or other forms of morbidity. These effects depending on the nature of the material and root cause of exposure may be localized over a part of body or widespread.

Alveoli: Hundreds of millions of tiny sacs at the end of the bronchiole tubes in the lungs. Oxygen in the air passes through their walls to combine with haemoglobin in the blood and carbon dioxide passes from the blood back through the alveoli wells for exhaling.

Ambient: Surrounding. It is used to describe physical properties of air (temperature, humidity, pressure, etc.) or air pollution concentration in the open air, as against, at the point of emission or indoors for example ambient temperature, ambient air quality.

Anemometer : An instrument for measuring wind/air speed.

Anoxia : Deficiency of oxygen in the blood or thereby in body tissues.

Anthracite: High calorific value coal yielding little ash and volatiles, hence low smoke production. It is slow burning and not normally used on open fires. It is cleaner to handle than most other coals.

Antibody : A substance protein in nature synthesized and released into the body's system specifically in response to invasion by an antigen.

Anticyclone: The condition of atmospheric pressure distribution in which pressure increases towards the centre. This is usually associated with fine, calm weather and with fog in winter.

Antigens: Foreign substances of different chemical types which when introduced into the body, cause the production of specific antibodies capable of reacting with them.

Aromatics : Hydrocarbon compounds containing, as part of their structure, rings of atoms like those found in benzene and other similar cyclic molecules

and generally having strong aroma. In petroleum products, this term distinguishes these hydrocarbons from those which are chain-like in structure (paraffins). Aromatics tend to have higher octane ratings.

Aspirator: Any apparatus such as a squeeze bulb, fan, pump, or venturi, that produces movement of a fluid by suction.

Atmosphere, Stable : State of the atmosphere in which vertical air movements are restricted. This happens when there is temperature inversion.

Atomization: The process by which a solid or liquid is reduced, not to atoms but, to very small particles or droplets as in a fine spray. Good atomization of fuel oil allowing increased fuel/air mixing necessary to obtain satisfactory combustion. Atomized pollutants may persist remaining suspended in air because of their small particle size.

Autometer, Thomas: A device for continuous recording of sulphur dioxide based on the electrolytic conductivity of water through which air passes.

Background: The levels of pollution (in terms of concentration) present already in the atmosphere exclusive of that due to the pollution source under consideration . In general, the term is used to imply the leave of any entity present exclusive of the specified source, for example, background noise, background illumination. Sometimes the term is used to mean the concentration of the substance some distance from the particular source and therefore largely uninfluenced by it.

Baghouse/Bag Filter: Fabric filter used for dust removal usually made into bag of tubular or envelope shape. The entire structure housing the bags is called a baghouse.

Balloon, Pilot: Balloon filled with a light gas (for example, hydrogen or helium) released to determine the wind at various heights in the atmosphere. The balloon is tracked by theodolites and successive locations of the balloon are computed, from which winds can be estimated. This is done on routine basis at several stations by national weather services. Radar is also used for this purpose.

Biome: Complex of communities characterised by a distinctive type of vegetation and maintained under the climatic conditions of the region.

Biosphere: The portion of earth and its atmosphere that supports life.

Biota: All living organisms both plant and animal.

Breathing Zone: That location in the atmosphere at which persons breathe. Generally, a layer 0 - 1.5m above ground level is considered as breathing zone.

Breeder Reactor: Nuclear reactor that produces more nuclear fuel than it consumes. It does this by converting nonfissionable uranium-238 into fissionable plutonium-239.

Bronchitis: Basically bronchitis is inflammation of bronchi, the two branches of the air pipe leading to the lungs. It is a reaction of the mucosa lining to an irritant. The word is less exactly, but more widely used to describe a variety of lung disablements which can be associated with air pollution and smoking.

Bronchus: One of the two large tubes entering the lungs which divide and subdivide into the bronchiole tubes and eventually lead to the alveoli.

Brown Air City: Popular name for a photochemical smog city such as Los Angeles, Tokyo, Sydney, Mexico city or Buenos Aires. Typically an automobile dominated City where a major pollutant is yellow brown nitrogen dioxide (NO_2) formed by internal combustion engines.

Calm: The air is described as calm in meteorological terms if the wind speed is less than 1 knot. (1 knot=1.8 km per hour = 0.5 m per second approximately). Sometimes the term is also used when the wind speed is below the measurement threshold of the anemometer.

Calcination: The process of heating a waste material to a high temperature with fusing in order to effect useful changes (eg. oxidation, pulverisation).

Calorific Value : A measure of the heating quality of the fuel usually expressed as available heat units from complete combustion of a unit mass of fuel. For example kJ/kg for solid or liquid fuels and kJ/m^3 for gaseous fuels.

Carburation : The mixing of air with a volatile fuel to provide a combustible mixture for use in the internal combustion engine. The device in which this occurs is the carburetor.

Carcinogen : A substance which causes carcinoma or cancer.

Catalyst : A substance which, though not itself permanently changed, alters the rate of (usually speeds up) a chemical reaction.

Chimney (Stack) Height, Effective : The effective height of a chimney is the sum of its actual physical height and the plume rise. The latter is the rise of the effluent due to buoyancy and efflux velocity.

Chromatography : A method of analysis in which a flow of solvent or gas promotes the separation of substances by differential migration from a narrow initial zone in a porous sorptive medium.

Chronic: Referring to injurious effects of air pollution, particularly effects on health. It implies lasting or long term morbid effects as against acute effects.

Clinker: Aggregated or sintered ash formed when the ash is heated strongly in a furnace.

Coffin: A thick walled container (of lead) used for transporting radioactive materials.

COH: Coefficient Of Haze. This is a unit for measuring smoke stains which depends on the reduction of light transmission through the filter after it has collected the smoke sample. Its object is to measure haze over a distance of about 300 meters.

Coke : A smokeless solid fuel of low volatile content, traditionally formed from coal by destructive distillation.

Combustion: The chemical combination of oxygen with fuel with rapid heat evolution so that the temperature rises. The products of combustion are the oxidation products of the components of the fuel. Thus hydrocarbons produce carbon monoxide, carbon dioxide and hydrogen oxide (water). Combustion of the sulphur in fuels produces sulphur dioxide.

Condensate: Liquid or solid matter formed by condensation from the vapour phase. In sampling, this term is applied to those components of an atmosphere which have been isolated by simple cooling.

Convection: The transfer of heat in a fluid by flow of parts of the fluid at different temperatures. Convection currents can be set up in air with the rise of hotter, less dense parts and downward flow of cooler, more dense parts.

Curie: Measure of number of atoms disintegrating per second i.e. the strength of radioactivity. Curie equals 37 billion disintegrations per second approximately equal to the radioactivity of 1 gram of radium.

Defoliation: Stripping of leaves from plants especially using chemical sprays.

Death Rate: Number of deaths in one year per 1000 population at mid year.

Desorption: The removal of absorbed or adsorbed material.

Dew Point: The temperature to which the sample of air has to be cooled to make it saturated with respect to water at its existing pressure and humidity mixing ratio. It is a measure of moisture content of air. The higher the moisture content, the higher is the dew point.

Diffusion, Molecular: Mixing of substances caused by molecular motion.

Dispersion: The method by which a pollutant spreads from its point of emission and becomes diluted in the atmosphere. It includes transport by winds and simultaneous spread by turbulence.

Distillate: Any product such as distilled water obtained by vapourisation from a still or distillation apparatus. The term distillate fuel is often applied to a fraction heavier than petrol or to paraffin (kerosene or gas oil).

Ecocide: Substance that kills an entire ecosystem.

Ecology: The relation or interaction of living systems with each other and their environment.

Ecological Backlash: Unexpected and often undesirable side effect of changing ecosystem.

Ecological Niche: Profession and total role of an organism in a biotic community.

Eddy: A fluctuation from the mean motion of a fluid; also used for parcels of air having circular whirlpool type of motion in the atmosphere. Eddies are the result of turbulent motion of the atmosphere.

Effluent: Literally anything which flows out or is discharged. Usually applied to the discharge of a waste material into a water body or the atmosphere.

Efflux Velocity: The speed with which something is discharged from an orifice, for example gases from the top of a chimney. Also called discharge velocity.

Electro Magnetic Energy: Energy that can move through vacuum in the form of waves (such as visible light)

Elutriation: A process for separating fine particles into sized fractions by their different rate of settling down under gravity in a stream of fluid.

Emphysema: Pulmonary or lung emphysema is a distension or swelling of the lung air spaces due to destruction of the alveoli which diminishes the area for exchanging oxygen and carbon dioxide between the air and the blood.

Environment: Literally surroundings; may apply to the indoor or working conditions but commonly refers to man's total surroundings, natural and man-made. Parts of the environment, are often specified. For example biological environment, water environment, air environment, marine environment etc.

Environmental Impact Assessment (EIA): The report which identifies and analyses the environment impacts of the applicant's proposed source and feasible alternatives.

Environmental Protection Agency (EPA): The agency responsible for federal efforts in the control of air and water pollution, radiation and pesticide hazards, ecological research and solid waste disposal.

Extrapolation: Estimating the value of something beyond the range in which it has been measured. For example, estimating pollution levels in the near future from a number of values over past years may be called extrapolation of pollution in time. Estimation of winds at higher levels from those measured at two or more levels below may be called extrapolation in height.

Flash Point: The lowest temperature at which a liquid fuel will give off a flammable vapour which will burn momentarily on application of a small flame.

Flora: Plant population of a region.

Flue Gas: The gaseous product of combustion from a combustion equipment, for example, a boiler furnace or a kiln.

Fluidised Bed: A bed of solid particles through which air or any other gas is made to flow upwards in such a fashion as to support the particles and to make them act, in many ways like a liquid. Furnaces have been devised in which oil or powdered or granulated coal can be introduced into such a heated bed where it can burn evenly and produce an even temperature throughout the bed.

Fluorimetry: Exciting a sample with light (usually UV) and measuring intensity of resulting fluorescence as a measure of pollutant concentration.

Fossil Fuels: A general term covering coal, mineral oil, natural gas, etc., which are fuels derived from organic deposits in ancient geological periods. They consist mainly of carbon and hydrocarbons. By comparison wood and nuclear fuel are not fossil fuels.

Freons: A range of hydrocarbons with hydrogen replaced partly or totally by fluorine or chlorine. These wholly man-made compounds are used as refrigerants, in fire extinguishers and as aerosol propellants.

Front, Cold: The sharp boundary between two extensive air masses where cold air is replacing warm air.

Front, Warm: The sharp boundary between two extensive air masses where warm air is replacing cold air.

Grain: In air pollution this is often encountered as a unit of mass.

(One grain = 0.0648 g)

Gray Air Cities: Popular name for an older industrial smog city such as London, Chicago, New York, Baltimore, Birmingham, Philadelphia or Pittsburgh that depends heavily on the burning of coal and oil. Major pollutants are particulates and sulphur oxides that produce a gray haze over the city.

Grit: Particles of solid ranging from 75 to 200 μm in diameter in the air or flue gases which fall out or deposit under their own weight.

Hazardous Air Pollutant: An air pollutant to which no ambient air quality standard is applicable and which in the judgement of the control authority causes, or contributes to air pollution which may reasonably be anticipated to result in an increase in mortality, or in serious irreversible, or incapacitating reversible illness.

Haze: Fine aerosol dispersed through a portion of the atmosphere. The particles are so small that they cannot be felt or individually seen with the naked eye, but they diminish the horizontal visibility and give the atmosphere a characteristic opalescent appearance which subdues all other colours. Blue haze is found due to the combustion of sulphur or its compounds or some other organic compounds.

Heat Island: Horizontal pocket of relatively warm air surrounded by cooler air. Often found over city centres, industrial complexes or other man-made features.

Habitat: Place where an organism of a community of organisms naturally lives or grows.

Homeostasis: The maintenance of internal constancy and independence of the environment within a living substance. Thus, despite changes in ambient temperature, body maintains a nearly constant temperature. Similarly, inspite of deteriorated air quality, the body maintains its functions through proper compensation. There is however a limit beyond which the compensation is not possible leading to permanent damage.

Impingement: The act of bringing matter forcibly in contact with any surface. In air sampling it refers to a process for the collection of particulate matter in which the gas being sampled is directed forcibly against a surface.

Incineration: A waste disposal process by means of which solid, liquid and gaseous combustible wastes are converted, through controlled combustion, to a residue, which contains virtually no combustible matter and to gases.

Inversion: In meteorology an inversion exists when the air temperature increases with height. Under such conditions, vertical movements are damped and vertical spread of the pollutants is attenuated. Inversion may occur in isolated layers also. During inversion, atmosphere is said to be stable.

Isopleth: A line drawn on a map linking places with the same value of some parameter, for example, height, annual rainfall, pollutant concentration.

Lean Mixture: The air/fuel mixture in an internal combustion engine is described as lean if it contains a low proportion of fuel while a mixture with a high proportion of fuel is described as rich.

MAC: Maximum Allowable Concentration. A term similar to the TLV.

Micrometeorology: Study of physical phenomena in the very lowest layers of the atmosphere (of the order of 100 meters) or occasionally over a restricted area, generally of a few kilometers in extent.

MINAS: Minimum National Standards - Standards prescribed by Central Pollution Control Board in the Air (Prevention and control of pollution) act, 1981, section 17(1)(g) for effluent discharges and stack emissions.

Mixing Height: The height in the atmosphere within which emitted pollutants are dispersed and mixed vertically, the vertical mixing being attenuated by presence of inversion layers above that height.

Monitoring: Measuring concentration levels continuously or regularly over a period of time. More specifically it may imply checking that the level of an air pollutant is within the prescribed limits. Stack monitoring implies the monitoring of the concentrations in the stack effluents from which total emission rates can be estimated.

Obscuration: Concealing from sight. In meteorology it relates to restriction of visibility.

Olfactory Threshold: Pollutant concentration below the point at which none of the receptors detect malodours.

ORSAT: Oxidation Reduction Selective Absorption Technique for analysis of gases.

Oxidants: Materials which have an oxidising action on other materials, that is, generally adding oxygen to them chemically or extracting hydrogen. Typical atmospheric oxidants are ozone and nitrogen dioxide whose action on vegetable material can be damaging.

PAN: Peroxy Acetyl Nitrate. This is an eye irritant compound associated

with photochemical smog.

Plume: The flow or path of effluent from a specific outlet such as a chimney stack or vent. While for smoke, the plume is visible, for many pollutants it may not be so.

Pneumoconiosis: A term applied to various diseases of the lung caused by the inhalation of dust particles in such occupations as coal mining, quarrying and asbestos working; an excess of fibrous tissue forms in the lungs around the dust particles.

Pollen: The small grains from the feathers of flowers which contain the male reproductive nuclei. Transported in the air certain of these grains in the air can induce hay fever or asthma in some people by action in the nose. They are thus natural air pollutants.

Pollution Rights: Sale on the open market of a limited number of rights to pollute upto a specific amount in a given place over a particular time period.

ppb (European) : A billion in European usage is a million times a million (10^{12}). So ppb is parts per million million that is one part in 10^{12} parts.

ppb (US) : In America a billion is used to mean a thousand million as against a million million in Europe. Thus 1 ppb (US) = 1000 ppb (European).

ppm : Parts per million. It refers to the number of parts by volume of the gaseous pollutant in one million parts of the total air.

Pressure, Static: The pressure of a fluid at rest or in motion exerted perpendicularly to the direction of flow.

Probe: A tube used for sampling or for measuring pressures at a distance from the actual collection or measuring apparatus. It is commonly used for reaching inside stacks and ducts.

Pyrolysis : Breaking down burnable waste by combustion in the absence of oxygen. Usually high heat is applied to the waste in a closed chamber evaporating all moisture and breaking down materials into gaseous hydrocarbons and carbon-like residue.

Radiosonde: A balloon borne instrument which transmits data on temperature, pressure and humidity as it rises and moves with the wind.

Ratio, Benefit / Cost : The benefit/cost ratio seeks to compare the benefits of a particular action with its cost. In the case of pollution control expenditure the benefits have to be assessed in terms of the effect of reduced pollution. A benefit/cost ratio of 10:1 implies that for every 1 rupee spent on controlling the pollution the benefits can be valued at Rs.10.

Residence Time: Average time for which any pollutant or particulate matter remains in the atmosphere before settling on earth's surface. It is equal to the time required for the removal of half the quantity of matter divided by 0.693 or the time required for the contents to reach $1/e$ or 36.8 percent of original value, where e is the base of log_e.

Respirator: A device used by a person for breathing filtered air, or artificial air from a cylinder while working in an area having air contamination.

Response Time: Time taken by an instrument to change the indication from the initial level to $1/e$ times ($e = \text{base of natural logarithms} = 2.721$) the final level on giving a step incremental input.

Sample, Grab: A sample taken or grabbed at a single point in a short time rather than accumulated over a period. This is representative of only the conditions at the particular time of sampling. This is also known as snap sample.

Saprophytic: Organisms living on dead organic matter.

Scrubbing / Scrubber: An absorption operation in which gaseous or fine particulate pollutants are removed from a stream of air or gas by contact with a liquid spray or a bath or wetted packing / wet surfaces in a tower. The apparatus/equipment used is known as scrubber.

Smelter: A place where fusion of an ore or concentrate is carried out with suitable fluxes, to produce a melt consisting of two layers; on top a sag of the flux, and below, molten impure matter.

Smuts: Small aggregates of soot, unburnt solids or fly ash which may be emitted from chimneys and then be deposited in the vicinity. In certain circumstances, the production of sulphur trioxide during combustion may give rise to acid smuts which are corrosive.

Somatic Damage: Damage by radiation to tissues, other than reproductive cells which can cause various forms of cancer, miscarriages, cataracts, shortening of lifespan and damage to unborn children.

Sorption: A process consisting of either absorption or adsorption.

S.T.P.: Standard Temperature and Pressure. Usually the same as N.T.P. but sometimes referring to other conditions, for example, 27°C, 760 mm of mercury etc. While referring to air, 65 percent humidity is also assumed.

Sublimation: Conversion to gas directly from solid state bypassing liquid state. (eg. camphor and dry ice)

Suspended Particulates: Particles which are too fine to have an

appreciable falling velocity and therefore tend to stay suspended in atmosphere for a considerable period.

Tar: A thick dark brown or black viscous liquid obtained by distillation of wood, coal, peat, crude, oil etc. The distillation need not be in a still. Distillation may occur in a domestic grate and chimney.

Temperature, Critical: The critical temperature of a given gas is the temperature above which it cannot be liquefied.

Temperature, Potential: Temperature that a parcel of air in the atmosphere would attain if it is brought adiabatically to a pressure of 1 000 mb .

Tetraethyl lead: Form of lead added to gasoline to reduce engine knock, considered a major source of lead that is now accumulating in our bodies.

Threshold, Odour: The lowest concentration of an odour bearing gas at which only half of a panel of sniffers can detect its presence.

TLV: Threshold Limit Value. This is the concentration of any of a number of pollutants recommended as a maximum to which healthy adult workers may be exposed 8 hours a day for five continuous days a week without adverse effects. The TLV values of some of the air pollutants in ppm are 5000 for CO₂; 1000 for LPG and ethyl alcohol; 100 for terpentene ; 50 for CO and NH₃; 25 for CS₂ and chloroform ; 10 for acetic acid , H₂S and benzene, 5 for NO - NO₂, HCl, SO₂ and phenols; 3 for HF and HBr; 2 for HNO₃ and formaldehyde; 1 for chlorine; 0.1 for ozone, iodine, fluorine and bromine.

Toxic Pollutant: Those pollutants, or combinations of pollutants, including disease causing agents, which after discharge and upon exposure, ingestion, inhalation or assimilation into any organism, either directly from the environment or indirectly by ingestion through food chains, will cause death, disease, behavioural abnormalities, cancer, genetic mutations, physiological malfunction (including malfunctions in reproduction) or physical deformations, in such organisms or their offspring.

Wind Shear: The change in speed and direction of the wind, usually with height.

Zoning: A method of abating air pollution at a location by a systematic planning of sites for dwellings and for factories / industries which discharge effluents taking into account the micrometeorological conditions in and around the location.



CHAPTER - 2

SOURCES OF AIR POLLUTION

One of the early steps involving air pollution problems is to locate the source from which air contaminants are being emitted. There are more than 7,50,000 man-made chemicals present in our environment and to these 1000-2000 new ones are added every year. Massive production of such chemicals directly or indirectly releases thousands of tonnes of a variety of air pollutants into the atmosphere. Some of the air pollutants emanated into the atmosphere by man are CO, CO₂, SPM, SOx, odours, noise, NH₃, gases and vapours, dusts of toxic metals like Lead, Arsenic, Asbestos, Nickel, Mercury, Phosphorus and their oxides, Vanadium, Zinc, various hydrocarbons, Fluorides etc. The pollution made by man is vast and the pollutants made by men are plentiful.

2.1 CLASSIFICATION OF AIR POLLUTANTS

Air pollutants and their sources may be classified as follows :

- Primary and secondary pollutants
- Line and areal sources
- Natural and artificial sources

2.2 PRIMARY AND SECONDARY POLLUTANTS

Primary pollutants are those which are emitted directly from identifiable

sources. Particulates, SO_2 , oxides of nitrogen, CO, radio active elements, halogens and organic compounds, fumes, carbon, tar, resins, pollens, bacteria etc. are the different primary pollutants.

Secondary pollutants are those which are formed in the air due to interaction of primary air pollutants among themselves or by reaction with normal atmospheric constituents like sunlight, water vapour etc. with or without photoactivation.

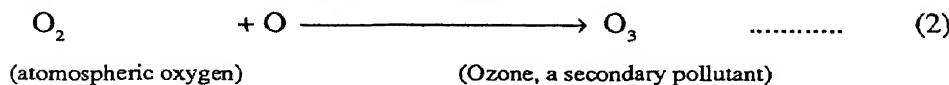
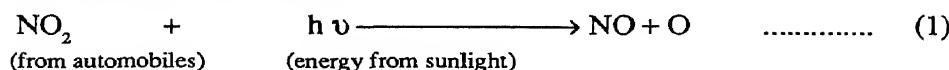
Eg :- Ozone, O_3 ; Formaldehyde, CH_2O ;

PAN (peroxy acetyl nitrate) $\text{CH}_3(\text{CO})\text{O}_2\text{NO}_2$;

Acidic mists like H_2SO_4 (SO_2 + Moisture); smog; photochemical smog

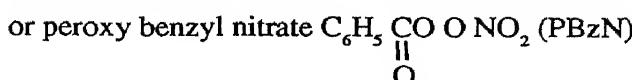
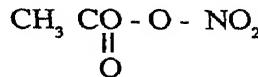
Photochemical Smog

It was first discovered in Los Angeles, U.S.A. in 1940s and now has been detected as a common phenomenon in most of the metropolitan cities of the world including Bombay and Calcutta. The conditions for the formation of photochemical smog are air stagnation, abundant sunlight and high concentrations of hydrocarbons and NO_x in the atmosphere. Huge quantities of NO_x and HCs are released due to the massive emission rates of automobiles and some stationary sources. Due to complex photochemical reactions secondary pollutants such as ozone, aldehydes, ketones and PAN are formed. A simple methodology is as follows :



Under normal circumstances this ozone decomposes back to O_2 and the nascent oxygen combines with NO to form NO_2 .

The nascent oxygen reacts mainly with NO_x to form PAN.



Also, ozone reacts with hydrocarbons to form aldehydes and ketones. CO and SO₂ also play vital roles in the formation of photochemical smog.

A typical composition of photochemical smog is given below :

Constituent	Concentration in ppm
NOx	20
NH ₃	2
H ₂	50
H ₂ O	20,00,000
CO	4,000
CO ₂	40,000
O ₃	50
CH ₄	250
Higher paraffins	25
C ₂ H ₄	25
Higher olefins	25
C ₂ H ₂	90
C ₆ H ₆	10
Aldehydes	60
SO ₂	20

Effects of Photochemical Smog

- (i) The compounds of formaldehyde, acrolein, PAN and PBzN are highly irritant to eyes.
- (ii) O₃, NO₂ and PAN present in photochemical smog cause necrosis and silvering or bronzing of the underside of leaves. Vegetation is badly affected by photochemical smog.
- (iii) Carbon, sulphur and halides present in the smog cause visibility problems. The usual size of aerosols present is about 0.3 microns.
- (iv) Ozone present in the photochemical smog badly damages the side walls of automobile tyres, unless anti-ozonants are used. Gaskets, hoses, wire insulations and other miniature electronic circuits are also badly affected.
- (v) The national ambient air quality standard for photochemical oxidants expressed as equivalent to ozone is 240 $\mu\text{g}/\text{m}^3$ (0.12ppm) averaged over

one hour period. Highly motorized areas like Los-Angeles often experience much higher concentrations causing a severe economic loss.

The photochemical smog can only be controlled by controlling the pollutants responsible for its formation viz. NO_x, CO, HC, O₃ etc., for which automobiles are the main sources.

2.3 STATIONARY AND MOBILE SOURCES

Stationary and mobile sources of air pollutants are classified as follows.

STATIONARY SOURCES

Single or point sources

- Industrial process chimneys
i.e. stacks of steel mills, power plants, oil refineries, pulp and paper industries etc.
- Municipal incinerators

Multiple or area sources

- Domestic combustion of fuel in residential areas, offices, apartments, hotels, hospitals and institutions
- On site incinerators
- Evaporation
- Commercial heating
- Open burning

MOBILE SOURCES

Line sources

Highway vehicles,
trains, channel vessels

Areal sources

air crafts, light, medium and heavy duty vehicles, railyard locomotives, port vessels.

2.4 SIGNIFICANCE OF NATURAL AND ARTIFICIAL SOURCES

The different natural and artificial pollutants - their sources and sinks, emission rates, background concentrations etc. are described in detail in the following Table 2.1

Out of the total particulate emissions of about 2900×10^6 TPA, about 2600×10^6 TPA is from natural sources only, with less than 300×10^6 TPA from artificial sources. Similarly, bacterial activity of soil, a natural process, releases about 400 million tonnes/year of NO whereas the total artificial production is less than 50×10^6 TPA. Thus 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

TABLE 2.1 SOURCES, SINKS, BACK-GROUND CONCENTRATIONS AND EMISSIONS OF AIR POLLUTANTS

Pollutant (residence time)	Sources		Annual Global Emission (Tonnes)		Atmospheric concentration	Sinks
	Artificial	Natural	Artificial	Natural		
CO ₂ (2-4 years)	Combustion	Release from plants and animals, biological decay of fossil fuels etc., oceans	1.4x10 ¹⁰	10 ¹²	305 ppm (daytime) 320 ppm (average) 400 ppm (nights)	Photosynthesis, oceans
CO (3 years)	Auto exhaust, industrial processes like stationary combustion in boilers, incinerators etc., ferrous metallurgical operations, petroleum refining, organic chemical industries.	Forests, oxidation of CH ₄ and formaldehyde, decay and synthesis of chlorophyll, photochemical oxidation of terpenes and oceans.	400 x 10 ⁶	3364x10 ⁶	0.1 ppm	Oxidation to CO ₂
SO ₂ and other products of sulphur (4 days)	Combustion of coal and oil, stationary combustion sources like power plants, boilers, ore processing, roasting and heating of non-metallic	Volcanoes, oceans and biological decay by sulphide bacteria	132x10 ⁶	130x10 ⁶	0.2 ppb.	Oxidation to SO ₄ ²⁻ , precipitation and rain

minerals, sulphuric acid plants, fertilizer manufacturing, plastics, paints and varnish manufacturing, oxidation towers, etc.				
H_2S (2 days)	Sewage treatment, chemical processes	Volcanic eruptions, biological actions in swamps and marshes.	3×10^6	1.1×10^6 0.2 ppb.
NOx (5 days)	Combustion - both stationary and mobile, heating of non-metallic minerals, processing of cement, glass, refractories etc.	Lightning and electrical storms, bacterial action in soil, fossil fuels, biomass burning	60×10^6	430×10^6 0.1 to 2 ppb.
NH_3 (7 days)	Fertilizer manufacturing, sewage treatment	Biological decay, soil	4×10^6	5300×10^6 6 to 20 ppb.
Hydrocarbons (3 years)	Combustion exhausts	Biological processes	88×10^6	16000×10^6 CH_4 -1 to 2 ppm
				Oxidation to SO_2
				Oxidation to NO_3^- after absorption by aerosols aided by light and HC.
				Reaction with SO_2 to form $(NH_4)_2SO_4$
				Non- CH_4 photochemicals with $NO-H_2O$.

CFCs (200 years)	Propellants in aerosols, refrigerents, cleaning solvents	Not completely estimated	Newly established	Nil
CH ₄ (10 years)	Rice production (paddy) animal husbandry, landfills, coal seams, melting permafrost, biomass burning	Animals, decaying vegetation, wetlands	(Refer to Hydro carbons)	Oxidation to CO, soils
Primary particulates (several days)	Agriculture, flyash from coal, industrial operations for steel, iron, cement etc. combustion and incineration of non fossil fuels	Sea salt sprays, soil dust and dust storms, forest fires and volcanic eruptions micro organisms and other aero allergens like pollen etc. from vegetation	100x10 ⁶ 1500x10 ⁶	
Gas to particle conversion	SO ₄ from H ₂ S and SO ₂ , NO ₃ from NO and NO ₂ ; NH ₄ from NH ₃	Organic aerosols from terpenes, hydro carbons etc.	200x10 ⁶ 1100x10 ⁶	Not established Rain and precipitation

TABLE 2.2 - ESTIMATED EMISSIONS OF MAJOR POLLUTANTS IN INDIA

Sources	Quantity Consumed per year (million tonnes)	Estimated Pollutant Emissions (in thousand tonnes)						Total Pollutants	
		CO	SO ₂	NO _x	C _x y	Particulate	H ₂ S	NH ₃	
Coal	67.6	115	1350	270	1630	2160	80	90	80
Fuel (diesel, petrol, kerosene)	5.9	35	100	41	110	1	1	1	290
Petroleum automobiles air crafts	1.6	730	1.6	32	128	3.2	1.6	1.5	1.6
Petroleum refinery	12.0	26	13	11	8	1.7	-	-	60
Natural gas	0.8	-	0.2	3.6	1.8	0.3	0.3	0.2	0.2
Fuel combustions	6.7	38	110	4.5	100	1.2	1.0	1.1	1.0
Industrial processes	66.2	115	1380	370	1650	2170	90	85	87
Solid waste products	32	75	600	120	720	960	36	35	36
Forest fires	100	163	1960	390	2350	3140	120	118	180
Cattle dung	55	39	440	90	540	710	25	26	25
Coal refuge burning	200	1400	1100	1000	1395	1400	-	-	6225
Structural fires	100	160	1950	400	2350	3040	120	120	180
Total	475	9390	2660	5500	1988	6898	280	290	26050

Courtesy - NEERI - Nagpur - 1968

the entire globe whereas the artificial pollutants are concentrated only in highly industrialized and urbanized areas. For example, If the characteristic global values of CO are 0.1 to 0.5 ppm, the concentration in some urban areas are even 100 times more i.e. 1 to 50 ppm. Like water, air also has self purification capacity, the capacity to purify herself. But, the massive emission rates of the artificial pollutants often overwhelm the self purifying capacity of the environment. They not only threaten the health and well being of population in a particular area but may also cause several adverse and irreversible effects on a global scale.

The depth of oceans range from 6-12 km. But even a 1m (i.e. 0.01 %) increase in depth due to global warming by green house gases may submerge 5 million sq. km of land surface. Thus the anthropogenic pollution load, however small it may be compared to the natural pollution load, may have a significant impact on man and his environment. In addition, the anthropogenic pollutants can be controlled whereas the natural pollutants cannot be. Control of artificial pollutants is gaining a greater significance as a means of preserving and protecting the environment. The different anthropogenic pollutants and their sources are presented in Table 2.3 and Table 2.5 Artificial air pollutant emissions from India are tabulated in table 2.2 and Table 2.4

TABLE 2.3 ARTIFICIAL POLLUTANTS AND THEIR SOURCES

S.No.	SOURCE	MAIN POLLUTANTS
1.	Domestic combustion of fuels like coal, wood and oil - Cigarettes :	Smoke, CO, CO_2 , SO_x , metallic oxides. 4% CO, 0.5 μg of lead per cigarette, NO_x
2.	Power generation - Thermal power plants : - Nuclear power plants : - Hydro power plants : - Diesel generators : Incinerators : - Open burning : - Commercial, municipal and industrial incinerators	Smoke, CO, CO_2 , SO_x , dusts Radio active compounds like I-131, Argon-41, Sr-90, Cs-137, C-14 etc. Methane as marshy gas from water logged areas. HC, CO, NO_x , Noise Smoke Smoke, CO, NO_x and flyash
3.	Petroleum refineries - Boilers, process heaters and regenerators - Reactors, storage tanks, compressors, generators	Noise, SO_x , HC NO_x , SPM, CO, odour

S.No.	SOURCE	MAIN POLLUTANTS
5.	Inorganic chemicals and fertilizer manufacturing	SPM, noise, odour, HF, NH_3 , H_3PO_4 and acid mists
6.	Organic chemicals manufacuturing - Plastics, paints, varnishes, rubber, pesticides, insecticides, soaps and detergents, phenols, methanol, alcohol etc.	SPM, noise, odour, SO_x , CO, gases and vapours
7.	Pulp and paper manufacutring: Blowers, washers, furnaces, evaporators, oxidation towers	Mercaptans, SO_2
8.	Agriculture - Ploughing - Crop spraying and dusting	SPM, noise, odour, H_2S
	- Field burning	Dusts and odours
9.	Food processing : Drying, preserving & packaging	Insecticides, pesticides, chlorinated hydrocarbons, lead, arsenic, phosphates
10.	Transportation : Bullock carts, motor vehicles, cars, trucks, aircrafts, trains.	Smoke, flyash, soot
		Dusts, vapours, odours
11.	Roasting and heating processes of non metallic minerals : crushed stone, gravel, sand processing, cement, glass refractories, ceramics - manufacturing, coal cleaning.	HCs and CO (95% of total CO & HCs are from transportation only)
		lead, dusts, noise, NO_x and rubber and evaporative emissions like Olefins, paraffins, aromatics, benzene etc.
		Minerals and organics, SPM, SO_x , NO_x , dusts
12.	Ferrous metallurgical material handling, ore sintering and pelletising, coke ovens, blast furnaces, steel furnaces	Smoke, fumes, CO, odours, H_2S , vapours, fluorides.
13.	Non ferrous metallurgical processes	Dusts, fumes of Cu, Zn etc.
14.	Roasting, smelting and refining	SO_x

TABLE 2.4 AIR POLLUTANT EMISSIONS FROM INDIA
 (Million Tons Per Year)

Source	Weight of pollutant produced					Total wt. of pollutant
	CO	NO _x	Hydro carbons	SO _x	Partic- ulate	
Transportation						
Gasoline	54.6	6.1	13.9	0.2	0.5	
Automobile						
Diesels	1.2	0.7	1.4	0.1	0.3	
Air craft	3.2	0.1	0.3	0.0	0.0	
Rail roads	0.5	0.5	0.4	0.1	0.2	
Vessels	1.1	0.3	0.2	0.3	0.1	
Non highway	3.2	0.4	0.4	0.1	0.1	
	63.8	8.1	16.6	0.8	1.2	90.5
Fuel Combustion (Stationary)						
Coal	0.8	3.8	0.2	18.8	7.8	
Fuel oil	0.2	1.2	0.1	4.4	0.5	
Natural gas	0.0	4.6	0.0	0.6	0.3	
Wood	0.9	0.4	0.4	0.6	0.3	
	1.9	10.0	0.7	24.4	8.9	45.9
Industrial Process						
Steel	5.5	0.1	2.3	3.5	4.2	
Petroleum	2.7	0.0	0.8	1.3	1.0	
Paper	0.8	0.0	0.7	1.2	1.0	
Others	0.7	0.1	0.8	1.3	1.3	
	9.7	0.2	4.6	7.3	7.5	29.3
Solid waste disposal	7.8	0.6	1.6	0.1	1.1	11.2
Miscellaneous						
Forest fires	6.9	1.1	4.5	0.1	6.8	
Structural fires	0.4	0.1	1.2	0.0	0.2	
Coal refuse burning	1.2	0.2	1.3	0.5	0.4	
Agricultural burning	8.4	0.3	1.5	0.0	2.2	
	16.9	1.7	8.5	0.6	9.6	37.3
Total	100.1	20.6	32.0	33.0	28.3	214.0

2.5 NATURAL AIR POLLUTANTS

The first and the foremost source of air pollution is nature itself. Some of the natural air pollutants and their sources are discussed below :

1. Water Vapour and Humidity

Humidity is caused in nature by the evaporation of water bodies, seas, rivers, streams, ponds etc. This water vapour present in the atmosphere causes isnophelia, asthma and other respiratory problems and brings electrical storms. The earth's crust and the clouds are positively charged whereas the atmosphere in between is negatively charged. Due to the physico-chemical actions, electricity is produced. As water vapour is a good conductor of electricity, electricity travels through atmosphere and is observed as "electric storms" with temperature reaching up to 10,000°C. Due to such high temperatures, the surrounding air gets heated suddenly and expands. This is immediately replaced by cooler air and thus lightnings and thunders are formed. Thus due to the presence of moisture every second thousands of electrical storms take place. Depending on the temperatures we can visualise few only. In coastal regions, humidities, upto 80% are common. In arid regions with no water sources, humidity as low as 5% also is observed. Also, water vapour enhances the action of air pollutants like SO_2 , NO_2 and particulates on men, material and vegetation.

2. Temperature

The average temperature of earth is about 16°C with maximum recorded being 75°C in Turkisthan and minimum recorded being -90°C in Greenland. However the comfortable temperature is about 70°F i.e. 21°C. Temperature, which decreases with elevation, aggravates the chemical actions of various other air pollutants on materials. Being the main meteorological factor it plays a vital role in controlling the concentrations of pollutants in atmosphere. The mean global temperature is increasing due to the emission of a variety of green house gases into the atmosphere.

3. Salt Particles

Every year about 900 million tonnes of salt particles are emanated from the sea. The sea sprays are highly corrosive, as a result the structures in coastal areas have less life. In addition, the abrasive action of sea breezes damage the building materials and art treasures. Ancient temples, mosques and other historical monuments on the coastal areas are damaged due to abrasion of particulates from oceans. In addition, the coastal atmospheres are sweaty and often are uncomfortable for inhabitants.

4. Dusts

The dust particles emanated into the atmosphere by natural dust storms are 182 million tonnes per year. Not only clouds but also dusts can travel from country to country. In the seventies the dust storms used to carry huge quantities of dusts from 'Thar' desert (area 2,50,000 km²) of Rajasthan to Delhi, badly affecting the visibility. Dust storms carrying dusts for several kilometers is a common phenomenon. Recently there was an inter - continental dust storm from 'Sahara' desert (area 9,00,000 km²) of North Africa to Florida of U.S.A. It whirled 8 kms. upwards with a width of 2500 km and deposited millions of tonnes of dust and sand in Florida.

5. Smoke and other Particulates

Every year about 7 million tonnes of smoke, soot and other particulates are emanated from volcanoes and forest fires. Smoke affects visibility and black smoke is often considered as the layman's index of air pollution.

6. CO₂

CO₂ is released into the atmosphere due to respiration by humans, animals and vegetation and eruptions of volcanoes and forest fires. 'Dating' is a technique of geologists used to find the age of rocks based on amount of CO₂ accumulated. The excess CO₂ released from volcanoes, forest fires etc. may misguide the geologists and the archeologists in estimating the correct age of rocks. CO₂ being a green house gas, increases mean ambient air temperature and mean sea level.

7. Products of Sulphur

The natural sources of S, SO₂, H₂S and SO₄, the products of sulphur are volcanoes, oceans and biological decay. About 100 million tonnes of H₂S is produced every year due to biological decay by sulfide bacteria. Oceans emit sea sprays containing 120×10^6 tonnes of sulfates per annum i.e. in total 130×10^6 tonnes of sulphur is emitted every year by natural air pollutants. An equal amount is released by artificial sources from coal combustion, petroleum industries and smelting of various metals.

8. Hydrocarbons

Nature releases hydrocarbons from swamps, marshes and water bodies. About 170 million tonnes of terpenes are released every year. Also 1450 million tonnes of CH₄, known as natural gas is evolved every year due to the anaerobic decomposition of organic matter. Due to the construction of thousands of impounding reservoirs, water logging is taking place as a result the quantity of marshy gas, CH₄ has increased significantly.

The exploitation of natural sources for methane generation also has resulted in increasing the methane concentration in atmosphere. Being a green house gas it joins hands with CO₂ in increasing the mean global temperature. Only 90 MTPA of hydrocarbons are released by artificial sources against 1600 MTPA by natural sources.

9. Ozone

Ozone is a photochemical oxidant and is produced in the upper atmosphere by solar radiation. Also small concentrations of ozone are produced by lightning and forest fires. Background concentration of ozone ranges from 39 to 78 µg/m³ in the atmosphere. Ozone is usually accumulated in the upper strata of atmosphere at around 25-40 km range from earth and is known as "Ozone blanket" or "Ozone layer". It does not allow the dangerous incoming UV rays. Life on earth is probably possible only due to this protective umbrella of ozone.

10. Aeroallergens

Viruses, fungi, algae, protozoa, terpenes, bacterial spores, pollens, moulds and danders are the main natural aeroallergens and are emanated from plants, vegetations and animals. The terpene molecules combine to form aerosols that produce the "Blue haze" over forested areas. The life time of these is very small due to lack of nutrients and presence of UV rays in sun. However bacteria and fungi can survive for larger periods.

11. Odours

Natural sources of odours are insects, animals, fires and decay of organic matter and dead animals. Noted artificial sources are refineries, industries sewage treatment plants etc.

12. Noise

Noise is emitted in nature by lightnings and thunders. The noise levels produced by thunders may exceed even 110 dB(A) which is nearer to the threshold of pain. The main artificial sources of noise are automobiles and industries.

NO_x, SO_x and CO : The natural and artificial sources and their emission rates of these pollutants are detailed in the table.

2.6 PROPERTIES OF MAJOR AIR-POLLUTANTS

Particulates

Particulates may be solid, liquid or gaseous matter. Size is one of the most important physical properties of particulates. Particle sizes are measured in

micrometers, μm . Particles larger than $50 \mu\text{m}$ can be seen with the unaided eye. Particles may be classified according to their mode of formation as dust, smoke, fumes, flyash, mist or spray. Dusts are small solid particles created by the breakup of larger masses through processes such as crushing, grinding or blasting and may come directly with processing or handling of materials such as coal, cement or grains. Capable of temporary suspension in air or other gases, dusts do not diffuse. They settle under the influence of gravity. Smoke and fine solid particles resulting from the incomplete combustion of organic matter such as coal, wood or tobacco, consists mainly of carbon and other combustible materials. Fumes are fine solid particles formed by the condensation of vapours of solid materials. Fumes may be from sublimation, distillation, calcination or molten metal processes. Settling properties are one of the most important properties of particulates. As such, settling is the major natural self-cleaning process for the removal of particulates from the atmosphere. Particulates can be generally classified as suspended or settleable.

Chemical Characteristics : There is great variation in the chemical composition of the particulates found in the atmosphere. Atmospheric particulates contain both organic and inorganic components. Some of the more common organic matters found in particulates include phenols, organic acids and alcohols.

Biological Characteristics : The biological particles in the atmosphere include protozoa, bacteria, viruses, fungi, spores, pollens and algae. Micro-organisms generally survive for only a short time in the atmosphere because of the lack of nutrients and ultra radiation from the sun. However, certain bacteria and fungi form spores and can survive for long periods. Many of these may be treated as aero-allergens.

SO_x : Of all anthropogenic air pollutants, the oxides of sulfur are probably the most widespread and the most intensely studied. Sulfur dioxide (SO_2) and sulfur trioxide (SO_3) are the two oxides of sulfur of most interest in the study of air pollution. SO_2 is a colourless gas, non flammable and non explosive. SO_2 has a suffocating odour. The odour threshold of SO_2 is $1306 \mu\text{g}/\text{m}^3$ (0.5ppm) and taste threshold is $784 \mu\text{g}/\text{m}^3$ (0.3ppm). SO_2 is highly soluble in water (113 grams/litre at 20°C). Molecular weight of SO_2 is 64.06 and is about twice as heavy as air. Thus the problem of SO_2 is an important one. The Cp, Cv, R values of SO_2 in J/kg.°K are 635, 505 and 129.7 respectively.

CO : Carbonmonoxide is a colourless gas. CO is chemically inert under normal conditions. The atmospheric mean time of CO is about two and half months. CO reacts with the haemoglobin (Hb) of blood to give carboxy haemoglobin (COHb). This reduces the capability of blood to carry oxygen.

The molecular weight of CO is 28. The Cp, Cv and R values of CO in J/kg. °K are 1038, 741 and 296.8 respectively.

NOx: The stable gaseous oxides of nitrogen include N_2O , NO , N_2O_3 , N_2O_4 , NO_2 and N_2O_5 . Of these N_2O , NO and NO_2 are present in a significant amount and are potential contributors to air pollution. N_2O is an inert gas with unaesthetic characteristics. NO_2 is a reddish brown gas. N_2O is a colourless gas and is an active compound in photochemical formation. The Cp, Cv and R values for NO in J/kg. °K are 975, 698 and 277.1 respectively.

Ozone : Ozone is a colourless gas. The molecular weight of ozone is 48.0 and the melting point is $-192.7 \pm 0.2^\circ C$. The boiling point of ozone is $-111.9 \pm 0.3^\circ C$. Ozone is about 1.66 times heavier than air. The vapour density of O_3 at $0^\circ C$ and 760mm of Hg is 2.14 g/liter. Ozone reacts with free ions of F and Cl and dissociates into oxygen ions. The Cp, Cv and R values of ozone in J/kg. °K are 82, 647 and 173.2 respectively.

PAN : Peroxyacetyl nitrate is the main air pollutant obstructing visibility. Its molecular formula is $CH_3(CO)O_2NO_2$. PAN has a molecular weight of 121. It has no boiling point and decomposes before boiling. PAN is a colourless gas with a vapour pressure of about 15mm of Hg.

TABLE 2.5 ANTHROPOGENIC SOURCES OF AIR POLLUTION

1.	Aldehydes	Auto exhaust, waste incineration, fuel combustion, photochemical reactions, thermal decomposition of oils.
2.	Ammonia	Chemical industries, coke ovens, refineries, stock yards and fuel incineration.
3.	Arsenic	Metal smelters, arsenical pesticides and herbicides, processes involving arsenic soldering.
4.	Asbestos	Asbestos factory or mines, construction sites.
5.	Barium	Industries mining, refining or producing barium and barium-based chemicals, smoke suppressing additives in diesel fuels.
6.	Beryllium	Industrial usage, production of fluorescent lamps, rocket motor fuels.
7.	Boron	Industry producing boron, petroleum fuel additive pressed in coal.

8.	Cadmium	Metal industries engaged in extraction, refining, machining, electroplating and welding of cadmium materials. By-product of refining lead, zinc and copper. Pesticides, fertilizers, cadmium-nickel batteries, reactor poison in nuclear fission plants, used in production of tetraethyl lead gasoline.
9.	Chlorine	Process industries using chlorine, accidental leakage during storage and transportation.
10.	Chromium	Metallurgical and chemical industries. Products employing chromate compounds, cement and asbestos.
11.	CFCs	Sterilants for medical suppliers, air refrigerants, propellants, deodorants, cleaning solvents, fire extinguishers, blowing and foaming agents.
12.	Ethylene	Motor vehicle emissions, chemical industries, incineration of agricultural wastes, emissions from growing plants.
13.	Hydrochloric acid	By-product from chlorination of organic compounds, burning of coal, burning of chlorinated plastics and paper, combustion of gasoline containing ethylene chloride.
14.	Hydrogen sulfide	Biological decay of protein material in stagnant water, kraft paper mills, industrial waste disposal ponds, sewage treatment plants, refineries, coke ovens.
15.	Iron	Iron and steel plants, fly ash from combustion of coal and fuel oil, municipal waste incineration, use of welding rods.
16.	Lead	Automobile emissions, lead smelters, combustion of coal and fuel oil, lead arsenate pesticides.
17.	Manganese	Blast furnaces producing ferro-manganese compounds, organic manganese fuel additives, use of welding rods, incineration of manganese containing products.

18.	Mercury	Mining and refining of mercury, use of mercury in laboratories. Pesticides containing mercury.
19.	Nickel	Metallurgical plants using nickel, engines burning fuels containing nickel additives, burning coal and oil, nickel plating facilities, incineration of nickel products.
20.	Phosphorus	Plants producing phosphate fertilizer, phosphoric acid, phosphorus pentoxide, emission from vehicles and aeroplanes using phosphorus as corrosion inhibitors (in fuel).
21.	PAN	Automobiles and sunrays.
22.	Radioactive substances like H-3, C-14, Be-7, Radium, Radon etc.	Combustion of fossil fuels like coal and oil, nuclear power plants, research laboratories, radioactive minerals of earth crust, reaction of cosmic rays with atmospheric gasses etc., atmospheric dusts.
23.	Selenium	Combustion of industrial and residual fuels, refinery waste gases and fumes, incineration of wastes including paper products.
24.	Vanadium	Vanadium refining industries, alloy industries, power plants and utilities using vanadium - rich residual oils.
25.	Zinc	Zinc refineries, manufacturing of brass, zinc galvanising processes.
26.	Hydrogen cyanide	Blast furnace, fumigation, chemical manufacturing, metal plating etc.
27.	Phosgene or carboxyl chloride	Chemical and dye making processes.
28.	Suspended particles (ash, soot, smoke etc.)	Incinerators and almost all manufacturing processes.



CHAPTER - 3

EFFECTS OF AIR POLLUTANTS

A normal human being breathes about 25,000 times a day at a rate of about 1-2 litres of air per breath i.e. about 25,000 to 50,000 litres/day i.e. about 30 to 60 kg of air per day. Thus the quantity of air consumed by an average man is about 25 times more by weight and 20,000 times more by volume than the quantity of water consumed. A person can survive for five weeks without food and five days without water but only five minutes without air. In addition, the air we breath interacts with the most sensitive organs of human body. Hence the air we breath must be of a very good quality. Unfortunately man is not equipped with household or portable air cleaning devices unlike water filters etc. and thus demands a clean ambient air for his health and well-being which is more than a luxury today.

Air that surrounds a man has a direct impact on his health and property. The health of a man is determined by the interplay and integration of the internal environment of man himself and the external environment that surrounds him. A disease is only due to a disturbance in the delicate balance between man and his environment. Now-a-days it is not only stacks or chimneys alone where soot is detected as a cause of cancer but carcinogens are found elsewhere also in the environment where very potent cancer causing agents such as benzopyrene and many other polycyclic aromatic hydrocarbons are present in significant concentrations in air. Ofcourse, man is the primary source of air

pollutants. He breathes fresh air and emits polluted air containing pathogens and other aeroallergens, CO, CO₂ and odours. A study by the World Health Organisation shows that 75-90% of all cancers are caused due to environmental factors and are related to agents present in air, water, work environment and personal choice of life style including tobacco smoking and chewing, alcohol consumption and sexual promiscuity. The effects of air pollutants on atmosphere, animals including man, materials and vegetation are thoroughly discussed in this chapter.

3.1 EFFECTS OF AIR POLLUTION ON MAN

"Health is a state of complete physical, mental and social well-being and not merely an absence of disease or infirmity" is the widely accepted definition of health. Health is a fundamental human right and is the essence of life and is man's world-wide social goal. The signs of physical health of an individual are a good complexion, a clean skin, bright eyes, lustrous hair, a physique that is good looking - neither too that nor too lean, neither too tall nor too short, firm flesh, a sweet breath, a good appetite, sound sleep, regular activities of bowels and bladder, smooth, flexible and coordinated bodily movements, normal functioning of different organs, special senses, normal pulse rate and normal blood pressure. Mental health may be defined as a state of balance between the individual and the surrounding world, a state of harmony between oneself and others, a co-existence between the materials of the self and that of their people, and that of the environment. The health of a man is determined by the interplay and integration of the internal environment of man himself and the external environment that surrounds him. A disease is due to disturbance in the delicate balance between man and his environment.

Man's health is easily affected by air pollution. The inhalation of gases and particulates through human respiratory system is a direct form of air pollution. The factors governing the impact of air pollutants on man are (i) the type of pollutants (ii) concentration and duration of the pollutants and (iii) health condition of the recipient.

The Human Eye

Even though no lasting damage to the eye has been attributed to air pollution, the sharpness of vision is reduced by excess carbonmonoxide. Smog, when present in considerable amount causes irritation to the eye. When gaseous or particulate materials contact the external coat of the eye and the internal mucous lining of the eyelid, the eye will be irritated. However to relieve this irritation, excessive rubbing will be done, which will cause physical damage. Some particulate materials combined with ozone, oxides of nitrogen, aromatic hydrocarbons and synthetic pollutants cause irritation.

The Respiratory System

It is certain that the respiratory system is affected more than any other part of the human body because the basic functions of the respiratory system are to inhale air into the lungs, filter impurities from the inhaled air, supply oxygen contained in this air to the circulatory system, and exhaling CO₂ from the circulatory system.

The upper respiratory tract removes particulates larger than 10 microns in diameter by inhaling and then immediately exhaling the air. The lower respiratory tract consists of the bronchi, bronchioles, alveolar ducts, alveolar sacs and the alveoli of the lungs. Air is first drawn through the large bronchi and then through a system of branching ducts. Human respiration may be divided into ventilation and respiration.

Pollutants enter the body through the respiratory system, which can be divided into the upper respiratory system, consisting of nasal cavity and the trachea, and the lower respiratory system, consisting of the bronchial types and the lungs. At the entrance to the lungs, the trachea divides into two bronchial trees which consist of a series of branches of successively smaller diameter. At the end of the bronchioles are large collections of tiny sacs called alveoli. It is across the alveolar membranes that oxygen diffuses from the air in the sacs to the pulmonary capillaries and CO₂ diffuses in the opposite direction.

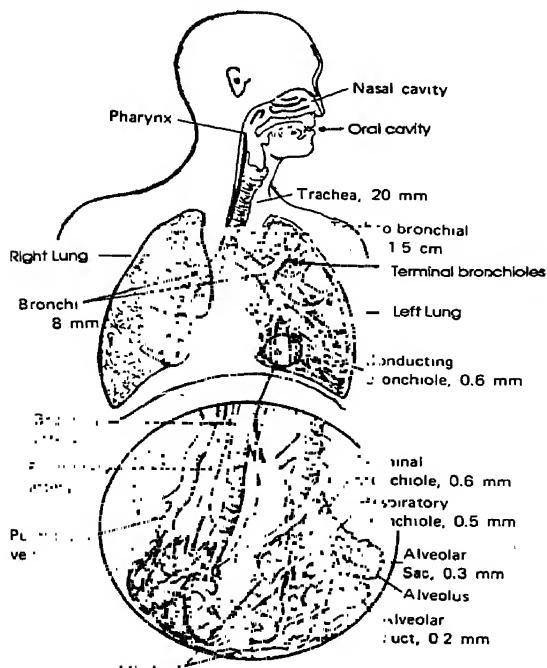


Fig. 3.1 Human Respiratory System

The respiratory system has several levels of defense against invasion by foreign material. Large particles are filtered from the air stream by hairs in the nasal passage and are trapped by the mucous layer lining the nasal cavity and the trachea.

3.2 EFFECTS OF NATURAL AIR POLLUTANTS

(i) Atmospheric Pressure

Atmospheric pressure decreases with increase in altitude. At an altitude of about 30 km above MSL the pressure is hardly 10 mm of Hg. The pressure increases at the rate of 1 kg/cm^2 i.e. 760 mm of Hg for each 10m depth under water below sea level. Barometers are the instruments employed for measuring pressure.

A pressure of about 1kg/cm^2 is comfortable for man. Density of air and pressure decrease with altitude. Man cannot survive at an altitude of about 8 km without breathing equipment. This is mainly due to increase in respiration , the concentration of hemoglobin and the increase in cardiac output. Persons at higher altitudes and exposed to lower pressures suffer from headache, insomnia, breathlessness, nausea, vomiting and impaired vision.. This may be due to various intricate biochemical and hormonal disturbances in the body and is popularly known as mountain sickness.

Persons exposed at altitudes of above 4 km. experience irregular breathing, oliguria, mental confusion and hallucinations, stupor, seizures and coma. The condition known as High Altitude Pulmonary Oedema does not respond even to antibiotics. When man is exposed to high pressures of the order of 10 atmospheres, gases like oxygen, carbondioxide and nitrogen are dissolved in the blood and tissues. Excess nitrogen exerts a narcotic action leading to loss of mental functions and consciousness. Excess carbondioxide increases the narcotic action of nitrogen and excess oxygen leads to convulsions and death. When the person returns to normal pressure condition, the dissolved gases are released causing air embolism. This is a common disease observed in persons working in diving wells and compressed air chambers. The disease is popularly known as Caisson Disease.

(i) Relative Humidity

Relative humidity is the percentage of moisture present in the air, complete saturation being taken as 100%. The greater the RH the nearer the air to saturation. If RH exceeds 65% air inside the room feels sticky and uncomfortable. Better ventilation serves to lower such humidity. RH below 30% also is unpleasant. Permanent exposure to such low humidities can cause drying of the nasal mucosa which may predispose to infection, exemplified by sore throat and cough. Usually coastal regions and areas adjacent to huge water bodies are humid. Humidity acts as a catalyst in the reaction of air pollutants like SO_2 , NO_2 and particulates on materials. In indoors, humidity increases due to evaporation of moisture from skin and lungs. The exhaled air contains about 6% of moisture.

(iii) Temperature

Thermal comfort is a complex entity . For a long time, air temperature was used as an index of thermal comfort, but it was realised that air temperature alone was not an adequate index of thermal comfort. Later, air temperature and humidity were considered together to express thermal comfort. A temperature of about 77-88°F i.e. 25 - 27°C is the comfortable range of temperature. The average temperature of earth is about 16°C ranging from 75°C in Turkisthan to minus 90°C in Greenland .

(iv) Heat (Maximum Allowable Sweat Rate)

4.5 litres of sweat excreted in four hours is considered as the maximum allowable sweat rate compatible with physiological normal reaction in acclimatized, healthy young-men for repeated exposure to heat. Comfort zone may be defined as the range over which majority of adults feel comfortable. There is no unanimous decision on a single zone of comfort for all people because comfort is quite a complex subjective experience which depends not only on physiological factors but also on psychological factors which are difficult to determine.

PREDICTED FOUR HOUR SWEAT RATE

1. Comfort Zone	1 - 3 litres
2. Just tolerable	3 - 4.5 litres
3. Intolerable	4.5 litres

The rate at which a man sweats is a good index of the heat stress to which he is subjected. A sweatrate of 4.5 litres in 4 hours is the upper limit of tolerance in health for work in hot environment. A sweat rate of 2.5 litres in 4 hours is considered optimal for a working man. When humans are exposed to heat as many as 14 disorders have been recognised. Some of them are:

Heat Stroke: This is attributed to failure of the heat regulating mechanism and is characterised by very high body temperature and profound disturbances including delirium, convulsions and partial or complete loss of consciousness. The skin becomes dry and hot. Death is often sudden and may be due to hyperpotassemia. Hyperpotassemia may be due to the release of potassium from red blood cells which have been injured by heat. The treatment consists in rapidly cooling the body in ice water baths till the temperature falls to below 103°F. The patient should be kept in bed for several days.

Heat Cramps: Heat Cramps occur in persons doing heavy muscular work in high temperature and humidity. The cause of heat cramps is loss of sodium and chlorides in the blood.

Heat Syncope: This is a common ill-effect of heat. In its milder form, the person standing in the sun becomes pale, his blood pressure falls and he collapses suddenly. The blood pressure is lowered due to lack of blood supply to brain. This condition is quite common among soldiers when they are standing under the sun for parades.

Cold Stress: In general cold injury, the individual is said to be suffering from exposure to cold. This is characterised by numbness, loss of sensation, muscular weakness, desire for sleep, coma and death. Local cold injury may occur at temperatures above freezing as in immersion or trench foot. It is extremely important to dress for the temperature with which the body part will be in contact. Intake of hot fluids promotes general rewarming.

Preventive Measures for Heat Stress: The ill effect of high temperature may be prevented by replacement of water. Persons should be encouraged to drink cool water. The duration of exposure to a hot environment, should be cut down. There should be periods of rest between intense work. The clothing worn should be light, loose and of light colours. The temperature and humidity in the work environment may be controlled by proper ventilation and air conditioning.

(v) Aeroallergens

Allergy is a misdirected activity of the immune system. It is the body's reaction to foreign substances which do not otherwise harm the system. Allergy is supposed to be caused by everything under the sun including the sun.

According to the Asthma Research Society, there are several hundred types of air borne pollens and spores that are responsible for bronchial asthma. Thus, office workers and house-wives are more susceptible to asthma than industrial workers. Industrial processes like cotton mills, feather and hair processing, jute and leather processing, tobacco processing, wood working, floor milling etc. also contribute significant quantities of aeroallergens. The different diseases caused by aeroallergens are asthma and other respiratory problems, dermatitis and other skin diseases.

Air borne substances causing allergy are known as aeroallergens. Pollens, molds, danders and glues, spores, bacteria, viruses, fungi and some dusts are the cause of allergic reactions in sensitive persons. Ragweed pollens with a typical diameter of about 20 microns is usually deposited within 100m from

the parent plant accelerating hay fever or asthma. Bangalore, the garden city of India may also be called as the 'Asthma City' of India. Finely powdered industrial materials also may be allergic. Submicron sized allergens are more dangerous for human health as they cannot be filtered out by the hairs in the nose.

3.3 EFFECTS OF SPECIFIC POLLUTANTS ON MAN, MATERIAL AND VEGETATION

Agate Dust : Epidemiological survey of workers in agate industry where stones are produced for making ornaments, has shown the presence of various categories of pneumoconiosis in workers. The incidence of pulmonary infection, including tuberculosis, in these workers was marked high. Experimental study on animals exposed to agate dust has shown that the exposed animals become more susceptible to E. Coli.

Aldehydes : Aldehydes are usually emitted by auto exhaust, waste incineration, fuel combustion and photo-chemical reaction. Generally, aldehydes present in air cause eye, skin and respiratory irritations in addition to the odour pollution. Aldehydes are products of incomplete combustion of hydrocarbons and other organic materials. Further more these aldehydes may be formed as secondary pollutants due to photochemical reactions after entering the atmosphere. Damage appeared in petunias as neurotic banding of the upper leaf surface and glazing of the lower leaf surface.

Ammonia, NH₃: Ammonia is emitted mainly from chemical industries, coke-oven refineries, stock yards and fuel incinerators. Ammonia when present in excess in air is corrosive to mucous membranes and causes damage to eye and respiratory tract. Ammonia has caused serious damage to vegetation only as a result of accidental spills that allowed high concentrations of the gas to be carried by the winds over vegetation in the vicinity. Ammonia injury causes acute tissue collapse, with or without chlorosis. Its extreme solubility in water and ability to react with acidic components of air made NH₃, a significant air pollutant. Ammonia causes damage to varnish and paint surfaces and discolours fabrics. High concentrations of NH₃ corrode a number of non-ferrous metals such as copper, tin, zinc and their alloys and carbon steels. It can soften wood through interaction with cellulose fibres and can soften natural rubber. Plastics like epoxy, fibre glass, nylons and PVC also are adversely affected.

Arsenic: Arsenic is emitted from metal smelters, arsenical pesticides and herbicides. Arsenic and its compounds are known to be toxic to humans, animals and plants. At normal atmosphere, the poisoning is less likely, but when proper control devices are absent at arsenic metal smelters, poisoning

episodes can occur. Arsenical herbicides are used to eliminate aquatic plants. If not properly controlled, arsenic herbicides will become an air pollution problem. Arsenic, when present in air causes irritation to eye, skin and respiratory system. Arsenic trioxide causes chronic poisoning in horses, cattle and sheep. When arsenical compounds are not used in strict compliance with instructions they cause damage to plants. In several cases copper and gold smelter arsenic emissions have caused damage to plants in the vicinity of the smelters. Forbes, in the year 1950, described that in arsenic mines, air was hard to endure on account of injurious odour of ore and workers faced different health disorders.

Asbestos : Asbestos is released from asbestos factory or mines or construction sites. Asbestos is the general name given to a variety of useful fibrous minerals. Inhalation of asbestos dust is an industrial hazard as well as a non-occupational environmental hazard for persons living near an asbestos factory or mine. According to one researcher lung cancer deaths among asbestos workers who smoked cigarettes were eight times higher than the non-smokers exposed to asbestos. Asbestos fibres irritate membrane and cause pulmonary fibrosis and pleural calcification. The use of asbestos in pottery along with clay was prevalent even in stone age. The gradual wear and disintegration of asbestos containing products of roofing material, floor-tiles, asbestos containing coatings, brake lining and dust produced in air due to the demolition of buildings result in high concentrations of asbestos in air. The inhalation of asbestos may result in lung fibrosis, bronchial carcinoma, mesothelioma of pleura and peritoneum. The exposure to asbestos may also cause acute or chronic visceral plearisy and pleural calcification.

Barium: The sources of barium are industries, mining, refining or producing barium and barium based chemicals, smoke suppression additives in diesel fuels. Barium is a soft, silvery metallic element found in nature only in combination with other elements. Insoluble compounds such as barium sulfate are generally non toxic; however soluble compounds are highly toxic when ingested and produce a strong stimulating effect on all muscles of the body. More research is needed to evaluate barium as a possible air pollutant. Barium affects heart muscles, central nervous system and respiratory tract.

Beryllium: Beryllium is evolved from industrial usage, production of fluorescent lamps and rocket motor fuels. Beryllium is the most toxic and the most hazardous of the non-radio active substances used in industry. Chronic berylliosis develops slowly, in which lungs show multifocal granulomatous inflammation. Granulomatous lesion due to chronic exposure to beryllium compounds may cause hyper sensitivity reaction. Berylliosis is reported to be an autoimmune disease. The causes of berylliosis have been

reported from electronic and neon industry, ceramic industry and areas surrounding beryllium manufacturing plants. Beryllium is commonly found as an atmospheric pollutant within the confines and in the proximity of industrial plants producing beryllium. Beryllium present in excess of 1 ppm in soil solution is proved to be toxic.

Boron: Boron is evolved from industries producing boron and petroleum fuel additives. Boron is also present in coal. Boron and its compounds are considered moderately to highly toxic to man when ingested or inhaled. More research is needed regarding boron as an environmental contaminant. Boron hydrides can cause damage to central nervous system and death. Boron is one of the trace elements needed by plants in minute amounts without which the growth of a plant is abnormal. Boron used in large amounts in herbicides proves to be extremely toxic to most plants and precautions should be strictly taken to avoid accidents. Borates are also found in some commercial fertilizers.

Cadmium: is emitted from metal industries engaged in extraction, refining, machining, electroplating and welding. Cadmium is a by product of refining lead, zinc and copper. Pesticides, fertilizers, cadmium-nickel batteries release cadmium into the atmosphere. Inhalation of fumes or dusts of cadmium results in the development of clinical symptoms of cadmium poisoning such as dryness of throat, headache, vomiting, muscle cramps, difficulty in respiration etc. In many cases occupational workers inhaling high concentrations of cadmium might be without any discomfort, within hours of exposure to cadmium because of its delayed on-set of symptoms. Cadmium plants result in fuming of cadmium increasing the mortality in workers. Pulmonary edema, acute inflammatory changes in kidney, lung neurosis and fatty degeneration of liver were the causes for mortality after inhaling cadmium vapours. Prolonged (25 years) exposure of workers to cadmium fumes results in emphysema of lungs, mild liver damage along with anosmia (loss of sense of smell). Chronic cadmium poisoning leads to 'itai-itai'. This disease is a respiratory disorder. The initial symptoms of the disease resulting from cadmium enriched diet were pain in back and legs followed by pressure on bones of limbs and ribs. The bones become so fragile that even bumps and knocks may cause a fracture. The individual may even lose his weight due to deformities. Studies show that cadmium may be a cause of heart-diseases, hypertension and cancers.

Cadmium capsules administered to cows for control of intestinal worms caused a decline in milk production. Even medicines with small amounts of cadmium killed pigs. Animals grazing in close proximity to zinc refineries where there will be emissions of cadmium, may be endangered by cadmium air pollution.

Chlorine: Generally, process industries using chlorine emit chlorine. During transportation and storage, accidental leakage of chlorine may occur. Chlorine is a gas with distinctive irritating smell. Chlorine is a strong oxidizing agent and is able to mix with both organic and inorganic matter. This makes it dangerous to humans, animals, plants and numerous materials. Chlorine is irritating to eye, nose and throat. Large doses of chlorine damage lungs producing edema, pneumonitis, emphysema and bronchitis. Chlorine used in swimming pools as a disinfectant causes eye irritation. Chlorine causes marginal and tip neurosis and bleaching of foliage at high concentrations. Chlorine causes corrosion and discoloration in metals, paints and textiles.

Chromium: Chromium is emitted from metallurgical and chemical industries. Products employing chromate compounds, cement and asbestos evolve chromium. Chromium is thought to be relatively non-toxic in metal form. But when trivalent and hexavalent chromium compounds are found in the air, they are toxic to humans. Chromium trioxide is perhaps the most important hexavalent chromium compound in the air. When added to water it produces chromic acid which is corrosive. The industrial poisoning in the occupational workers of chrome plants are recognized as early as in 1927. The prolonged exposure to and inhalation of chromium and its salts often results in perforation of nasal septum termed as "chrome holes". It is now well established that prolonged inhalation of trivalent and hexavalent chromium compounds results in the development of lesions in lungs, respiratory passage and characteristic chronic "Chromate lung". Alkaline dichromates can permeate through skin lesions in appreciable amounts to cause renal damage. Dermatitis, erythema and oedema are common disorders seen in persons when chromium comes into contact with their skin.

Chlorine believed to exert carcinogenic action, develops dermatitis and ulcers of skin and perforation of nasal septum. Chromium can be toxic to plants, depending on the type of plants and the amount of chromium in the soil. Failure to apply proper safeguards and over-dosage of chromium containing fungicides cause damage to plants. Chromium causes corrosion in the form of chromic acid and discolorates metals, paints, building materials, paper and textiles.

Ethylene : Ethylene is found in the emissions of motor vehicles, chemical industries, incineration of agricultural wastes and is emitted by growing plants. Ethylene is a colourless hydrocarbon gas of the olefin series which although non-toxic to humans, presents a considerable air pollution problem. It is the most abundant of the hydrocarbons in the lower atmosphere. Ethylene contributes to photo-chemical air pollution and when it combines

with nitrogen oxide and ozone the reaction causes eye irritation. It is one of the few hydrocarbons possessing ability to injure plants without undergoing photochemical reaction with nitrogen oxides. Ethylene has a unique effect in that it does not directly attack plant tissue but interferes, directly with plant hormones resulting in morphogenetic and physiological changes in tissues.

Hydrochloric Acid: Hydrochloric acid is a by-product from chlorinations of organic compounds. Burning of coal and burning of chlorinated plastic and paper result in the emission of hydro-chloric acid. When gasoline containing ethylene chloride undergoes combustion, hydrochloric acid is evolved. Hydrochloric acid causes coughing and choking from inhalation. The upper respiratory tract is inflamed and ulcerated by hydrochloric acid. Hydrochloric acid is an aqueous solution of hydrogen chloride, which is a hygroscopic, colorless gas with a strong, pungent and irritating odour. There are no known chronic or acute systemic effects of hydrochloric acid. However, the strong dehydrating properties of hydrochloric acid can result in serious injuries to man. Hydrochloric acid causes corrosion of metals and alloys.

Hydrogen Sulfide: Hydrogen sulfide is evolved due to biological decay of proteins in stagnant water, kraft paper mills, industrial waste disposal ponds, sewage treatment plants, refineries and coke ovens. Even at low concentrations, hydrogen sulfide 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.

Scorching of young roots is observed when plants are exposed to hydrogen sulfide. Generally, young plant tissues are easily damaged by hydrogen sulfide. It discolourates and tarnishes paints, copper, zinc and silver.

Iron: Generally, iron is emitted from iron and steel plants, fly-ash from combustion of coal and fuel oil and municipal waste incinerators. Iron and its compounds present as pollutants in the atmosphere can cause deleterious effects on humans. Iron pigmentation of lungs is a well known problem. Iron oxide acts as a vehicle for transporting carcinogens and sulfur dioxide deep into lungs. Iron, on paints and other materials like textiles, causes stains in the form of iron oxide.

Kaoline: Kaoline is known as china clay. Kaoline is used mostly in textile industry. Kaoline dust on prolonged inhalation can produce pneumoconiosis. Exposure to kaoline also may cause silicosis.

Lead: Lead is available in atmosphere as Pb , PbO , PbO_2 , PbS and $PbSO_4$. Lead is emitted into air through automobile emissions using leaded gasoline, lead smelters, combustion of coal and fuel oil and lead arsenate pesticides. Lead is a known poison. Alkyl lead compounds, used primarily as automo-

tive fuel additives are readily absorbed by skin and mucous membranes and are preferentially distributed to liquid phases of the body, including the brain. About 50 percent of lead inhaled is retained and when the quantity of lead reaches a high enough level, it interferes with development of red blood cells and the production of hemoglobin. The symptoms of lead poisoning encountered today have been known to exist since times immemorial. The ancient Egyptians knew about the homicidal property of lead. The problem of lead poisoning among miners and occupational workers in pottery and painting industries attracted attention of all concerned. Lead poisoning from food contamination, cosmetics, medicines and ceramic glazes is encountered even today despite the legislations. Lead salts having high solubility are more hazardous than some other in their industrial use. However, chronic industrial lead poisoning may occur from dusts of lead sulphate, carbonate and metallic lead as well. The symptoms of acute and immediate lead poisoning as a consequence of ingestion of large amounts of lead are well-known. In children lead levels of $< 1 \mu\text{g}/\text{m}^3$ can inhibit enzymatic systems.

Acute lead poisoning is characterized by vomiting, colic, bloody diarrhoea, insomnia and other central nervous system effects, irritability, convulsions and death. Symptoms of chronic lead poisoning are headache, weakness, lassitude, constipation and a blue line along the gums. The systems of the body which are most affected by lead poisoning are nervous, renal, gastrointestinal and haematopoietic systems. Lead encephalopathy is encountered more in children than in adults. Thus children living in the vicinity of zinc lead smelters show acute encephalopathy characterized by vomiting, drowsiness, apathy, ataxia, stupor and other neurological problems. One of the effects of subclinical poisoning by lead is the development of anemia due to interference of lead in hemoglobin biosynthesis and shortening the life span of circulating erythrocytes. Cattle, grazing near the zinc and lead refineries may become lame. About 97 percent of all air borne lead is by automobiles burning leaded gasoline. Animals when inhale lead, frothing at the mouth, delirium and collapse are observed. Lead accumulates in the skeleton, kidneys, liver, pancreas and lungs of animals including man.

Manganese: Manganese is emitted from blast furnaces producing ferromanganese compounds, organic manganese fuel additives, use of welding rods and incineration of manganese containing products. Manganese or its compounds when inhaled may produce chronic manganese poisoning or manganic pneumonia, which has a mortality rate four times that for normal pneumonia. It may also act as a catalyst in the oxidation of other air pollutants, producing even more undesirable pollutants. Manganese on most materials and textiles acts as a soilant, especially near ferromanganese plants.

Mercury: Mining and refining of mercury causes emission of mercury into air. Use of mercury in laboratories and pesticides containing mercury also emit mercury. Mercury is a liquid metal at normal temperature that emits vapours into the atmosphere causing pollution. Inhalation of metallic mercury vapours and organomercurials by mice, cats and dogs has resulted in weight loss, ataxia, tremor, palsy, anorexia and renal damage. Inhalation of mercury vapour is more dangerous than its entry through digestion tract. The workers exposed to mercury dusts and inorganic salts showed profuse diarrhoea, kidney lesions, disorders of cardiac function and neurological function. It has been found that organomercurials cause skin lesions, erythema, edema and itching when they come in contact with skin. Inorganic mercury salts have also been reported to cause allergic contact, dermatitis, irritation and formation of blisters after topical application. Elemental mercury and most of its derivatives are protoplasmic poisons that can be lethal to animals. Russian experiments on animals indicate that continuous exposure to mercury vapour above $0.3 \mu\text{g}/\text{m}^3$ of air may present a health hazard. Some organic mercury compounds are even more toxic than elemental mercury. Farm animals have been poisoned as a result of eating plants treated with mercury-containing pesticides. The mining and refining of mercury and the use of mercury in various industries appear to be the significant sources of air pollution. One incident of mercury poisoning was reported in cows and other domestic animals after fire in a nearby mercury mine.

Animals exhibit toxicity symptoms similar to man, but are more susceptible to lower concentrations of mercury. Animals are poisoned by eating forage treated with mercury containing lead. Mercury damage to plants includes chlorosis, abscission of older leaves and growth reduction. Injury is usually restricted to green house crops where mercury vapours from bichloride of mercury mixed with soil as a fungicide and mercury in antimildew paints are produced in a more confined atmosphere. Floral parts are more susceptible.

Mica dust: Mica is industrially used for insulation in thermal and electrical goods. Miners working in mica mines are prone to fibrosis of lungs.

Nickel: Metallurgical units using nickel, engines burning fuels containing nickel additives, burning coal and oil, nickel plating facilities and incineration of nickel products will evolve nickel into the atmosphere. Nickel and its compounds taking the form of dusts and vapour can be serious when inhaled or absorbed through skin. The parenteral administration of metallic nickel powder or inhalation of metallic nickel powder has been reported to produce sarcoma in bone nervous tissue, connective tissue and nasal septa. Nickel carbonyl has been reported to produce pulmonary and nasal carcinomas.

Nickel salts are reported to cause dermatitis, "Nickel itch", to occupationally exposed individuals. The symptoms of nickel induced dermatitis includes erythematous, erythematopapular or follicular primary eruption on the part of skin which comes in contact with nickel. This is followed by the development of crust of eczema and in chronic stages plaques may appear. The nickel salt may also induce hypersensitivity reactions at the site of contact with skin.

Nickel carbonyl is one of the volatile vapor form of nickel and is most hazardous compound in nickel industries. The chronic exposure to nickel carbonyl produces nasal and pulmonary cancer. The acute poisoning with nickel carbonyl initially causes headache, dizziness, nausea and vomiting followed by tightness in chest, shortness in breath and caynosis to death.

Pesticides: Pesticides have been defined as substances or mixture of substances intended to prevent, destroy, repel or mitigate insects, rodents, fungi or any form of terrestrial or aquatic plant or animal life. Since pesticides beyond the area of their deliberate applications behave as environmental pollutants, a great degree of caution and control is required not only at the stage of production but also at the hands of their users. Besides posing grave health hazards to people exposed to their handling, chemical pesticides also cause immunological suppression of the hosts living in the environment and can cause various forms of toxicity even at low doses. The toxicity of pesticides may be either direct toxicity or indirect toxicity.

Phosphorus: Phosphorus is emanated into the atmosphere by plants producing phosphatic fertilizers, phosphorus acid and phosphorus pentoxide and by vehicles and air planes using phosphorus as corrosion inhibitors in fuel. Depending upon their chemistry and compounds, phosphorus and their compounds have varying effects. Tests have been made on the effects of yellow (white) phosphorus, but acute or chronic effects have been studied only with respect to organophosphorus pesticides. Phosphorus causes skin irritation to systemic poisoning. High concentrations of phosphorus affect nervous system. Most of the materials will be affected by corrosion if it is in the form of phosphoric acid.

Radio Active Substances: Radio active substances are released into the atmosphere by direct disintegration of radio active elements in the earth, gases or suspended dusts from natural or artificial sources and indirect contamination when radio nuclides are ingested from food chain as a result of contaminated ground, water, plants or animals. Somatic effects such as leukemia and other types of cancer, cataracts and reduction in life expectancy are results of direct contamination of radio active substances. Genetic effects include mutations in human genetics that show up only in future generations. Radio-active substances can cause injury to man by exposure

from a distant source, direct contact with the skin or entrance into the body when radio nuclides are ingested from food contaminated by these radio active substances. Although at present there have been no significant exposures reported from nuclear industry, projected nuclear expansion may create more problems in future. The effects of radiation on animals is primarily due to damage to the blood-forming centres in the bone marrow and lymph glands. Leukemia, cancer and genetic mutation effects may result from long term exposure to radiation levels too low to cause death. Animals consume plants that contain radionuclides and tend to concentrate them in their flesh and milk. Man is subjected to radio active contamination when he consumes the flesh and milk of these animals. In general radiation damage in plants is difficult to detect except at dose rates many times higher than those normally encountered in ambient air. Radiation cannot be detected without special instrumentation and the biological effects are usually not evident until some time after exposure.

Selenium: Poisoning of humans from ingestion of foods containing toxic amounts of selenium is a problem of great concern. Selenium may enter these foods from air pollution resulting from fuel combustion, refinery waste gases and fumes and incineration of paper products containing selenium. Selenium poisoning causes irritation of eye, nose, throat, respiratory tract and gastro intestinal tract. Chronic intoxication from industrial exposure has possible long term effects on kidney, liver and lungs. Herbivorous animals will be killed from eating plants or foods containing toxic amounts of selenium. Ingestion of plants containing organic selenium compounds has caused chronic poisoning, known as blind staggers. Another type of chronic poisoning known as alkali disease, has resulted from eating plants or grains containing protein bound selenium. Selenium in small amounts is required for growth of some plants. These plants may accumulate high concentrations of selenium and thereby become poisonous to animals that eat them. Often plants like corn, wheat, barley and rye, that do not require selenium can be damaged by the accumulation of small amounts of selenium.

Silica: The exposure to silica causes silicosis, a lung disease and is frequently found among workers involved in mining, cutting of sand-stone and granite, cement industry etc. The main symptoms of the disease are reduced vital capacity of lungs, shortness of breath, cough and exhaustion.

Talc: Talc is commonly used in preparation of the cosmetics like face powders and other medicated powders. Workers exposed to talc are reported to suffer from pneumoconiosis. The main symptoms of talc induced pneumoco niosis are cough, short breath, exhaustion and dyspnea. 'Osho' Rajneesh might have discouraged ladies from using face powders because of this reason only!

Vanadium: Vanadium is emanated into the atmosphere by vanadium refining industries, alloy industries, power plants and utilities using vanadium-rich residual oils. Vanadium is moderately toxic to humans, especially in its pentavalent form. Physiological effects of varying severity are on the gastro - intestinal and respiratory tracts and inhibition of cholesterol synthesis. Chronic exposure to vanadium leads to heart disease and cancer.

Zinc: Most of the zinc is evolved from zinc refineries, manufacturing of brass and zinc galvanizing processes. Except in high concentrations, zinc and its compounds are generally considered to be non toxic to humans. However, inhalation of zinc oxide fumes produces metal fume which is a non fatal but self-limiting illness. Accidental poisoning can result from ingestion of acidic foods prepared in zinc galvanized containers. Since zinc is commonly associated with other metals in the air, it is difficult to assess its value as a separate air pollutant. Inhaling zinc in air causes emaciation and swelling of limb joints of cattle and horses requiring slaughter.

3.4 EFFECTS OF PRIMARY AIR POLLUTANTS

The effects of the main air pollutants namely CO, SO_x, NO_x, oxidants, HCs and particulates on man, material and vegetation are described in detail as follows :

Carbon Monoxide: The sources of CO are both natural and anthropogenic. Oxidation of methane gas from decaying vegetation, human metabolism and gasoline powered internal combustion engines lead to CO emission.

Carbonmonoxide, at present ambient levels, has little effects on property, vegetation or materials. 'CO', when inhaled, passes through the lungs and diffuses directly into the blood stream where it combines with the red blood pigment called hemoglobin forming carbaoxl hemoglobin, COHb. The affinity of carbon monoxide for hemoglobin is 210 times greater than that of oxygen and as a result the amount of hemoglobin available for carrying oxygen for body tissue is considerably reduced. The body tissues are thus deprived of their oxygen supply. Heart patients may lack sufficient cardiac reserve to compensate. Patients with angina pectoris require less exertion to induce chest pain. Carbonmonoxide concentrations are especially high in congested urban areas where traffic is heavy and slow moving. A person trapped in traffic at such a location for an hour would show a COHb blood level close to 2-3 percent. This exposure would affect the central nervous system, impairing a person's time interval discrimination, brightness discrimination and other psycho-motor functions. The absorption of CO by the human system increases with its concentration, exposure time and the activity being performed.

The chronic effects of CO are not fully known but they may induce heart and respiratory disorders. While CO itself has not been found to be carcinogenic, there is concern that it may increase the carcinogenic effects of other air pollutants by inhibiting the mucociliary clearance mechanism in the lungs. 1-2% of COHb levels have an evident effect on the behavioral performance of the humans. If COHb levels exceed 5%, cardiac and pulmonary functional changes are observed. 10% and more COHb levels may cause headaches, fatigue, drowsiness, coma, respiratory failure and death.

Oxides of Sulfur: The burning of fossil fuels contributes more than 80 percent of anthropogenic SO₂ missions. Fuel combustions in stationary sources and industrial processes are the principal contributors of SO_x. Combination of these oxides with water (H₂SO₃ and H₂SO₄) and the salt derived from these acids, when combined with other elements are well-known atmospheric pollutants. Intense irritation and reduction of visibility have also been recorded from epidemiological studies pertaining to sulfur oxides.

Plants are more sensitive to SO₂ during periods of intense light, high relative humidity, adequate moisture and moderate temperature. Excess exposure to SO₂ accelerates corrosion rate of many metals such as iron, steel, zinc, copper and nickel. Sulfuric acid mists can cause damage to cotton, linen, rayon and nylon. Leather also weakens and disintegrates in the presence of excess amounts of products of sulphur. Paper absorbs SO₂ and becomes brittle.

Sulfuric acid (H₂SO₄), Sulfur dioxide (SO₂) and sulfate salts tend to irritate the mucous membrane of the respiratory tract and expedites the development of chronic respiratory diseases, particularly bronchitis and pulmonary emphysema.

Nitrogen Oxides, NOx: Some oxides of nitrogen are produced naturally. Small concentrations of NOx produced in the upper atmosphere by solar radiation reach the lower atmosphere thorough downward diffusion. Small amounts of NOx are produced by lightning and forest fires. Bacterial decomposition of organic matter also releases NOx into the atmosphere. The implementation of more stringent controls for carbon monoxide and hydrocarbons resulted in the increased emissions of NOx. The greatest significance of NO is related to its tendency to undergo oxidation to NO₂.

Affinity of hemoglobin for absorbing NO₂ is 3,00,000 times that for O₂. This affinity drastically reduces the O₂ carrying capacity of the blood. NO is a relatively inert gas and only moderately toxic. NO₂ irritates the alveoli of the lungs. The response of the human respiratory system to long-term exposure to nitrogen dioxide depends upon the concentration of NO₂. The olfactory

threshold value of NO_2 is about $225 \mu\text{g}/\text{m}^3$ (0.12 ppm). Exposure to $9.4 \text{ mg}/\text{m}^3$ for 10 minutes has produced transient increase in air way resistance and occupational exposure to $162 \text{ mg}/\text{m}^3$ for 30 minutes has produced pulmonary oedema. NO_2 is the basic pulmonary irritant. Long term exposure to NO_2 at concentrations between 100 and $200 \mu\text{g}/\text{m}^3$ and mean suspended nitrate level at $3.8 \mu\text{g}/\text{m}^3$ results in acute respiratory disease. It has been stated that 95 percent of nitrogen oxides inhaled remain in the body where they can also produce mutations in cells. Nitrogen oxides cause lung tissues to become leathery and brittle and may cause lung cancer.

There is no evidence that NO is damaging to plants outside the laboratory while NO_2 and primary pollutants can cause some injury to vegetation. PAN and O_3 , the secondary pollutants produced during photochemical reactions involving NO are far more likely to be damaging to plants. Textile dyes may be faded due to exposure to high levels of NO_2 and yellowing of white fabric and oxidation of metals may also take place.

Oxidants: Ozone contributes about 90% of the total oxidants. Concentrations of ozone exceeding $200 \mu\text{g}/\text{m}^3$ will cause eye irritation. The threshold for both nasal and throat irritation is set higher at 0.3 ppm over an 8-hour period. Some states permit 0.15 ppm for 1-hour periods. When the level of ozone in the ambient air is more than 0.7 ppm over a 20 to 90 minutes period, coughing, chocking and severe fatigue will result. Exposure to oxidants causes severe chest pains, headache, damage to red blood cells, loss of coordination and difficulty in articulation. Other important oxidants are nascent oxygen, ' O' ; excited molecular oxygen, O_2 ; peroxy acetyl nitrate, PAN; peroxy propynol nitrate, PPN; peroxy butyl nitrate, PBN; nitrogen dioxide, NO_2 and hydrogen peroxide, H_2O_2 . The desirable ambient air levels of photochemical oxidants are $240 \mu\text{g}/\text{m}^3$ for 1 hour duration.

Hydrocarbons: Hydrocarbons are evolved into the atmosphere from crank-case of automobile, various refrigerants, decay of several organic matters and from trees. Methane is the major naturally occurring hydrocarbon emitted into the atmosphere. Human activities contribute nearly 20% of the hydrocarbons emitted to the atmosphere every year. Animals contribute about 80-85 million tonnes of methane in the atmosphere every year. The hydrocarbons on reacting with nitric oxide and sunlight form photochemical smog which causes irritation to eye and decreases visibility. Formaldehyde and peroxy acetyl nitrate (even at 1 ppm) are eye irritants. PAN also causes plant damage. The oxidation reactions accompanied by formation of aerosols or haze also result in eye irritation and plant damage.

Hydrocarbons at high concentrations have carcinogenic effects on lungs.

They cause swelling when they enter the lungs. Aromatic hydrocarbons are more dangerous than acyclic and alicyclic hydrocarbons. The inhalation of their vapours cause acute irritation to the mucous membrane. Excess of hydrocarbon increases mucous secretion as a result of which respiratory tracks are blocked and man coughs regularly. Because of continuous cough much pressure is caused on the trachea of lungs due to which the lining membrane of alveoli bursts and very small area is left for exchange of oxygen and carbon dioxide. Benzopyrene, which is present as trace amounts in tobacco, charcoal, boiler stacks and gasoline exhausts etc. is a dangerous cancer inducing hydrocarbon pollutant. Methane also is a severe gas pollutant and occurs in air by volume of 0.0002 percent. Its higher levels in absence of oxygen, create narcotic effects on human beings. A group of hydrocarbons, especially the carcinogenic hydrocarbons, cause cancer in man and animal affecting DNA and cell growth.

TABLE 3.1 : HAZARDS OF CARCINOGENIC HYDROCARBONS:

S.No.	Compound	Health Hazards
1.	Benzine	Bladder cancer
2.	Naphthylamine	Cancer in urinary bladder
3.	Bichloromethyl ether	Lung caner
4.	Ethylene dichloride	Stomach, spleen and lung cancer
5.	Vinyl chloride	Liver cancer
6.	Ethyleneamine	Cancer
7.	Propiolactone	Potential carcinogen
8.	Naphthylamine	Bladder cancer
9.	Nitrophenol	Bladder cancer
10.	3-3' dichlorobenzidine	Cancer

Hydrocarbons and photochemical oxidants are injurious to plants also. Ethylene, even at 1 ppm concentration, shows adverse effects on vegetation. Acetylene and propylene at 50-500 ppm show extreme toxicity towards plants damaging growth of vegetation. Ethylene hydrocarbons inhibit plant growth, damage leaf tissues and cause death of flowering plants. Hydrocarbon pollutants damage long chains of carbon atoms in materials and reduce the strength of polymers.

Particulates: The effect of particulates on human beings depends mainly on their size and characteristics. Size is one of the most important physical parameters of particulates. Particle sizes are measured in micrometers. Particle sizes larger than 50 μm can be seen with unaided eye. Particulates

smaller than 1 μm do not tend to settle out rapidly.

Settling is the major natural self-cleansing process for the removal of particulates from atmosphere. Particulates can generally be classified as suspended or settleable. Suspended particulates vary in size from less than 1 μm to nearly 20 μm . Settleable particles or dust, are larger and heavier and settle out close to their sources. They are generally greater than 10 μm in size. Particulates greater in size (over 10 μ) are easily removed by hairs at the front of nose. Generally, coarse dusts, fly ash etc. are greater in size and seldom enter the human system. Particulates with size range in between 2 to 10 μm , like fumes, dusts and smoke particles, are removed as movement of cilia sweeps mucous upward, carrying particles from wind pipe to mouth where they are swallowed. If the size of the particulates is less than 2 μm (like aerosols and fumes) they will enter the lungs easily. Lymphocytes and phagocytes in the lung attack some submicron particles, but all of them cannot be removed effectively.

Similarly, there is a great variation in the chemical composition of the particulates found in the atmosphere. Atmospheric particulates contain both organic components like phenols, organic acids and alcohols and inorganic components like dusts. The biological particles include protozoa, bacteria, viruses, fungi, spores, pollens and algae. Their life time is very small due to lack of nutrients and presence of UV rays from sun. However certain bacteria and fungi can survive for longer periods.

Effects of Particulates: The success or failure of respiratory defense system depends, in part upon the size of the particulates inhaled and the depth of their penetration into the respiratory tract. About 40 percent of the particles 1-2 μm in size are retained in bronchioles and alveoli. Particles ranging in size from 0.25 to 1 μm show a decrease in retention. The various ill effects of particulate matter on human beings are tabulated in table 3.2

Effects of particulates on Plants, Animals and Materials : Little information is available on the detrimental effects of particulate matter on vegetation. Dry cement kiln dust appears to cause little damage if deposited on a leaf surface, yet in the presence of moisture, such dust imparts damage and consequential growth inhibition to plant tissues. The dust coating on leaves reduces photosynthesis and the increased plugging of stomata reduces plant growth. Particulate matter can damage materials by soiling clothing and textiles, corroding metals, eroding building surfaces, and discolouring and destroying paint surfaces. The effects of particulates containing metals like fluorides, arsenic, lead etc. are explained later.

TABLE 3.2 : EFFECTS OF PARTICULATES ON HUMAN HEALTH

Concen- tration $\mu\text{g}/\text{m}^3$	Other factors	Time	Effect
750	715 $\mu\text{g}/\text{m}^3 \text{SO}_2$	24 hr average	Considerable increase in illness
300	630 $\mu\text{g}/\text{m}^3 \text{SO}_2$	24 hr	Acute worsening of chronic bronchitis
200	250 $\mu\text{g}/\text{m}^3 \text{SO}_2$	24 hr average	Increased absence of industrial workers
100-130	120 $\mu\text{g}/\text{m}^3 \text{SO}_2$	Annual mean	Children likely to experience increased incidence of respiratory disease.
100	sulfation rate above 30 $\text{mg}/\text{cm}^2/\text{mo}$	Annual geome tric mean	Increased death rate for those over 50 likely
80-100	sulfation rate above 30 $\text{mg}/\text{cm}^2/\text{mo}$	2 hr geome tric mean	Increased death rate for those 50 to 69 years.

TABLE 3.3 : EFFECTS OF ATMOSPHERIC SO_2 ON HUMANS

Concentration (ppm)	Effects
0.2	Lowest concentration causing a human response
0.3	Threshold for taste recognition
0.5	Threshold for odour recognition
1.6	Threshold for inducing reversible broncho- constriction in healthy individuals
8-12	Immediate throat and eye irritation
20	Immediate coughing

TABLE 3.4 EFFECTS OF ATMOSPHERIC NO₂ ON HUMANS

NO ₂ conc. (ppm)	Exposure	Effect
0.06-0.1	2-3 years	Increase in acute respiratory disease
Upto 0.1	6 months	Increase in acute bronchitis in school children
0.12	24hours	human olfactory threshold
5	10 min	Increase in airway resistance
90	30 min	Pulmonary oedema

TABLE 3.5 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	Behavioral changes, peripheral neuropathy, mental depression, ataxia, narcosis, parkinsonism, stupor, vomiting and drowsiness
Immune system	Suppression, modulation
Musculoskeletal system	Osteoporosis, dystrophy
Hemopolisis	Bone marrow depression, leukemia, aplastic anemia, methemoglobinemia,
Liver	MFO induction, neoplasia, cirrhosis, necrosis
Kidney	Uremia, lithiasis, aminoaciduria.

3.5 EFFECTS OF AIR POLLUTION ON ATMOSPHERE

The effects of air pollutants on atmosphere at macroscale are covered in detail in the topic on "Global effects of air pollution". The localized effects of air pollutants on atmosphere are:

1. Visibility reduction
2. Fog formation and precipitation
3. Solar radiation reduction
4. Temperature and wind distribution alteration

Perhaps the most noticeable effect of air pollution on the properties of atmosphere is the reduction in visibility which may lead to safety hazards. The prevailing visibility is defined as the greatest distance at which it is just possible to see and identify a prominent dark object in day time and an unfocussed, moderately intense light source at night. Visibility is reduced by absorption and scattering of light. Visibility is reduced when there is significant scattering. This decreases the contrast between the object and the background sky, thereby reducing visibility. Large particles scatter light by three processes, reflection, diffraction and refraction. Particles of very small size scatter light equally in forward and backward directions. This effect in fact, is responsible for the reddish hue of sunsets, since the shorter wavelength blue component of sunlight is scattered out of the line of sight leaving the red components to reach the observer.

Scattering and absorption of both solar and infrared radiation, occur within the polluted layer. During the day the net effect of pollutants on the temperature of the urban dome depends on the relative magnitude of heating caused by absorption of solar radiation and cooling due to emission of infrared radiation. In addition to reduction in visibility air pollution effects urban climate with respect to increased fog formation and reduced solar radiation.

Economic Significance of Visibility Impairment

Reduction in visibility due to air pollution creates an economic burden because of increased requirements for electricity in homes, in business establishments and in the streets when sunlight cannot penetrate the haze. Air port operations are slowed down because of the delays in air traffic, which add to operational costs, inconvenience to passengers and pose additional hazards to safety that may result in death, personal injury or property damage.

Highway traffic is impaired when a motorist's vision is limited. Traffic arteries may be closed to a stand still and accidents causing bodily injury,

death and increased property damage may occur. If the community is near a harbour, ship traffic may suffer in the same way as air and highway traffic. Serious indirect costs may arise if air ports have to be relocated or enlarged to handle slower traffic. Additional highway requirements and increased insurance rates and other indirect economic costs may result from reduction in visibility if it becomes exceedingly severe or frequently occurring.

Scattering of sunlight by particulates suspended in the atmosphere is the main cause of reduction in atmospheric visibility. This condition is comparable to a dirty automobile wind-shield. At night with no on-coming vehicle, it is not too bothersome, however, when strong light from the sun or vehicular light strikes the dirty wind-shield the driver's visibility is impaired. A concentration of $150 \mu\text{g}$ of 1 micron diameter particles per m^3 of air borne particulates affects visibility which is dependent primarily on the number of particulates and their size. Submicron sized particles or smaller scatter more light than the large particles, since scattering area per gram of material is greater for smaller particles. Since light scattering is the main cause of reduction in visibility, this aspect of air pollution is manifested primarily during bright days when there is strong light to be scattered by the suspended particulates.

Pollutants Contributing to Impairment of Visibility

Major contributors to impairment of atmospheric visibility are hygroscopic particulates. Some hygroscopic particles, such as soluble organics and sulfur trioxide from industry, are produced by man; others come from natural sources, such as sea salt spray. Opaque agglomerations such as carbon, fur and metal particles in the atmosphere also contribute to reduced visibility. Crystalline compounds such as iron, aluminum, silicon and calcium which may exist as sulfates, nitrates, chlorides and fluorides also contribute to light scattering.

3.6 AIR POLLUTION EFFECTS ON VEGETATION

The most obvious damage caused by air pollutants to vegetation occurs in leaf structure. The surface of 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 epidermis will protect the inner tissues from excessive moisture loss and prevent the admission of CO_2 and oxygen to these internal tissues. The leaf surface has a large number of openings called the stomata. Guard cells will protect the stomata and also control the opening and closing of stomata. A typical plant cell has three components—the cell wall, the protoplasm and the nonliving inclusions within the cell. Because the cell wall is extremely thin during the formative stage, new growth is very much susceptible to air pollution damage. The

protoplasm is composed of several chemical compounds, water and the central nucleus which contains the hereditary and reproductive mechanism. The leaf also contains the chloroplasts, which are the key structures in the photosynthesis process of food manufacture in the green plant. These plant inclusions are the store house for food and waste material.

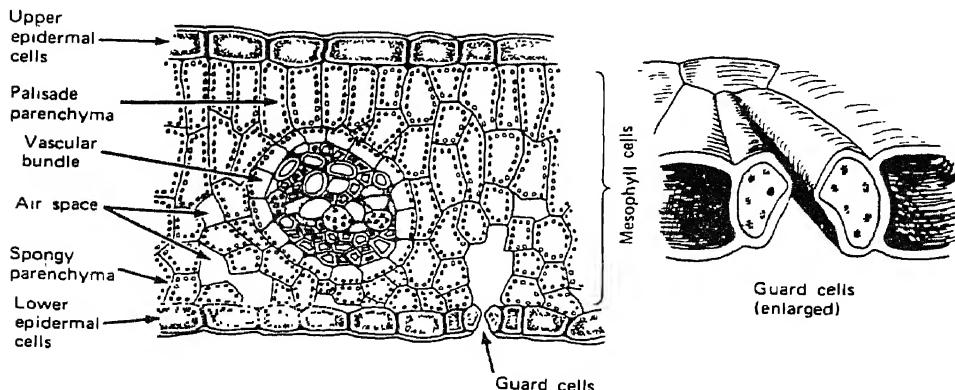


Fig. 3.2 Cross Section of Leaf

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 epidermal cells that protect the inner tissues have oval openings called stomata bounded by guard cells. Through the stomata, gases and airborne pollutants enter the leaf. The guard cells act to close or open the stomata by changes in water content. During the day time plants take in carbon dioxide and water, which combine to form sugar and starch. The excess oxygen generated in this process escapes from the plant into the atmosphere. At night due to lack of sunlight the photosynthetic action is inactive. The plant cells then take in oxygen and release carbon dioxide to the atmosphere. The exchange of moisture between the leaf and the atmosphere has a cooling effect on the leaf. Some of the important diseases caused by phytotoxins (plant damaging substances) are:

Bifacial Necrosis: The result of all tissues being killed on both upper and lower surfaces of the leaf.

Pigmented Lesions: May result with dark brown, black, purple or red spots appearing on the leaf surface.

Epinasty: The rapid growth of the upper side of the leaves, causing the leaf blade to curl under.

TABLE 3.6 EFFECTS OF AIR POLLUTANTS ON VEGETATION

POLLUTANTS	SOURCES	EFFECTS
Aldehydes	Photochemical reactions	The upper portions of Alfalfa etc. will be affected to Necrosis if 250 ppm of aldehydes are present for 2 hrs duration.
Ozone (O_3)	Photochemical reaction of hydro carbon and nitrogen oxides from fuel combustion, refuse burning and evaporation from petroleum products and organic solvents.	All ages of tobacco leaves, beans, grapes, tomato, pine, pumpkins and potato are affected. Fleck, stipple, bleaching, bleached spotting, pigmentation, growth suppression, and early abscission are the effects. Tips of conifer needles become brown and necrotic if 0.03 ppm of O_3 is present for 4 hrs duration.
Peroxy Acetyl Nitrate (PAN)	The sources of PAN are the same as Ozone	Young spongy cells of plants are affected if 0.01 ppm of PAN is present in the ambient air for more than 6 hrs. Glazing, silvering or bronzing on lower surface of leaves takes place.
Nitrogen dioxide (NO_2)	High-temp, combustion of coal, oil, gas and gasoline in power plants and internal combustion engines.	Middle aged mesophyll cells of citrus, cotton and bean plants, lettuce, tomatoes, tobacco seedlings, pine and potato are affected if 25 ppm is present for 1 hr. or 1.0 ppm for 24-48 hrs. or 0.25 ppm for 8 months duration. Irregular, white or brown collapsed lesion on intercostal tissue and near leaf margin. Suppressed growth is observed in many plants.
Ammonia & Sulfur dioxide	Thermal power plants, oil and petroleum refineries.	0.3 ppm of SO_2 present in air for 8 hrs. affects middle aged mesophyll cells and young spongy cells of spinach and other leafy vegetables, pumpkins, apples and ragweed. Bleached spots, bleached areas between veins, bleached margin, chlorosis, growth suppression, early abscission, reduction in yield and tissue collapse occur.
Hydrogen fluoride (HF) and Silicon tetrafluoride	Phosphate rock processing, aluminium industry, and ceramic works and fibre-glass manufacturing.	Epidermis and mesophyll of grapes, large seed fruits, pines & fluorosis in animals occur if 0.001 ppm of HF is present for 5 weeks

Chlorine (Cl_2)	Leaks in chlorine storage tanks, hydrochloric acid mists.	If 0.10 ppm is present for atleast 2 hrs. the epidermis and mesophyll of plants will be affected by bleaching between veins, tip and margin burn and leaf abscission.
Ethylene (CH_2)	Incomplete combustion of coal etc. and automobile and track exhaust	Epinasty, chlorosis, sepal withering, leaf abnormalities, flower dropping, and failure of flower to open properly, necrosis and chlorosis of plants will happen. Flowers of all ages will be affected. Indirect attack on plant hormones and growth regulators resisting in morphogenic and physiological changes in tissues.
Mercury, Hg	Processing of mercury containing ores, burning of coal and oil	Greenhouse crops and floral parts of all vegetation are affected ; abscission and growth reduction occur in most of the plants
Selenium, Se	Combustion of industrial and residential fuels, incineration of wastes including paper	Growth reduction occurs mostly in corn, wheat, barley and rice.
Pesticides & Herbicides	Agricultural operations	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.
Particulates	Cement industries, thermal power plants, blasting, crushing and processing industries	Affects quality of plants, reduces vigor & hardness and interferes with photosynthesis due to plugging of leaf stomata and blocking of light.
Hydrogen chloride &	Alkali and glass manufacturing units.	Browning of tips of grasses at 50 ppm, interveinal bronzing of tomato leaves at 5 ppm and necrosis in 3 days in presence of humidity ; leaf burning of broad leaf plants, bleaching and necrosis happens.

Acute injury: Results from short term exposure to high concentrations of pollutants. A severe visible damage to leaf tissues often associated with plasmolysis and tissue collapse. The destruction of leaf tissues or severe drying or burning is referred to as necrosis.

Chronic Injury: Resulting from long-term exposure to low levels of pollutants and often shows up as a colour change or chlorosis because of destruction of chlorophyll with no apparent cell damage.

Chlorosis: The loss of the green plant pigment chlorophyll is called chlorosis. The loss of chlorophyll results in yellow pattern. Chlorosis indicates a deficiency in some nutrient required by the plant.

Abscission: Leaf abscission is the dropping of leaves. This will decrease the life of the plant.

Necrosis: It is the killing or collapse of the plant tissue. Tissue injured by phytotoxins often has a characteristic colour. For example, bleaching is associated with SO_2 , yellowing with ammonia, browning with fluoride and silvering or bronzing of under surfaces of some leaves with PAN.

3.7 AIR POLLUTION EFFECTS ON MATERIALS

Air pollution damage to 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. The processes responsible for the effects of air pollution on materials are:

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

2. Chemical Action: Some air pollutants react directly and irreversibly with materials to cause deterioration. SO_2 bleaches marble, hydrogen sulfide tarnishes silver and acidic mists cause etching of metallic surfaces .

3. Absorption: Certain materials absorb some pollutants and get damaged, when the pollutants undergo chemical changes. SO_2 absorbed by leather will be converted to sulfuric acid, which deteriorates the leather.

4. Corrosion: Action of air pollutants facilitated by 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.

Effects of air pollutants on materials depend upon various factors such as:

1. Temperature: 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. Precipitation: 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 the alternate wetting and drying, the materials may be damaged .

3. Sunlight: Moisture present on materials becomes the host of several organisms like algae and fungi in the presence of sunlight. Sunlight may directly damage materials as in case of fading of dyes and cracking of rubber. 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. Humidity: The presence of moisture in the atmosphere greatly helps the process of corrosion. Without moisture in the atmosphere, there would be little atmospheric corrosion, if any, even in the most severely polluted environments. In case of SO₂ and various particulates, rate of corrosion of metals will increase as relative humidity in the air increases.

5. Air Movement: Wind direction plays a very important role as it drives the air pollutants from stacks of factories. Damage to crops in the vicinity of 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 wind blowing 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 materials.

7. Concentration and Duration: Material damage is directly related to the concentration of the pollutants and exposure time. For example, 260µg/m³ of particulates for 24 hours may affect a material in a manner similar to the effect of 75µg/m³ for one year. Usually the concentration of pollutant changes from time to time depending on meteorological conditions.

The effects of various air pollutants on materials are tabulated in Table 3.7

TABLE : 3.7 EFFECTS OF AIR POLLUTANTS ON MATERIALS

S. No.	Material	Air Pollutants	Other Factors	Effects
1.	Metals and alloys	SO ₂ , acids, NO ₂ , gases	Moisture, temperature	Tarnishing of surfaces; corrosion of metals
	Silver	Cl ₂ , chromium,HCl	Particulates	Silver is tarnished by chemical attack. Particulates enhance the corrosive action of SO ₂ by more than 50%
2.	Ferrous metals zinc, aluminium, copper and glass	SO ₂ , acids, CO ₂ , NO _x . H ₂ S, P	Moisture	Etching of surfaces by acidic mists ; electrochemical corrosion due to the destruction of protective film of oxygen on the metal surfaces ; etching of glass by hydrogen sulfide ; Loss of metal and loss of strength due to reaction of acids formed by SO _x , CO ₂ , phosphorous etc. with moisture & stress corrosion of non ferrous metals by NO _x
	Building materials	SO ₂ acids, gases	Moisture, wind, sea sprays and oily particles	Soiling, discoloration and erosion due to physical actions like abrasion, alternate wetting and drying.
	Bricks, stones	CO ₂		Deterioration by carbonic acid formed due to combination of CO ₂ and moisture.
	Limestone, sand stone, marble, roofing slate, mortar, statues.	SO _x , NO _x	Moisture	Indirect chemical action wherein SO _x and NO _x form loose surfaces that flake off.

	Wood, fibreglass, rubber, P.V.C., carbon steels.	NH ₃	Moisture, temperature	Softening ; stress corrosion of carbon steel due to NH ₃
3.	Textiles	SO ₂ acids, gases, O ₃ , NO ₂ , NH ₃ , chromium, iron and manganese	Moisture, sunlight	Soiling and reduction in wear life due to abrasive action of particulates and extra washing and dry cleaning required to remove soiliants. Loss of tensile strength in cotton curtains and nylon drapes due to SO ₂ and acidic mists. NOx, SO ₂ and O ₃ oxidise dyes turning white fabrics to yellow. NH ₃ , Cl ₂ , chromium, iron and manganese may cause staining due to formation of their oxides.
4.	Paints and varnishes	SO ₃ , H ₂ S and particulates, iron, NH ₃ , Cl ₂ , chromium microorganisms	Moisture, fungus.	Microbial attack on organic constituents of paints ; Discoloration : paints containing lead pigments darken due to formation of lead sulfide by H ₂ S; Deposition of particulates and abrasion due to wind (zinc and titanium based pigments are resistant)
5.	Paper	SO ₂ , acidic gases, chromium	Sunlight	Embrittlement and discolouration due to reaction of SO ₂ with moisture absorbed by paper. Similarly chromium forms chromic acid; exposure to 2-9 ppm of SO ₂ for 10 days decreases the folding resistance of paper significantly.

S. No.	Material	Air Pollutants	Other Factors	Effects
6.	Plastics & elastomers (rubbers), tyres and other rubber products, insulators.	Oxidants like O_3 , NH_3 , NO_2 , PAN	Sunlight, weather inversions	<p>Cracking of rubber (anti - oxidants added to rubber inhibit cracking); oxidants decrease molecular weight and increase the rigidity of the polymers making them more brittle and less resilient, cracking of rubber is initiated by O_3 attack at the double bond. Thus synthetic elastomers such as styrene, butadiene, poly isoprene are also susceptible to ozone damage. Elastomers with saturated chemical structures which contain hexzen atoms tend to be Ozone resistant. To combat ozone attack aromatic amines and phenols may be used.</p> <p>Chain scission decreases molecular weights and forms nitro and nitroso groups along the polymer backbone upon exposure to NO_2. Ozone of concentration 0.02 ppm takes 60 minutes for the first crack to appear on rubber. 0.06 ppm of ozone takes 5 minutes to crack rubber. 0.45 ppm of ozone takes 3 minutes to make first crack on rubber.</p> <p>20000 ppm of Ozone takes 1 second to make the first crack on rubber.</p>
7.	Bacteria and other food products	Biological aerosols	Moisture	Saprophytic bacteria and fungi cause food spoilation.

S. No.	Material	Air Pollutants	Other Factors	Effects
8.	Leather products like upholsters and book bindings	SO ₂ , microorganisms	Temperature, humidity	Embrittlement due to action of SO ₂ on moisture absorbed and bacteriological degradation.
9.	Minatured electronic circuits, solid state devices and computers, electrical equipments, high voltage tension wires.	SO _x , NO _x , H ₂ S	Moisture	* Saprophytic bacteria can grow on the surfaces of many inanimate materials in the presence of high humidity and can damage them unless they are coated with varnishes containing fungicides. Minute amount of corrosion also may impede free flow of electricity.

*Saprophytic bacteria are the living beings that feed on dead or decayed organic matter. These are fungi and bacteria which contain no chlorophyll.

3.8 EFFECTS OF AIR POLLUTION ON ART TREASURES

Polluted air containing oxides of sulfur and nitrogen and particulates, deteriorate building materials and may ultimately result in a loss in structural integrity. When buildings dating from antiquity and structures of great artistic and historic values are disfigured the loss is irreparable. Less than 100 years of exposure to air pollutants in London has done more damage to the Cleopatra's Needle than what was caused by nature during 3500 years in the dry atmosphere of Egypt (The obelisk was moved to Victoria embankment in London from Alexandria in 1878). This clearly indicates the gravity of the problem. The miraculous and historical monuments built by long years of hard labour are losing their faces. This shows how materialistic man has become in years where he is giving importance to industrial production even at the cost of the art treasures brought up by his ancestors. Disintegration of stone caused largely by the expansion of iron by corrosion had badly damaged the houses of parliament in London in 1920.

The Parthenon of Athens, the Coliseum and Arch of Titus in Rome and the San Marco Basilica in Venice are fast deteriorating. The situation in Florence, Italy has been described as disastrous. The massive twin spired cologne cathedral, the most magnificent church building of German High Gothic era is facing the threat of corrosion. Similar is the case in Japan where, in most of the industrial areas, the century-old shrines and temples are facing the threat. Apart from air pollution caused by man, freezing and thawing accelerated the damage to England's cathedrals and art treasures. The situation is same with the Indian monuments or may be more.

Would the Moghul Emperors were alive, will they prefer monuments like Taj in memory of their begums? Certainly not, not only because they won't last longer than their period of construction, but also of the patches disfiguring the shiny surfaces will deprive them of their prettiest memories of their begums. The Taj Mahal at Agra in India , a miracle in marble is facing the grave danger from pollution caused by existing foundries, power houses, railway yards and other industrial units. The problem now seems to be aggravated because of the commissioning of the Mathura refinery, within 30 km. range of the priceless monument. The discussion on situating the Mathura refinery at that place in the prevailing wind direction of Agra is of more concern than the 6 million tonne capacity of the oil refinery at Mathura.

However controversial the above situation may be, perhaps the black and brown patches and the scars on the artistic beauty cant be scrubbed. There are also reports about the formation of gypsum scaling and flecking effects.

Even though it looks ironical but it looks as though more money will have to be spent on protecting the Taj Mahal from the effects of pollution than it took Shahjehan to construct it. Perhaps the immediate solution is to shift the foundries and other industries from Agra, and effectively supervising the anti pollution measures adopted by the refinery and this is highly impracticable since there is no proven technology that can be used to reduce all the corrosive air pollutants like oxides of sulphur nitrogen and carbon to the barest minimum to ensure safety on the marble miracle TajMahal. Some alternative solutions must be considered. One of the methods that may prove successful is to transport the corrosive gases form the refinery through a set of anticorrosive pipelines bypassing Agra, purify the gases and release the emission into atmosphere at a safest place on the down-wind side of Taj Mahal. Plantation of trees around the Taj will give a cover which may absorb atleast a part of the pollution.

The renowned temple of Sri Channakeshava at Belur (Hasan district, Karnataka State) India is threatened with a similar hazard. A plywood factory located close to the temple emits soot-laden fumes which get deposited on the sculptures in the temple and discolour the surface, inside and outside. Paintings of great painters like Leonardo Da Vincy , books, fabrics and some historical documents have suffered damage . Jagannath temple at Puri and the Konark Sun temple situated on the East Coast of India are badly hit by particulates present in air. The abrasive action of the sea sprays is threatening the longevity of these temples. The Statue of Liberty is also badly affectedby air pollution.

Sensitive art objects displayed inside buildings can be placed in hermetically sealed containers. Air conditioning can also be used as a protective measure. The sides of books kept in closely packed rows with restricted air circulation remain in good conditions for a much longer period, than their exposed backs. Bactericides may be used to protect stones as some bacteria convert atmospheric SO_2 to sulfuric acid which they use as a digestive fluid in attacking the carbonate stone. All these historical monuments and art treasures withstood the ravages and plunders of the fury of nature for centuries but are showing the signs of decay in this century only due to the atmospheric pollution.

3.9 AIR POLLUTION DISASTERS

The series of air pollution disasters, from the Meuse Valley disaster to the Chernobyl Nuclear disaster made man realize that he will kill himself as a result of rapid industrialisation. Several tens of thousands of people were killed in these disasters and several hundreds of thousands are suffering from

permanent disabilities. The disasters may cause deleterious genetic effects in addition to the global problems. The various air pollution episodes are presented in table 3.8 and are discussed later.

**TABLE 3.8 REPORTED (DISEASE MORIBIDITY AND)
MORTALITY DURING AIR POLLUTION EPISODES**

Year and month	Location	Excess deaths reported
1873, Dec. 9-11	London, England	250
1880, Jan. 26-29	London, England	1000
1892, Dec. 28-30	London, England	
1930, December	Meuse Valley, Belgium	63
1948, October	Donora, Pennsylvania	20
1948, Nov. 26-Dec. 1	London, England	800
1950, November	Poza Rica, Mexico	22
1952, Dec. 5-9	London, England	4000
1953, November	New York, New York	250
1956, Jan. 3-6	London, England	1000
1957, Dec. 2-5	London, England	800
1958	New York, New York	
1959, Jan. 26-31	London, England	250
1962, Dec. 5-10	London, England	700
1963, Jan. 7-22	London, England	700
1963, Jan. 9-Feb. 12	New York, New York	400
1966, Nov. 23-25	New York, New York	170
1976, July	Sevesco, Italy	
1984, December 2	Bhopal, India	2500
1986, April	Chernobyl, Ukraine	2500

Meuse Valley Disaster

In December 1930, an anticyclone i.e. a high pressure area blanketed 25 km. stretch of Meuse Valley of Belzium. The area surrounded by 80-120 m high hills on all its sides has many industries, fertilizer, glass, sulfuric acid, zinc and steel manufacturing units and a thermal power plant. The thermal

inversion did not allow the pollutants to disperse and for three days continuously the area was under a thick cover of smog that contained several pollutants, mainly SO_2 , NO_2 , SPM and metallic fumes. Due to the building up of very high ground level concentrations of pollutants in the abnormal weather about 60 died and about 6000 became ill due to cough, irritation of eyes, nose and throat, shortness of breath, nausea and vomiting. Thousands of cattle also died. Elderly people, children and people already suffering from chronic diseases were the most affected. A mixture of SO_2 gas and SO_3 aerosols was believed to be the main pollutant responsible for the disaster. Other pollutants like fluorides from the glass factory, zinc particulates from the zinc smelter, ammonia from the fertilizer industry etc. were considered to have played only a minor role in the disaster. This was the first air pollution episode of the modern times.

Donora, U.S.A.

In October 1948, in Donora of Pennsylvania, a small mill town, dominated by steel and chemical plants, a 4-day fog made almost 60% of the 14,000 inhabitants sick. Twenty persons died. Anticyclonic weather conditions with no air movement, temperature inversion due to sea breeze conditions, and the winter fog did not allow the air pollutants to disperse for four days. Donora lies about 45 km south of Pittsburgh in a horse-shoe shaped valley on the Monongahela river with steeply raising hills on each side of the river. SO_2 (0.5 - 2 ppm) and particulates were believed to be the main pollutants responsible for the disaster. Other pollutants were NO_x and metallic ammonium sulphate fumes from the steel mill, zinc particulates from the zinc plants and acidic mists from the H_2SO_4 plants. Out of the 14,000 inhabitants about 60% became ill, 10% were severely affected and 20 persons died. Symptoms included irritation of eyes, nose and throat, cough, headache, vomiting and irritation of respiratory tract. The black mixture of pollutants was so concentrated with gas and soot that one could even taste it. 10 years later, affected donora residents were found to have a higher rate of sickness and to die at an early age.

London Series

London experienced a series of Air Pollution disasters in which several thousands of people were affected. London is situated in the Thames valley of southern England and experiences inversion regularly. It suffered from severe air pollution disasters about 10 times in the winter seasons of 1873, 1880, 1892, 1948, 1952, 1956, 1957, 1959, 1962 and 1963 in which several lakhs of people were affected. The 1948 disaster killed about 800 persons, followed by the 1952 disaster in which about 4000-5000 people died. This London smog disaster made it impossible to ignore any longer the serious

consequences of air pollution. On December 4, 1952 a high temperature air mass created a temperature inversion as a result of which a white fog blanketed London from 5th December to 8th December. About 4000 persons already suffering from bronchitis and other respiratory problems died. Particulates and SO₂ levels rose due to the extensive use of coal fired heating and power production systems. It should be noted that the coal used in great Britain has a sulphur content of 1.5 percent and that the coal was burnt in inefficient open grates. The subsidence inversion did not allow the pollutants to disperse as a result of which the fog became so black that a white shirt became almost black within 20 minutes. There was no movement of air and the visibility was practically zero on these days. It is said that one could not see one's hand in front of one's face. The smog was intensely irritating to the human respiratory system and the people soon developed red eyes, burning throat and nagging coughs. Again on 6 January, 1956 extra deaths in London were blamed on an extended fog and the parliament passed the Clean Air Act in 1956.

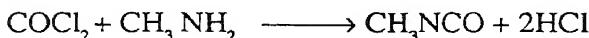
Poza Rica, Mexico: On November 24, 1950, Poza Rica, a town of 15,000 people on gulf of Mexico, was struck by a disaster. This disaster was originated from an accident at one of the local factories which recovers sulphur from natural gas. The release of hydrogen sulfide into the ambient air lasted for only 25 minutes. The gas under a shallow inversion with foggy and calm condition crept into the nearby houses and killed 22 people and hospitalized 320 .

Bhopal Gas Tragedy

Modern technological developments have multiplied the hazards to which human beings are exposed. Nearly 5 million chemicals have been synthesized in the world during the last 40 years and some 50,000 to 70,000 chemicals are used extensively in millions of different commercial products without the availability of proper toxicological information on the majority of chemicals.

On the fateful night of 2-12-1984 and in the early hours of 3-12-1984 more than one million residents of Bhopal, the capital of Madhya Pradesh of India reported irritation of eyes that quickly became unbearable, followed by the macabre death dancing in their dear houses. A cloud of poisonous gas was released from the union carbide plant. The plant was a pesticide manufacturing unit owned by Union Carbide India Limited, a subsidiary of Union Carbide, a leading company based in the USA. The factory was licensed to produce methyl iso cyanite, CH₃NCO, an extremely hazardous chemical, which is used in the manufacture of several pesticides like Sevin Carbaryl and

Temik 10-G. MIC is also used by various organic industries as an intermediate. Carbonmonoxide, CO obtained by partial oxidation of coal is combined with chlorine gas in the presence of activated carbon to form phosgene, COCl_2 . Phosgene and methyl amene combine to form methyl iso cyanate. The product is stored in tanks for further use to produce carbomite insecticide.



The carbide plant had three storage tanks for MIC, each capable of holding 45 tonnes. The union carbide manual on standard operating procedure warns that if water leaks into the system it results in the evolution of a lot of gas and liberation of heat . This is precisely that what happened.

Possible Reason for the Tragedy: On December 2, 1984 the supervisor on duty, who was new to the MIC unit asked an operator to wash the inside of a length of piping near the reactor. It was a standard procedure to insert a metal sheet called a slip blind near a valve to seal off the rest of the system from the tube being washed. The probable and possible reason for this tragedy is suspected to lie in this . Sources believe that the slip blind was not inserted when the operator connected the water hose pipes to the tubes required to be washed.

Shortly before the change in the night shift that Sunday, the count down to the Bhopal disaster started. At about 11 P.M. one of the operators noticed that pressure in a MIC storage tank read 10 pounds per square inch four times the normal and soon after a lot of workers noticed that their eyes began watering and stinging. The MIC drip at about 15 meters off the ground was accompanied by yellowish white gas. Sooner the leak had grown much larger and the entire area of MIC tanks was enveloped in the choking fumes. The concrete slab above one of the MIC tanks (of around 5" thick) was found shaking by the workers. The pressure has gone above 55 psi, which opened the safety valve and MIC vapour could be seen escaping from an atmosphere vent line 35m in the air. Bhopal tragedy, like other air pollution disasters was associated with a thick winter fog and thermal inversion which did not allow the pollutants to disperse and dilute.

Some observers had alleged that two other gases, hydrogen cyanide and phosgene were also present in the gas cloud. It was alleged that MIC is stored upto a purity of 99.5% and that 0.1% of phosgene is permitted as an impurity. If 40 tonnes of MIC vaporized that night, as much as 40 kg of phosgene also could have vapourised . However, the presence of phosgene was denied by Union Carbide.

About the Toxicity of MIC: MIC is a toxic gas which even in low concentrations causes lung, eye and skin irritation and larger doses would remove oxygen from lungs and thus cause death due to anoxia. MIC is just lighter than water and twice as heavy than air and hence moves at lower levels only. MIC can react with any chemical including itself, to evolve considerable heat and CO₂. MIC in the storage tank was stored for more than 2 months because of less carbaryl demand and it was against the safety rules.

Unusual Death Trap: On the ill fated 1984 December 2nd night the public woke up coughing and vomiting, with their eyes burning uncontrollably. Of Bhopal's one million population more than 5,00,000 fled on roads to nearby towns and hospitals. The roads were full of crowds and foul smelling due to vomitings. At about 3 A.M. the gas spread over to 40 sq.km. and seriously affected the people at a distance of 5 to 8 km . 'It was like breathing fire', said one supervisor.

In Hamida hospital the first patient with eye irritation was reported at 1.15 A.M. and by 2.30 A.M. there were 5000 patients. Thousands waited for medical care inside the hospitals and screams and sobs filled the air . Dead bodies were found lying all over the streets and in the corridors of hospitals with their bodies bloated and blood stinking over the floors. The manager of the three local cremation grounds said that 7000 more bodies were cremated in 1985 than in 1984 including 1,017 children in Hindu cremation grounds. Bhopal victims support committee claims that the death toll could have reached 15,000. Approximately 2,00,000 people had adverse health effects resulting from the disaster, ranging from the temporary blindness and burning lungs to permanent disability. Of 2500 women who were pregnant at the time more than 500 had mis- carriages and about 100 had still births. By 3 A.M. the safety valves reseated themselves as the tank pressure dropped below 40 psi. The public siren was resumed at around 3.30 A.M. but by that time there was no need for caution.

Many of the people died where they were. When the gas reached the railway station, the supervisors diverted the incoming trains. The diversion cut off a possible means of escape but may have saved hundred of lives. The whole station was quickly enveloped in gas. The deputy chief power controller, who alerted all the nearby stations to stop trains from coming into Bhopal died alongwith the station master. Cattle and animals were found lying dead on the roads.

A medical survey held about three months after the disaster revealed that out of 2,50,000 people exposed 70,000 were severely hit from eye, respiratory, gastro intestinal, neuromuscular and gynecological disorders. About 50,000

people were subjected to moderate medical treatment. Doctors predicted an increased risk of sterility, kidney and liver infections, tuberculosis, vision problems and brain damage.

The MIC unit was allowed to work without any preventive devices. On the ill fated night the vent scrubber, that neutralises the gas with caustic soda failed in its duty of detoxicating the escaping gas. The flare tower which is supposed to burn the escaping gas was without the pilot flame because the concerned pipe got corroded. It is unbelievable to know that the 30 tonne refrigeration system which is a must to keep MIC storage tanks at 15°C was out of condition, even though the boiling point of MIC is 39°C only, and flash point is 7°C. Even the water curtain which can be used to cool the escaping gas could not reach more than 15 meters high, though the safety valve outlet is at a much greater height. To the ill fated people of Bhopal every thing would have been right if not for the improper maintenance of the safety systems. For the people of Bhopal it was an ill fated Sunday night. Today many people work with dark glasses and with shrouds to protect their injured eyes and body. Everywhere there were remainders of the disaster. It is the unanswerable questions that will continue to haunt its population for generations to come, as survivors tell their children about the tragedy that rocked Bhopal. Bhopal holds out lessons that have to do with basic concerns, for safety, for standards and for good sense. If the lessons are not needed then it is possible that accidents such as this may be repeated in another factory in another city in another way leading to much more severe tragedies.

The Chernobyl Nuclear Disaster

April 27, 1986 was a sad day in the history of nuclear power generation as a major accident occurred at an atomic reactor at Chernobyl in the Ukraine area of the erstwhile Soviet Union. This had resulted in clouds of radioactive smoke over a large area in scandinavian countries about 2000 km away, and in the Russian region itself.

The first explosion at reactor number 4 at the Chernobyl complex occurred on April 26, 1986 and resulted in a massive and uncontrollable fire. The explosion on April 26 was followed by a second explosion on May 5th. Majority of the radiation was released in the 10 day period between April 26 and May 5 , 1986. After May 5th the fire was brought under control and a sharp drop in release of radiation was observed. But small amounts of radionuclides were released for several weeks even after the fire was controlled. The explosion and fire was caused by failure of emergency cooling system in the light water graphite reactor, due to human error. The explosion and subsequent hot fire (about 2500°C) blew large amounts of radionuclides high into the atmosphere . About 10.19 Bq of radio nuclides

were released during the period of explosion.

Mortalities: During the first 10 days after the explosion over 400 million people were exposed to the radiation . In the immediate vicinity of the plant 30 soviet citizens died from radiation poisoning. Approximately 1000 were treated for radiation burns and sickness and over a 1,50,000 people were evacuated from an area inside a 30 km range of explosion. The radiation levels in Western Europe reached 100 times the normal resulting in misery and panic death. The exposure caused ulcerate skin, loss of hair, nausea and anemia. After studying data relayed by a U.S. spy satellite which flew over the Ukrainian area (where the fire and radiation leak occurred), U.S. defense officials claimed that the death toll could be more than 2000.

Global Impact of Chernobyl Mishap: It is expected that the heavy fall out from the mishap could damage soviet agricultural output for years to come. The intense radiation has already killed several fields, trees, shrubs, plants etc. The immediate damage was put at 10% of the crop. Sweden and Denmark have banned food imports from the soviet union. Radiation stress caused reduction in several plant species and destroyed the flora and fauna on the planet, mainly the human beings. The chronic health effects noticed include blood abnormalities, haemorrhagic diseases, thyroid changes, mutagenic and somatic alterations, bone necrosis, skin cancer including erythema atrophy, pigment discolouration, alopecia ulceration, lung changes i.e. fibrosis, eye diseases, cataract and failure of reproductive organs.

Main Radionuclides Emitted and Their Effects: Four main radio nuclides cause major concern. Iodine-131 has a half life of eight and half years. This affects the body both internally and externally. The radionuclide is often deposited on grass and enters the food chain through milk . It is subsequently deposited in the thyroid gland and can cause cancer of thyroid in children. Cesium- 137 is deposited mainly in soft tissues of animals. This radionuclide irradiates the entire body. Cs-137 has a half life of 30 years. Strontium - 90 is a very dangerous radionuclide with a half-life of 28 years. Since it is chemically similar to calcium, it is deposited in the skeleton, and can cause leukemia, bone cancer and various genetic effects. It generally reaches humans through food chain. Carbon-14 (C-14) has a half life of 5730 years. This emits radiation which is readily absorbed by the body. Out of the above four radio nuclides the chernobyl explosion is said to contain mainly I-131 and Cs-137 and low concentrations of Sr-90 and C-14.

Adverse Meteorological Effects: Air flow dominated the plume transport. Upto April 29, South South East air flow had carried the plume to Finland, Sweden and Norway. By the afternoon of April 28, the northern part

of the plume began to move eastward across the northern Russia, eventually bringing elevated levels of radioactivity to Japan. By May 1, the radio activity had reached United Kingdom as plume shifted away from Scandinavian. By May 3, the plume moved over Southern and Western Europe, had extended into North Atlantic and parts of Mediterranean. Even after the plume was no longer over an area, plant and soil surfaces would retain the radio active substances allowing residual activity, wetness and small scale irregularities.

Lessons from Chernobyl: The European countries were under prepared to handle a disaster of this type and magnitude. The counter-measures implemented were often designed to minimize political impact and hard decisions made for the safety of the population were relatively rare. Second, to allow the correct assessment of the impact of such disasters a uniform system of measuring exposures and calculating equivalents on worldwide basis is needed. Third, there is a need to overcome political ideological differences to allow complete and rapid communication to minimize impacts from the disasters.

Effect on Indian Nuclear Policy: The chernobyl mishap had not seriously affected Indian nuclear policy and programmes. The Indian atomic plants, except the one at Tarapur, use heavy water and natural uranium whereas the ill-fated Soviet reactor used light water as coolant and enriched uranium as fuel. The kind of pressure which built up at the Soviet plant leading to fire and radiation leak seems improbable here. But the warning is clear.

Lessons from Air pollution Disasters

Almost all the disasters occurred in the winter months in the northern temperate zones with dense populations and heavy industrialisation. Adverse meteorological conditions such as stagnating air masses under shallow inversions with impeded ventilation and dispersion played a decisive role. Not one pollutant, but combinations of two or more gas-aerosol mixtures in moist and cold weather caused synergistic damage to health. Major air pollution disasters resulting in hundreds and thousands of excess deaths have periodically occurred since the industrial revolution. Air pollution episodes are not restricted to major centres of population and heavy industrialisation. Pollution sources entrenched in steep-side valleys in a stagnating air mass under a shallow inversion lid. Some of the air pollution episodes seem to occur now on a continental and sometimes on a hemispherical scale also. Air pollution forecast and warning systems coupled with legal authority should be instigated to prevent these episodic disasters.



CHAPTER - 4

GLOBAL EFFECTS OF AIR POLLUTION

Tropospheric and stratospheric ozone depletion, aerosol scattering and absorption of solar and terrestrial radiation, green-house gas warming, rain and precipitation quality, long-range transport of air-pollutants, heat-islands and urban air quality are known to be the main global air pollution problems. Man at the end of the 20th century has at last realized that the complexities of pollutant interaction with the atmosphere are not confined to a local scale. In the name of 'Pollution Control by Dilution' millions of tonnes of a variety of toxic air pollutants are released into the atmosphere by man which are transported to places several thousands of kilometers away from the source through atmospheric circulation systems causing irreparable damage to the quality of air on continental and global scales . The impacts of air pollution on biosphere and the quality of life have drawn considerable public attention, and air pollution problems are being considered and tackled on a global scale. The word 'global' need not necessarily mean that the pollutant under consideration encompasses the entire globe and are not unique to individual locations. The environment in which we live is unfortunately the host medium for air pollutants also. Man is the sole culprit in polluting the air and he alone should take the responsibility to clean the atmosphere and protect the environment. The various global effects of air pollution are discussed in this chapter.

4.1 GREEN HOUSE EFFECT

Solar energy in the form of light radiation has wavelengths in the range of 0.2 to $4\mu\text{m}$. It will lose some energy after striking the earth and will be converted to heat energy of longer wavelengths. Thus the wavelength of this terrestrial reradiation, from earth to atmosphere is more ($4-100\mu\text{m}$) ($E=h\nu=hc/\lambda$. After striking earth since energy decrease, λ , the wavelength increases). Carbon dioxide has radiation absorption bands in the range of $12-18\mu\text{m}$ wavelengths. Thus if CO_2 is present in the atmosphere, it allows the incoming solar radiation to pass through but does not allow the reradiation from earth to space to pass through. This is the origin of the term 'Green House Effect' since the glass in a green house also is transparent to short wavelength solar radiation and absorbs the long wave length radiation, emitted from inside the green-house. CO_2 , water vapour, methane, N_2O , ozone and CFCs cause similar effects and hence are called green house gases. As these green house gas molecules absorb energy, their temperature increases and they themselves start radiating heat. Only a part of it escapes out into the space while the remaining is radiated back to earth further increasing its temperature. Green House Effect, GHE is essential for mankind and life. But man's activities are accelerating or enhancing the warming process to cause concern.

Sources of Green House Gases

The various sources and sinks of green house gases are presented in Table 4.1

The main source of GHE is carbondioxide. About 50% of GHE may be attributed to CO_2 . The 1983 estimate gives a value of $5.6 \times 10^{12}\text{kg}$ of carbon, apportioned as follows globally.

North America	:	26.7 %
USSR	:	17.6 %
East Europe	:	15.6 %
West Europe	:	6.5 %
Asia	:	18.5 %
Japan	:	5.8 %
Others	:	9.3 %

Presently more than 10,000 million tonnes of carbon dioxide is released into the atmosphere every year due to the combustion of fossil fuels with about 25% of it from industries. USA alone produces about 2500 million tonnes of CO_2 per year. The CO_2 concentration in

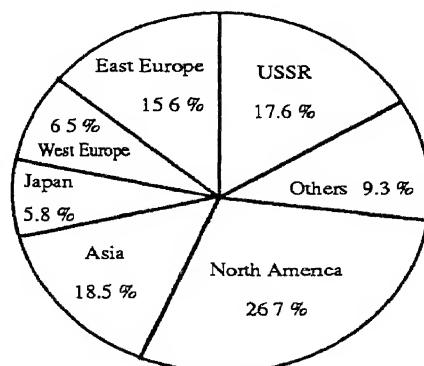


Fig : 4.1 Global Contribution of Green House Gases

the pre-industrial era was 265-290 ppm and today it is about 340 ppm. This change is mainly due to the combustion of fossil fuels of coal, petroleum etc. by industries. For example, modern thermal power plants release about 50 million tonnes of CO₂ per year into the atmosphere. The annual coal consumptions by NTPC of India alone are 10,8.7, 5.6 and 5.2 million tonnes at Singrauli, Ramagundam, Korba and Farakka respectively.

Water vapour is another green house gas that absorbs IR radiation below 8 μm (and < 20 μm) while CO₂ has absorption bands in the region of 12 to 18 μm. It has a residence time of about 10 days which is very low compared to that of other green house gases.

Impact of Green House Effect on Environment

1. Global warming-a global warning : Due to the specific characteristics of the green house gases, the radiation from earth cannot reach the space above as a result of which more and more heat is radiated back to earth. Due to this, the mean ambient air temperature is expected to increase at an alarming rate of about 0.5 to 1°C per decade. However, an increase in temperature will increase evaporation which may lead to more clouds, more cooling and less ambient temperature. Hence a logistic model considering different parameters must be developed while estimating the degree of global warming. The period from 1967 to 1986 showed an increase of 0.36°C in the northern hemisphere and 0.23°C in the southern hemisphere.
2. According to World Health Organisation, mosquitoes may have longer lives and breed in larger numbers due to global warming and hence may spread malaria. Warmer and humid conditions may also enhance the growth of bacteria and moulds and their toxic products resulting in increased amounts of contaminated and spoilt food. According to WHO, there is a potential for increased air pollution related morbidity and mortality in the world population due to the release of green house gases. Increase in mean global temperature in association with depletion of ozone layer may increase the incidence of 'non melanoma skin cancers' by even 35% by 2060. It will be much more in the southern regions where ozone depletion is high. It also forecasts an increase in natural disasters such as cyclones and floods and short-term but dramatic changes in temperatures, like heat waves.
3. CO₂ is also expected to influence intensely the process of depletion of ozone layer which would further make the climate hot.
4. Global warming may increase Mean Sea Level significantly. The factors influencing the phenomena of rise in Mean Sea Level are thermal

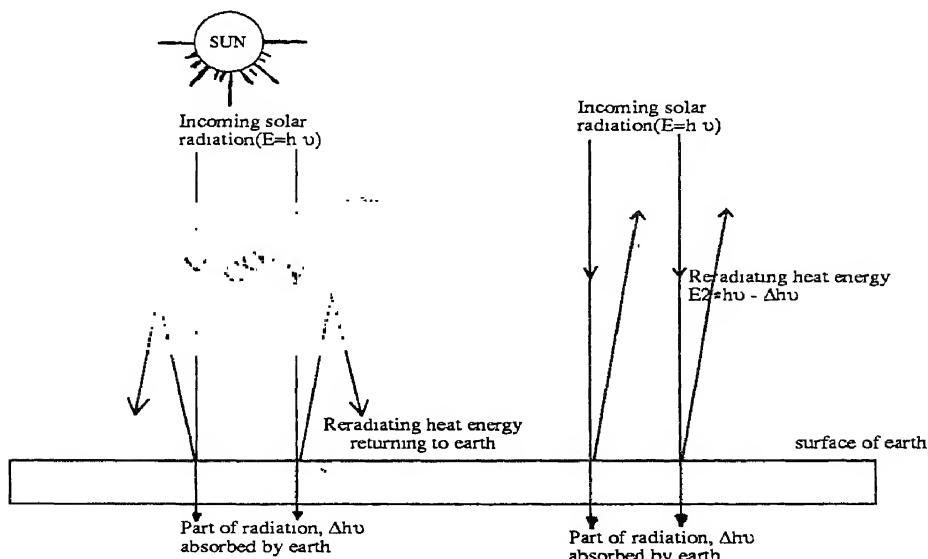
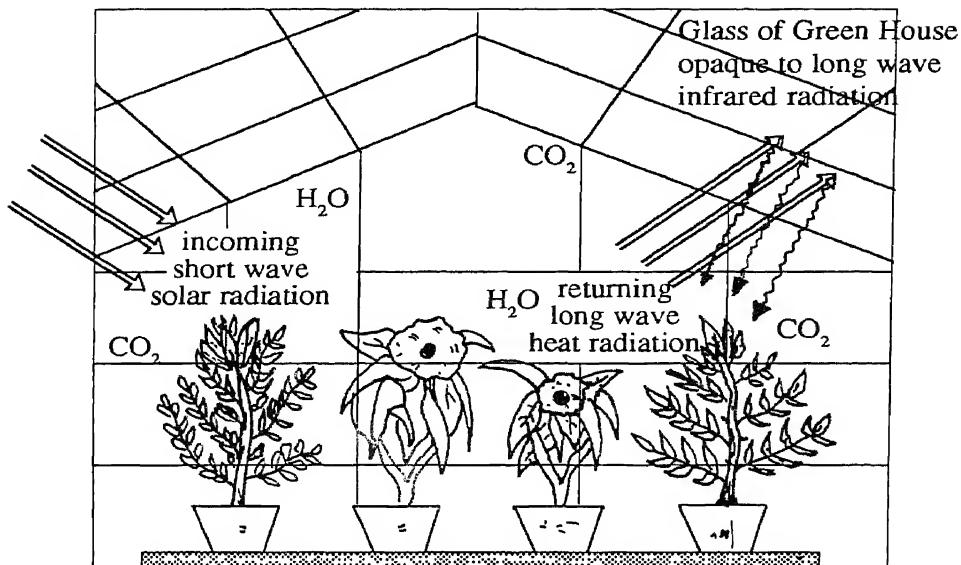


Fig.4.1 Green House Effect

TABLE 4.1: SOURCES, SINKS AND CHARACTERISTICS OF GREEN HOUSE GASES

	Properties	CO ₂	CH ₄	N ₂ O	O ₃	CFCs and Halons	
						CFC-11 CFCl ₃	CFC-12 CF ₂ Cl ₂
1.	Residence Time, years	2 - 4	10 - 12	150 - 200	-	75	110
2.	Main IR Absorption Wavelengths, μm	4.3,15	3.3,7.6	4.5,7,6,8,6	4.75,9,6	9.22,11,22	8.68,9,13, 10.93
3.	IR Trapping, W/m ² 1985 (2050)	50 (53)	1.7 (2.5)	1.3 (1.5)	1.3 (1.7)	0.06 (0.3)	0.12 (0.6)
4.	Estimated Temperature increase, °C	0.71	0.20	0.10	0.06	0.24	0.12
5.	% Contribution to GHE	50	18	6	-	-	14 -----
6.	More effective than CO ₂	1	30 times	200 times	-	1000 times	1000 times
7.	Rate of Increase in Concentration	25% since industrial revolution in the mid 1800s	0.7 to 65 ppm in 400 years	50% since industrial revolution in the mid 1800s	-	Increasing rapidly ever since they were invented in 1930	

8.	% increase/year	0.4	1.0	0.25	--	5.0	5.0
9.	Atmospheric Concentration by Volume	340 ppm	1650 ppb	304 ppb	Variable	0.230 ppb	0.400 ppb
10.	Sources	Combustion of fossil fuels, industries, agriculture, deforestation	Rice production, animal husbandry	Nitrogen fertilizers, land clearing, biomass burning, fossil fuel combustion	Photochemical oxidation	Propellents and deodorants in aerosols, refrigerants, cleaning solvents, fire extinguishers, blowing agents for foamed or extruded polymers, sterilants for medical suppliers.	
11.	Sinks	Oceans, vegetation, fossil fuels	Oxidation to CO ₂ , soils	Stratospheric photochemistry and aerobic soils	Injection of alkanes, ethanes or propanes into the atmosphere can destroy/immobilise CFCs	—	

expansion of water (especially the top 1000 m of ocean surface), changes in run off due to changes in precipitation and changes in evaporation into a warmer atmosphere. However, the main factor is the melting of ice caps and glaciers. About 10% earth is covered by glaciers. Out of the total amount of water (other than water in oceans) present in the environment, nearly 75% of water ($29,000 \times 10^{12} \text{ m}^3$ out of $38,000 \times 10^{12} \text{ m}^3$) is present in ice caps and glaciers at the Himalayas, Arctic and Antarctic regions. Thus the increase in ambient air temperature will increase the mean sea level. The following data indicates the water present in various sources.

Total water sources	$1360,000 \times 10^{12} \text{ m}^3$	100%
Oceans	$1320,000 \times 10^{12} \text{ m}^3$	97.3%
Atmospheric water vapour	$13 \times 10^{12} \text{ m}^3$	0.001%
Surface waters	$230 \times 10^{12} \text{ m}^3$	0.017%
Ground water + soil moisture	$8417 \times 10^{12} \text{ m}^3$	0.615%
Ice caps and glaciers (at Arctic and Antarctic regions)	$29,200 \times 10^{12} \text{ m}^3$	2.14%

The level of Caspian Sea has already increased by 1 meter as per recent reports. Sea level has been raising for centuries now and it has risen by about 15-20 cms during the last century. It is estimated that the MSL will increase by 0.2 - 1.5 m by 2030 and 0.5 to 3.0 m by 2100 A.D. It is to be noted that a 1-m rise could affect an area of about 5000 lakhs of hectares of land surface much of it being densely populated now and that hundreds of millions of people live in these areas. Displacement of these people may lead to food shortages and famine. For some regions, the problem is going to be severe as relocation is not possible for countries like Indonesia and for some non-human habitats, exemplified by the Everglades National Park of Florida. 90% of Maldives and 80% of Bangladesh would be submerged. In addition, salt water intrusion into coastal wetlands would occur and ground water sources may become more saline.

5. With the increased CO_2 levels, the oceans would be required to absorb and decompose more CO_2 which can raise their normal level of acidity. It would decrease the biological productivity of the marine ecosystems, thereby changing the whole oceanic climate. However, according to atmosphere feed back mechanism, CO_2 is released from oceans as solubility of CO_2 decreases with temperature. Due to this CO_2 concentration increases with a further corresponding rise in temperature.

6. Increasing concentrations of CO₂ may increase the atmospheric pressure. It would broaden the absorption bands and will increase the opacity of the atmosphere to the outgoing long wave terrestrial radiation. It may increase to such an extent that the whole biosphere may come to a grinding halt.
7. Global warming may also increase precipitation by 4 to 15% and may be characterised by late spring, winter rain down by 10-20% and early autumn rain up by 20-50%. It may also increase the frequency and intensity of tropical cyclones by 20-50%. Wind speeds may decrease by 20% N 36°S and increase to south.

Thus GHE may bring changes in mean sea level , energy supply and demand; water resource availability and its political consequences; agriculture; ecosystems and a variety of economic, social and political circles.

Control of Green House Effect

For the preservation and protection of man and environment, the emission of green house gases must be controlled. Following are some of the methods of control of green house gases.

1. In the natural "Carbon Cycle", CO₂ is removed by two sinks (Sink is a place or mechanism associated with the removal of a pollutant. For example, precipitations remove particulates, soil absorbs carbon monoxide and oceans absorb CO₂) - oceans and vegetation . The emission rates of CO₂ are more than the absorption capacities of the sinks. Nearly 30 million tonnes of CO₂ is released into the atmosphere everyday due to the burning of fossil fuels. Situation is worse as CO₂ emissions have increased exponentially and at the same time deforestation due to cutting of vegetation and reduction of soil organic matter due to fuel extraction are also at a rapid rate. In 1910, India had 40% forests and it is only 20% today. Due to increase in population deforestation is a rate of 50,000 km² per year. Every minute about 40 hectares of forests are destroyed worldwide. So, the only practical solution to the burning problem of global warming is social forestry i.e. community based forest schemes. For example, in China, forests increased from 5% in 1950 to 13% in 1980.
2. As 50% of green house gases are from energy production, the solution to control global warming is to adopt alternate energy sources like tidal power stations, wind power plants, solar power systems etc. Supply of non-conventional energy at subsidized prices may atleast to some extent decrease the emission of green house gases.

3. Majority of the beaches are situated on mild bed slopes. For example, the east coast of India is on a slope of about 400 m in 100 km whereas near Madras it is 40 m in 100 km i.e. 1 in 2500. If the bed slope at a place is 1 in 2000, it means that a 1m raise in Mean Sea Level would make the sea encroach into about 2000m of coastal area (Construction of dikes to protect lands from submerging also can be tried. In Holland, dikes of 10 m above mean high tide have been constructed to avoid the effects of increased M.S.L., but in 1953 severe storms with surges 5m above normal tide overwhelmed the existing dikes and nearly 2000 people died. Subsequently the dikes were raised by 3m!).
4. Water logging from fields, especially rice fields, releases methane, another greenhouse gas. Water logging is a common phenomenon that occurs due to construction of dams for hydro power plants. Hence water logging should be avoided.
5. As a green house gas, one mole of CFC is more than 100 times more powerful than one mole of CO₂. The already emanated CFCs will persist in the atmosphere for many decades and continue to contribute GHE because of their long life-spans and high absorbing power for IR radiation. Hence the use of CFCs should be banned all over the world.

History of Green House Effect

About 20,000 years ago the CO₂ concentration was about 200 ppm only, as a result of which earth's temperature was 4 to 5°K lower than now. It reached a value of 280 ppm about 10,000 years ago, 290 in 1860, about 320 ppm in 1970 , 340-360 ppm in 1988 and is expected to be doubled by 2030 A.D. The changing concentrations of CO₂ measured carefully at Maunaloa Hawaii, situated away from the industrial populations, indicated a net annual increase of CO₂ by 0.77 ppm. The role of CO₂ can be visualised by comparing Earth with Moon and Venus. Venus has a larger CO₂ content while Mars has very little. The net result is Venus is hot at 477°C, Mars is cold at - 47°C and the earth has an average temperature of about 16°C. The term Green House Effect was first coined by J. Fourier in 1827. The effect is also called as atmospheric effect or global warming.

Several years ago Dr. Gilbert Plass observed that the heat content in rooms with ordinary walls was much lower than the heat content of rooms with glass walls. This is attributed to the property of glass which allows the incoming short wave solar radiation to pass through and becomes opaque for the outgoing reradiated long wave infrared radiation. As mostly glass is used for the walls of green houses meant for plants, this effect of heat retention in a green house is called green house effect. This phenomenon can well be

understood when one returns to the car with closed windows after a while. The glass windows of the car would allow the incoming solar radiation and does not allow it to return, as a result of which more and more heat would be retained inside the car, on a warm day. The incoming UV-visible solar radiation exhibits maximum intensity around 413 nm while energy emitted from earth's surface lies in the infrared region of 2000 to 40,000 nm with a maximum intensity of 10,000 nm. The temperature of earth would have been - 20 to - 40°C if there were no green house gases present.

The CO₂ concentration increased from 265-290 ppm in the pre-industrial era to about 340 ppm in 1988. Similarly, N₂O concentrations in the pre-industrial era was 0.2 ppm. By 2035 it is expected to be 0.4 ppm. A doubling of its concentration will be equivalent to 0.3°C increase in temperature. Similarly, CFC concentrations are increasing rapidly ever since they were first manufactured in 1930. They have long life spans and are more powerful IR radiation absorbers. During 1860-1985, the cumulative heating rate from all gases was 1.9 W/m² as compared to the expected 3.5 W/m² for the period 1985-2035.

As early as the 1860s, some observers suggested that slight changes in the composition of the atmosphere might result in major changes in the earth's climate. In 1896, the Swedish scientist Svante Arrhenius had calculated that a doubling of CO₂ in the atmosphere would lead to a global warming of 7 to 11°F (4 to 6°C) which is remarkably close to today's predictions. Roger Revelle, Hans Suess and David Keeling established the first CO₂ monitoring station at Maunaloa, Hawaii and it was observed that the CO₂ concentration increased from 315 ppm in 1958 to 360 ppm in 1987.

The discovery of a hole in the stratospheric ozone layer over Antarctica prompted the signing of the Montreal Protocol on substances that deplete ozone layer, on 16th September, 1987. This protocol mandates significant decrease in CFCs and other hydro carbons that contribute to GHE and hence this is going to control the GHE to a great extent.

According to a recent report by Inter Governmental Panel on Climate Changes (IPCC) there will be a 1°C rise in temperature by 2025 and 3°C rise by 2100. According to UNEP, a 2°C rise in temperature is sufficient to disrupt the earth's heat budget and will cause catastrophic changes in the environment.

1993 was the second warmest ever after 1994!

4.2 EFFECT OF PARTICULATES ON EARTH-ATMOSPHERE HEAT BALANCE

Millions of tonnes of particulate matter is being put into the air by man and

nature every day. These particulates, dusts, fumes, aerosols (0.1 to 5 μm) etc. will scatter and absorb both solar and terrestrial radiation thereby affecting the heat balance of the globe. Aerosols could reduce the incoming radiation by 10% through back scattering and their increase could probably lead to the cooling of atmosphere. In addition, particulates, especially the dusts, play a vital role in the formation of clouds as they act as nuclei for the condensation of water vapour. The massive injection of particulates from automobiles and industries also increases the reflectivity of atmosphere besides controlling precipitation. Also the rate of increase of atmospheric turbidity has been observed to be greater than that of CO_2 concentration. Consequently, skies become more cloudy and atmospheric turbidity increases. Hence penetration of solar radiation will be less. Thus the various effects due to the discharge of particulates into the atmosphere could be on earth's reflectivity, its surface temperature, cloud formation and precipitation, earth-atmosphere heat balance and the evaporation-condensation cycle.

4.3 HEAT ISLANDS

The heat energy release causes a significant climate change in cities and may result in global climate effects. Because of the thermal capacitance of the streets, buildings and industries for solar input and because of energy dissipation, cities are warmer than their rural surroundings.

Energy release in urban areas may occur both through evaporation of water, particularly in generation of electric power and in the direct heat of air. As a result, the cities are warmer, rainier and fogger than their suburban surroundings. In highly urbanised and industrialized areas, a difference in temperature of 6°C is quite common. In such areas, the artificial production of energy approaches nearly 1000 watts/ m^2 while the solar absorption by the atmosphere averages out to be only 25 watts/ m^2 . Thus the city becomes a Heat Island . The city surfaces, due to this effect may be as much as 10°C hotter than their rural surroundings, when wind is calm. Compared to their rural surroundings, urban areas are typically 2.5°C warmer; 10% less humid; the wind movement is 25% less; solar radiation is 25% less; precipitation is 10% greater; clouds are 10% more and frequency of fog is 100% greater. Further, the concentration of green house gases just above the urban area may further increase the heat content of the area. Thus the heat islands play their role in increasing the mean global temperatures. This growing thermal burden would inevitably disrupt the climatological and ecological balances.

4.4 ACID RAINS

Thermal power plants, industries and other sources release thousands of tonnes of oxides of nitrogen and sulphur into the atmosphere everyday .

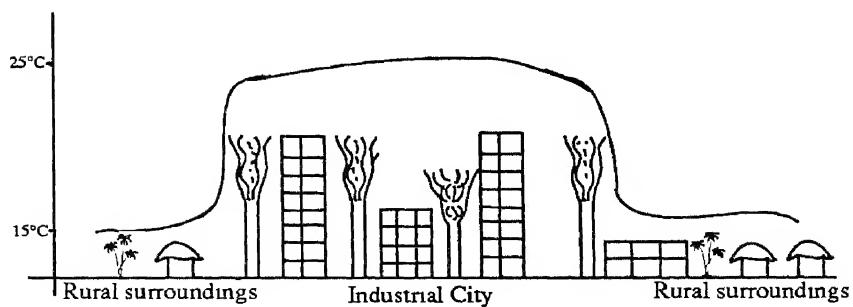
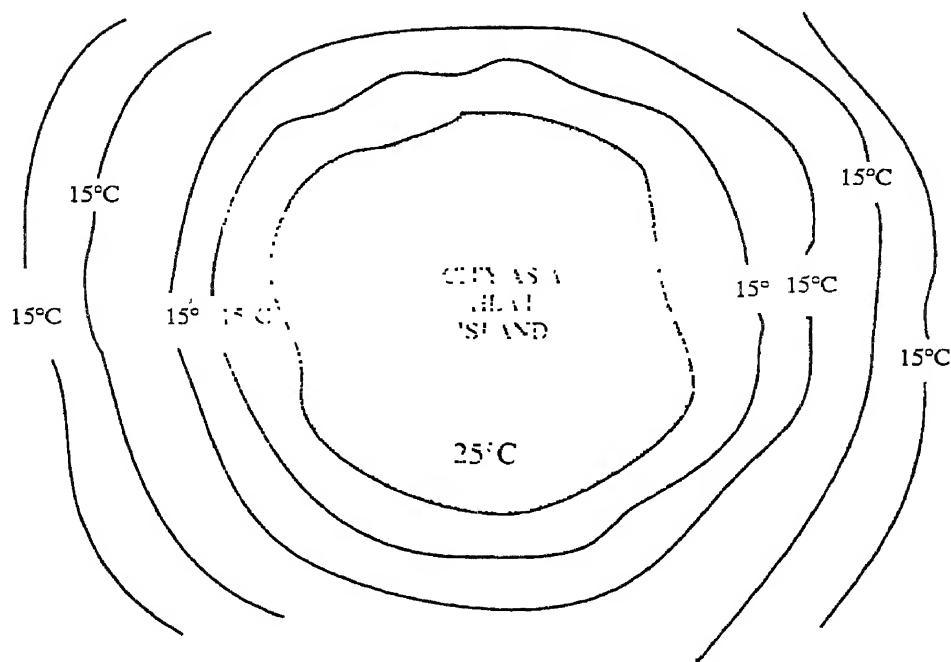
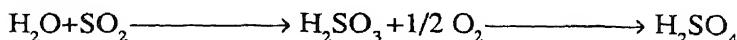


Fig. 4.3 Heat Island Effect

These gases undergo transformation in the atmosphere and form nitrates, sulfates, nitric acid or sulfuric acid droplets. Some of these pollutants, especially the oxides of sulphur can travel 200-300 kms in a day. Thus, the compounds emitted at a place may be carried hundreds of kilometers by the wind and deposited on ground or on vegetation directly as 'ACID RAINS'.



Rain is the purest source of water. 'Acid Rain' means any precipitation- rain, snow or dew, which is more acidic than normal. Acidity of water is measured on a pH-scale, ranging from 0-14 pH. Neutral solutions and freshly prepared distilled water have a pH of 7.0. Acidic solutions have a pH < 7 and alkaline solutions have pH > 7. Lemon juice (citric acid) has a pH of 3. pH scale being logarithmic, an acid of pH 3 is 10 times more acidic than water of pH 5 and 10,000 times more acidic than neutral water. Though rain is the purest water source, it absorbs the atmospheric CO₂ while falling and forms H₂CO₃, the carbonic acid with pH falling to even 5.6. If pH of rain is less than 5.6, it is termed as 'acid rain'. Nowadays, acid rains with pH < 4.5 are common in many developed countries.

Sources of Acid Rain

The massive emissions of oxides of sulphur and nitrogen-SO_x and NO_x, from thermal power plants and industries react with moisture and other atmospheric constituents to form a cocktail of sulfuric acid and nitric acid. About 70% of the acidity of an acid rain is due to SO_x emissions and 30% due to NO_x emissions. Majority of the fuels, especially coal, contain about 0.5 - 4% of sulphur and when they are burnt in air that contains about 80% of nitrogen and nearly 20% of oxygen, huge quantities of SO_x and NO_x are released. The super stack and the mammoth smelters at Sudbury of Ontario release about 2500 tonnes of SO₂ everyday. This largest stack of the world alone contributes about 1% of the total SO₂ released.

SO₂ and NO_x, swept up into the atmosphere can travel thousands of kilometers before being finally deposited as acid rain. For example, SO₂ can remain in the atmosphere upto 40 hours while a sulphate particle for 20 days. It is estimated that 87% of SO₄ in New York and New Jersey and 92% of it in New England has been carried in by long distant transport from the middle west. The origin of acid rains affecting the lakes, rocks and soils of Adirondack in New York is the industrial sector of the Midwest. Here, the rocks are mainly granites and gneisses which have no buffering capacity and hence the acid rains falling on these Adirondack slopes have greater levels of acidity than the rain itself.

Effects of Acid Rain

'Acid Rain' is dangerous to man, material and vegetation and can disturb the ecological balance on a global scale. The effects may be summarised as follows:

1. Green algae and many forms of bacteria, which are essential to aquatic life / system are killed due to acidity.
2. High acidity results in the reproductive failure, reduced growth and in the killing of fish. Change in pH prevents hatching of fish eggs and destruction of trout and salmon. Brook trout is the most acid tolerant while rainbow trout the least.
3. At low pH, decomposition of organic matter is less and hence results in the accumulation of organic matter in the water bodies like lakes and streams and hence increases the degree of water pollution. Self purification capacity of water body decreases.
4. Acidity increases the concentrations of heavy metals such as lead, cadmium, copper, zinc, aluminum, chromium and manganese in water. These are highly toxic and hence badly affect the quality of water.
5. Acidity affects germination of seeds. Growth of trees also is adversely affected which results in vanishing of greenery and destruction of forests.
6. Acidity also affects soil by decreasing its fertility. Plant nutrients like potassium are leached out of the soil whereas toxic elements like zinc accumulate. Beneficial microorganisms are killed or reduced. Earth worms, known as 'Farmer's Friends' cannot survive in acidic environment.
7. Acid Rains corrode buildings, monuments, statues, bridges, fences, railings and art treasures. It is an irreparable loss to mankind.
8. In 1958, the Rain falling over Europe had a pH of 5.0. It was 4.5 in 1962 in Netherlands and Sweden. In 1970, ecological damage was observed while in 1979, it was observed that 20,000 lakes of Sweden alone were suffering from loss of flora and fauna. In USA, in 1979, the average pH value of rain was 4.2. In Los Angeles, a pH of 3.0 was noticed for a dense fog. Wheeling (West Virginia) of USA and Pitlochry of Scotland recorded pH of about 2.2 which is more acidic than lemon juice (cytric acid) and was as acidic as battery acid. The rain on Aril 10, 1984 at Pitlochry was nearly one lakh times more acidic than normal water. In India, Bombay and other western parts have experienced acid rains. Taj Mahal, one of the wonders of the world is badly affected by SO_x emissions from Mathura refinery and elsewhere and the damage is named as 'Stone Cancer' or 'Stone Leprosy'

Acid rains have already caused severe damage to the environment. About 500 lakes of USA, Canada and Sweden are 'dead' and about 10,000 lakes are fishless. If the occurrence of acid rains continue, it is estimated that by 2000 AD, 50,000 lakes of Canada may perish. Similarly, 30% of West Germany's forests are dying.

Control of Acid Rains

The only remedial measure to control acid rains is to control the emissions of the oxides of sulphur and nitrogen from industries and power plants, by using proper control equipments and stringent legislations. Periodic application of lime to neutralize acidity is a solution but is expensive and cannot be applied on a large scale.

Black Snow

During the Gulf war of 1991, thousands of tonnes of smoke and dust were released due to the burning of hundreds of oil wells. A portion of these pollutants carried by wind were finally deposited on the shining skin of the Himalayas as a 'Black Snow'. Hundreds of acres of the Himalayas were covered by a black carpet of smoke and soot. This would not only damage the beauty of the Himalayas but also would lead to higher melting of snow due to the higher absorption of solar radiation by the black surface. The Himalayas are the extremely important components of India and is the main mountain system of Asia, the flora and fauna of which may greatly be affected even when exposed to very low concentrations of air pollutants.

4.5 OZONE HOLES

Earth has a protective umbrella in the form of Ozone Layer, of 24km thickness in the stratosphere about 15 km away from earth's surface. The concentration of ozone in this stratospheric ozone layer is about 10ppm compared to 0.05ppm (about 0.0000017%) in the troposphere. Higher ozone concentrations in the troposphere are highly injurious to man and vegetation on earth whereas the stratospheric ozone layer is essential for life to sustain on earth. The ozone layer absorbs the dangerous ultraviolet radiation (especially the UV-B rays with wavelengths from 200 to 280nm) from the sun and converts it to heat and chemical energy. It is this activity that is responsible for the rise in temperature. This layer is not of uniform thickness. Its profile is shaped like that of earth, being highest at equator and lowest at the poles.

In nature, ozone is continuously formed and destroyed through photochemical interaction and an equilibrium in ozone concentrations is ensured. However, this equilibrium is upset due to the discharge of anthropogenic air

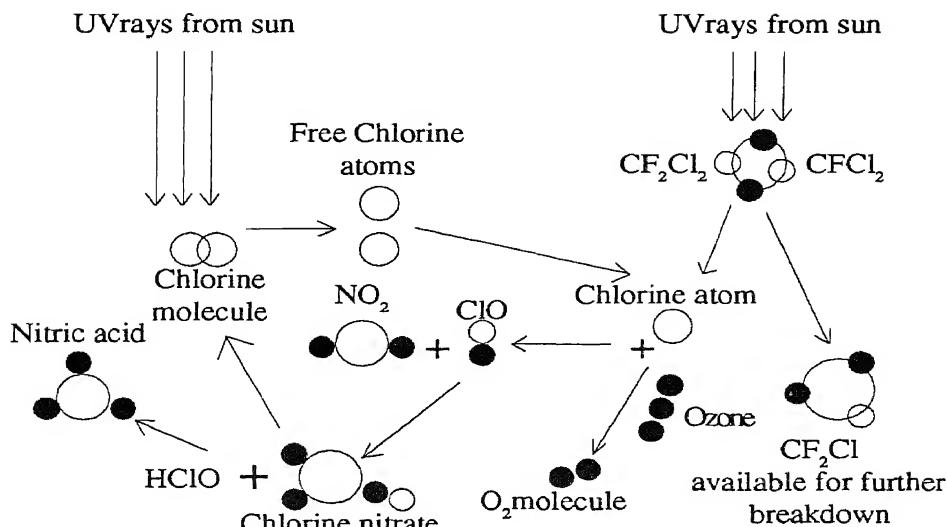


Fig.4.4 Process of Ozone Depletion

pollutants such as CFCs, the chlorofluorocarbons, into the atmosphere. The CFCs release free radicals of chlorine, fluorine or bromine which destroy the stratospheric ozone as a result of which the ozone layer is thinned. The patches of thinned ozone layer are known as "Ozone Holes". By definition the 'ozone hole' represents only a depletion of ozone concentration but not an empty space in the atmosphere. CFCs are the main pollutants responsible for ozone depletion. Their sources and photochemical activity are as follows:

Sources of CFCs

CFCs (chlorofluorocarbons) are a group of synthetic chemicals developed in 1930 by Dr. Thomas Midgley. Since the conception of Freon-12 in 1930, the use of new refrigerants has increased rapidly. These miraculous refrigerants could be traced as the origin of CFCs. The compound CCl_2F_2 is marketed under brand names such as "Freon" and "Genetron". More than three fourth of the world's production of CFCs can be attributed to the United States. The low toxicity, non-inflammability and least chemical reactivity of CFCs made them very popular in being used as refrigerants. CFCs are also used as propellants for dispersing aerosols. In 1940 'DU Point' developed a series of chlorofluorocarbons. The easy handling of CFCs made them popular in almost every field as aero-propellants, cleaning solvent, plastic foams, in fast food packaging, in dry cleaning industries, for sterilizing surgical instruments, in medicinal and oral inhalation products and for cleaning and degreasing electronic equipments. Thus, the demand of CFCs increased

their production at a hefty rate and this reached a staggering figure of about one billion kilograms in 1973. Prior to CFCs, ammonia and sulphurdioxide were used as the refrigerants. They are highly corrosive and toxic and hence their use was very much limited.

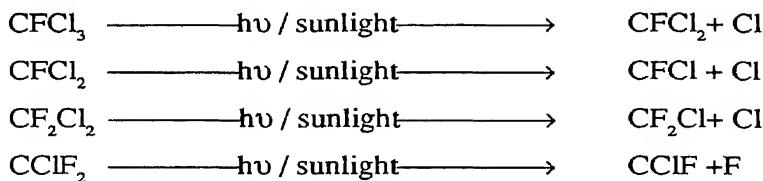
The chief chlorofluorocarbons are:

1. Freon-11, Trichlorofluoromethane (CCl_3F)
2. Freon-12, Dichlorofluoromethane (CCl_2F_2)
3. Freon-22, $\text{CHClF}_2\text{CClF}_2$
4. Freon-114, $\text{CClF}_2\text{CClF}_2$
5. Freon-115, CClF_2CF_3 .

The use of CFCs is of a wide range (as discussed earlier). Freon-11 is used in air conditioning, refrigeration, cleaning foams, aerosols etc. Freon-12 is widely used in aerosols, refrigeration, and sterilization. Freon-22 is used as aerosol-propellants. Freon-113 is mainly used in refrigeration. Freon-114 is used in aerosols, refrigeration, cleaning foams etc. Halons like $\text{CF}_2\text{Br Cl}$ are used in fire extinguishers.

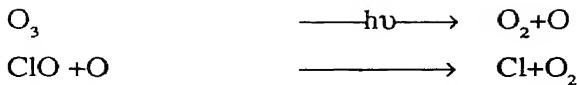
Photochemistry of Ozone Depletion

CFCs and halons are highly stable. However, the UV radiation between 1750 and 2200 \AA present in the stratosphere decomposes them. The chlorine, fluorine or bromine molecules of CFCs and halons are converted into their reactive free radical form by photochemical reactions, as follows:

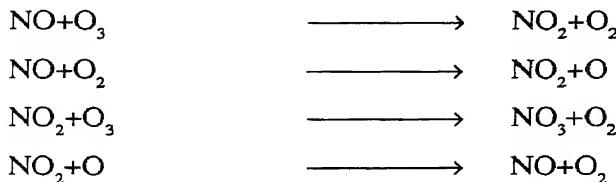


These free F or Cl radicals are released during the reaction in the 'ozone-sphere'. Chlorine is also ejected into the atmosphere by volcanic eruptions and a fraction of it reaches the ozonosphere. Oxides of nitrogen generally inactivate chlorine but the lowering stratosphere temperature changes NO_x into non-reactive nitric acid. Thus Cl or F are free to react with ozone, disintegrating it into O₂+O. Each atom of chlorine can destroy more than 1,00,000 molecules of ozone catalytically, converting O₃ to O₂.





This is more efficient catalytically. The NOx cycle also give the same result.



The above chain reaction takes about 40 years before the full effect is felt. The tiny ice particles during winter favour the conversion of chlorine into chlorinemonoxide, which behaves as a catalytic compound. The total ozone decreases by about 6.5% during the chain, although natural concentration of ozone is maintained by balancing of O_3^- - forming and O_3^- - destroying reactions. But, due to man - made materials, the abundance of chlorine monoxide-rich air in stratosphere continues to rise. This chlorine monoxides reacts with nascent oxygen and free chlorine is formed. Thus the cycle continues destroying the ozone level.

Recently it has been realised that unchecked, uncontrolled use of CFCs can spell an ecological disaster for the world in not too distant a future. Unlike other chemicals, CFCs cannot be removed from the atmosphere by the usual scavenging processes like photodissociation, rainfall, oxidation etc. Recently National Aeronautics and Space Administration (NASA) scientists concluded that CFCs and Halons are the real culprits in depleting ozone layer.

If this ozone layer is depleted, UV rays can travel through the ozone holes easily. Gaseous pollutants such as oxides of nitrogen and CFCs produced due to human activities are capable of bringing about reactions which cause the decomposition of ozone in the upper atmosphere. Supersonic jets and jumbo jets flying in the troposphere exhaust smoke that floats like thin clouds in the air. The CFCs in such clouds react with sunlight to form smog. This raises the temperature of the atmosphere and also causes the thinning of ozone layer.

History of Ozone Layer

When earth was born about 5000 million years ago, there was no ozone layer and UV rays used to reach earth directly. As life is not possible in the presence of strong UV radiations, life in biosphere was limited only to waters 5 to 10m deep where the dangerous UV radiation was cut off and only visible light could penetrate. Yeasts were known to be the first living organisms. Gradually, the photochemical reactions involving different gases in the

atmosphere resulted in the formation of ozone layer. Ozone is present at all altitudes. However the stratospheric ozone only is responsible for the filtration of UV rays. In the absence of Ozone layer the biosphere may turn into a 'blast furnace'.

The first conscious warning to sound the depletion of ozone layer was made by M. Molina and S. Rovland of the University of California, USA in 1974-75. The data through a satellite of USSR launched in 1967 confirmed their prediction. The sharp decline in its level during the sixties was attributed to the release of NOx from nuclear tests carried by USSR, USA and France during that time. A gradual stabilization of ozone layer was observed later which may be attributed to the fact that nuclear tests in air were banned later. In 1971, P.J. Curtzen of USA concluded that NOx released from supersonic transport fleet could reduce stratospheric ozone by 40%.

The British Antarctic Survey Team (BAST) led by Joseph Farman reported 40% loss of ozone layer during spring over Antarctica in 1985. Further research revealed that the ozone level was dropped by 50% from 15th August, 1987 to 7th October, 1987 and that ozone dropped by 100% in some parts literally forming 'ozone holes'.

The World Watch Institute, USA released the first authentic and well documented picture on 'Ozone Holes' in 1988. The first real measurement of an increase in UV radiation due to ozone holes was reported in 1991 by the geophysicists of Chicago University.

Ozone destruction is a function of several parameters. Greatest reductions would occur at distances of above 40km where the atmosphere is photo-chemically active. Ozone destructions also depend on the geographical locations. For example, the approximate ozone reductions are 4% in tropics, 9% in the temperate zones and 14% in the polar regions. The appreciable decrease in rainfall level in the British Island and the increasing draughts in the world indicate that ozone depletion and global warming have taken place in a slow but sure way.

Effects of Ozone Holes

1. The impacts of a depleted ozone layer on humans depend mainly on their reaction to UV-B rays. It is expected that every 1% loss in ozone leads to 2% increase in diseases. The most significant effect on human beings would be an increase in various skin cancers like melanoma which is malignant and can cause death. Two other types of skin cancers that are increasing are basal and squamous-cell carcinomas. These two cancers do not normally kill humans but may cause disfigurement.

2. It may also increase the incidence of cataracts and photokeratitis as UV rays are easily absorbed by the lens and the cornea of eye.
3. UV-B radiations may damage the cell DNA and thus the genetic structure of humans, animals and other organisms and vegetation.
4. Langerhans cells in the epidermis which produce melanin, that plays a key role in the human immune system, are destroyed by the UV rays. As fair-complexioned skin people cannot produce enough melanin, they are easily affected by skin diseases. For them sunbathing may not be a pleasure any more . Exposure to UV-rays is usually associated with burning sensation and skin aging.
5. UV- radiations make the blood vessels carry more blood making the skin hot, swollen or red and cause sun burns .
6. UV-radiation causes leukemia and breast cancers, although the reasons are obscure.
7. Many micro-phytoplankton are highly sensitive to UV-rays and hence may die. This would affect the productivity of zoo planktons, fishes and other marine animals and hence the whole aquatic system.
8. Crop yields, especially tea, cabbage and soybean will be reduced. The various effects on vegetation are reduction in leaf size, poor seed quality, increased susceptibility to weeds and diseases. Plant proteins are excellent absorbers of UV-rays and hence are susceptible to injury associated with chlorophyll reduction and mutation. UV rays may also lead to greater evaporation of surface waters through the stomata of vegetation and hence may decrease the soil-moisture content.
9. Ozone depletion changes the spectral composition of solar electromagnetic radiation. The increased solar UV-radiation activates the green house effect affecting the global energy and radiation balance. Formation of hydrogen peroxide, H_2O_2 , increases due to which acidity of rain or precipitation increases.
10. It was observed that the UV-B radiations may damage even the inanimate materials.

The ozone layer , if not protected, would enormously affect the productivity and stability of eco-systems and the overall environmental equilibrium.

Control of Ozone Depletion

1. More than 80% of ozone depletion may be attributed to the large scale

release of CFCs into the atmosphere. Hence CFCs must first be controlled. There are lot of efforts on earth to decrease the use of CFCs. The 'Montreal Protocol' was a major development in the prevention of the seemingly imminent disaster. There is severe amount of research for alternative technology and substitute chemicals. New techniques have been developed to decrease the leakage of these gases . In Japan success is in the vicinity in finding the alternatives for chlorofluorocarbons. Japanese companies- Mitsubishi Electric and Taiyo Senyo have claimed to have jointly developed an alternative of CFCs. Recently U.S. has developed Bioact FC-7, a successful alternative for Freon-12. Recently U.S. scientists have also discovered bacteria that can eat the main chemicals threatening the ozone layer.

2. The Satellite Research Institute of Frankfort, Germany has developed a method to use hydrogen as a propellant in aerosol sprays which is environmentally friendly and is a safe alternative to CFCs / butane.

After the Montreal Protocol, 'Ozone Treats' was held at London in 1990 and it was decided to totally phase out CFCs and halons by 2000 AD . As majority of Ozone Depletion Substances (ODS) are contributed by the developed countries, they should take the responsibility in mitigating this menace. For example, in India, the per capita consumption of CFCs was 8.8 grams in 1990 and at the most may reach 25 g by 2000 AD whereas the montreal protocol limit was 300gram. The developed countries which are the main contributors of ODS should provide funds for research and development of alternatives to CFCs that are safer, cheaper and have zero ODP (Ozone Depletion Potential). However successful the above research may be, if we want to survive we need to protect the ozone layer by containing ourselves from using CFCs.



CHAPTER - 5

METEOROLOGY AND PLUME DISPERSION

Meteorology means the study of earth's atmosphere. A close relationship exists between air pollution and certain atmospheric conditions like heat, temperature, wind speed and its direction, humidity and precipitation, and it is essential for an environmental engineer to have a thorough understanding of meteorology. Pollutants emanated by various sources into the atmosphere are transported and dispersed by meteorological and topographical conditions. The air borne cycle is initiated with emission of pollutants followed by their transport, diffusion or concentration in the atmosphere and completed by deposition on soil, vegetation, live stock, water surfaces and other objects and these pollutants are finally washed out of the atmosphere by rain or precipitation. In some cases the pollutants may be reinserted into the atmosphere by wind. Many air pollution episodes involved topographical and meteorological conditions that restricted dispersion of air pollutants, causing them to accumulate at harmful levels. In highly urbanised and industrialized areas the pollutants may hasten the deterioration of the buildings and adversely affect men, material and vegetation. Majority of secondary air pollutants like smog are formed due to the interaction of the primary pollutants with the atmospheric constituents. The results of such transformations may not

always be harmful as in the case of the formation of some mineral salts that are necessary for plant life.

However, in large urban areas, pollutants emitted from numerous concentrated sources as well as distributed sources are dispersed over the entire geographical area. Any given location within the urban area receives pollutants from different sources in varying amounts depending upon prevailing winds, presence of tall buildings etc. If the allowable concentration of a selected pollutant at a given location is not to be exceeded, the contributions made by different individual sources must be clearly established.

If the emission rate data for the area is supplied to the dispersion model, maps can be drawn of estimated concentrations of various pollutants throughout the region. If the model is successful, the maps should replicate actual data taken at monitoring stations and can be used to set emission standards for sources so that ambient air quality standards may be met. Such models are important for predicting the influence of new sources on air quality.

5.1 THE ATMOSPHERE

The atmosphere is an insulating blanket protecting the Earth. It softens the intense light and heat of the sun. Its ozone layer acts as a protecting umbrella that absorbs the dangerous ultraviolet rays coming from the sun. The atmosphere is bound to the earth by gravity. Satellites like the moon do not hold an atmosphere owing to their low gravitational power. Without the atmosphere the temperature at the equator would have been 82°C during the day and -140°C at night. It is a reservoir of oxygen needed by animals including man and of carbondioxide essential for plants. Without the atmosphere there would be no sound and no flight. There would be no conventional long distance radio communications, because this is dependent on the electrons in the upper atmosphere. Without atmosphere there would be no lightnings, no thunders, no clouds, no wind, no snow, no fire and no pollution! It is not possible to define the limits of the atmosphere. It becomes progressively thin with increasing distance from the earth. There is no boundary between the atmosphere and the outer space. However 75% of earth's atmosphere lies within 16 km from the surface and 99% of atmosphere below an altitude of 30km. The atmosphere has a total mass of 5.3×10^{18} kg and has an average density of 1.22kg/m³ at sea level. It exerts a pressure of 1 bar i.e. 1 atmosphere i.e. 1.03kg/cm² on every object on earth. It is composed of various gases and water vapour and in its upper most regions, it is charged with subatomic particles. Dry atmosphere surrounding man consists of about 78% nitrogen, 21% oxygen and minor percentages of argon, CO₂, neon, helium, methane etc. There is life only in the troposphere and hence this layer is of great significance in the field of air pollution. The observable universe

has a diameter of about 25 billion light years and the study of air pollution is limited to only about 30kms . The composition of atmosphere is presented in table 5.1 (Concentration in ppm, by vol. = Conc. in% by vol. x 10,000)

TABLE 5.1 COMPOSITION OF ATMOSPHERIC GASES IN DRY AND CLEAN AIR

Gas	Mass of different gases in world atmosphere in Trillions of tonnes	Concentration % by weight	Concentration % by volume
Nitrogen	3900	75.23	78.09
Oxygen	1200	23.14	20.95
Argon	67	1.29	0.93
Water vapour	14	0.27	---
Carbon dioxide	2.5	0.05	0.032
Neon	0.065	0.0012	0.0018
Krypton	0.017	0.0003	0.0001
Methane	0.004	0.000077	0.00015
Helium	0.004	0.000077	0.00052
Ozone	0.003	0.000057	0.000002
Xenon	0.002	0.000038	0.000008
Dinitrogen oxide	0.002	0.000038	0.00002
Carbon monoxide	0.0006	0.000012	0.00001
Hydrogen	0.0002	0.0000038	0.00005
Ammonia	0.00002	0.00000038	0.0000006
Nitrogen dioxide	0.000013	0.00000025	0.0000001
Nitric oxide	0.000005	0.00000013	0.00000006
Sulfur dioxide	0.000002	0.00000008	0.00000002
Hydrogen sulfide	0.000001	0.000000019	0.00000002

5.2 ZONES OF ATMOSPHERE

As we go higher and higher, the character 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 4. Ionosphere or thermosphere. The different zones of atmosphere are shown in figure 5.1

Troposphere: This is the lowest gaseous layer of the atmosphere and extends to a height of about 10 km. from the earth. It contains nearly two-thirds of the total mass of atmosphere and is the region of weather and clouds. In this region, temperature drops with increase in altitude. The familiar saying 'the higher we go, the cooler it is', applies to this region.

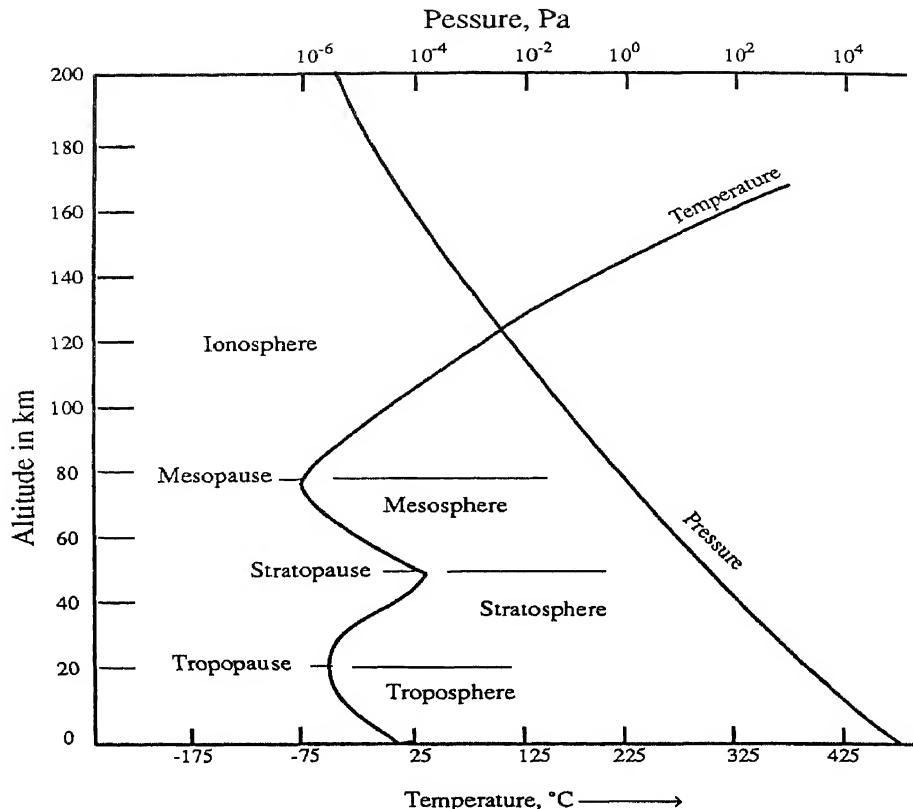


Fig. 5.1 Zones of Atmosphere

Tropopause: This is the layer that joins troposphere with the upper stratospheric layer. The height of tropopause varies with the latitude i.e. highest at the equator (18 km above earth) and lowest at the poles (6km above the earth). In India, the tropopause is generally at a height of around 16km.

Stratosphere: It is a 30km. thick layer that lies above the troposphere. This layer is free from the violent weather changes which occur below. So, it is preferred by the jet liners. In the stratosphere, temperature has a tendency to rise. This is due to the presence of ozone. There are only 8 ozone molecules to a million which are sufficient to keep the temperature rising .

At a height of 25-30 km above the surface within the stratosphere, ozone layer is present. It absorbs ultraviolet radiation from the sun and converts it into heat and chemical energy. Due to this activity, the temperature rises significantly. This layer is not of uniform thickness. Its profile is shaped like

that of the earth, being highest at the equator and lowest at the poles. The amount of ozone on the earth is only a fraction of the quantity in the stratosphere. This is a blessing, because any concentration of ozone beyond certain levels is injurious to life, both plants and animals.

Mesosphere: It is a relatively quite region where few energy releasing reactions occur. Here again the lapse rate is positive i.e. temperature decreases with altitude. In this region ionisation is strong enough to reflect very long radio waves sent up from the surface. This layer and the zones above have no significance in the field of air pollution and its control.

Ionosphere: It is also known as thermosphere because of the very high temperatures prevailing - as much as 870°C over the Equator and 1430°C over the North Pole. Almost all the atoms in this region are ionised, that is, their electrons are stripped off by the sun. Large numbers of free electrons flash about in this area. This makes ionosphere a good conductor. It is the highest and the vastest zone of the atmosphere starting at about 115 km above the earth upto 700km.

The region of atmosphere beyond 700 km. is termed as exosphere and as yet very little is known about it. It is believed to be a low-density, high temperature region with minimum atomic collisions.

5.3 SCALES OF METEOROLOGY

The main parameters that govern the changes in atmosphere are

- ❖ Heat and temperature
- ❖ Pressure and cyclones
- ❖ Wind direction and wind speed
- ❖ Moisture and humidity
- ❖ Rainfall and precipitation.

The interaction of these elements may be observed at different levels or scales. According to their geographic range of influence, the scales of motion are classified as follows :

(A) Macro scale (global or continental movements of air masses eg. continental dust storms, cyclones, winter storms etc.)

(B) Meso scale (regional eg. heat islands and sea breezes)

(C) Micro scale (local eg. pollution from chimneys)

A. Macro scale: It involves the planetary patterns of circulation and the

grand-sweep of air currents over hemispheres. These phenomena occur on a scale of thousands of kilometers and are exemplified by the high and low pressure areas over oceans and continents.

- a. The sun's rays heat the earth near the equator to a greater extent than at the poles. The heated air at the equator would rise and cool air from the poles would move in to take its place.
- b. The movement of the earth also has a profound effect on the air currents deflecting the winds to the right in northern hemisphere and to the left in the southern hemisphere. The effect of the earth's rotation on wind velocity and direction is called the "Coriolis Force", which has the maximum influence on the weather.
- c. The dual influence of thermal convection and coriolic force only cause high and low pressure areas, cold or warm fronts, hurricanes and winter storms. Movements of air masses are also influenced by the distribution of land and water over the surface of the earth. As land has more conductance, atmospheric temperatures over lands rise rapidly in the presence of solar radiation (i.e. during day time) and then drops with equal rapidity during night hours. Conversely, air temperature over water raises slowly and falls more slowly since heat energy received by water penetrates to deeper layers. Also landmass reradiates heat quickly whereas waters do not.

B. Meso scale (Secondary): The influence on the five basic parameters of meteorology is mainly due to the regional topography like location of mountains, oceans and large water bodies, forests and of urban and industrialized areas eg. heat islands, mountain or valley winds; land or sea breezes and some pressure fronts. These phenomena occur on a scale of hundreds of kilometers.

C. Micro scale: The phenomenon is limited to areas of less than 10 km. and is exemplified by dispersion of plumes from industrial stacks. This phenomenon is limited to the 'friction layer'. (The buildings and industries offer significant frictional resistance to winds and cause significant thermal changes in the atmosphere that winds may deviate markedly from a standard pattern. The layer of atmosphere near ground surface where these have effect is called friction layer.) The frictional resistance offered by buildings, trees, bushes or rocks causes mechanical turbulence which influences the air movement. The radiant heat from asphalt streets, buildings, industries and desert sands causes thermal imbalance that can change the pattern of air movements.

5.4 METEOROLOGICAL PARAMETERS

The various meteorological parameters significant in air pollution are:

1. Heat, solar radiation, temperature, environmental lapse rate and atmospheric stability.
2. Wind speed , wind direction and mixing height.
3. Moisture and humidity.
4. Rainfall and precipitation.
5. High and low pressures.

These are discussed in detail as follows :

5.5. HEAT

Heat is the critical atmospheric variable. The heat energy in the atmosphere comes from the sun as short wave radiation ($0.5 \mu\text{m}$), mostly in the form of

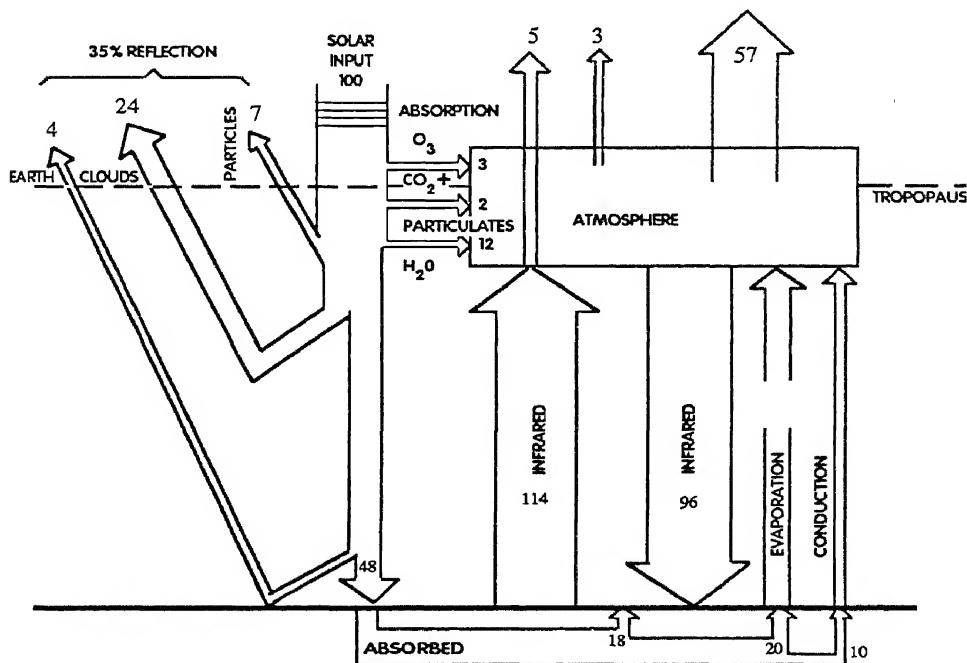


Fig. 5.2 Radiation - Energy Balance

visible light . After striking the earth, it loses energy and reradiates to the space as long-wavelength radiation ($10\text{-}18\mu\text{m}$), mostly in the form of non-visible heat radiation.

Some of the solar rays never reach the earth as they are reflected back to space by individual particles in the air and by clouds. Earth also reflects solar rays. For example, ice, snow and desert sands have a high rate of reflection while forests and cultivated fields have a low rate.

Some of the sun's rays are scattered by particulates. Due to such scattering of different wavelengths only, clear sky appears in deep blue colour. Scattering will be more as the sun approaches the horizon and it is this phenomenon that produces red sunrises and sunsets.

Some of the sun's rays are absorbed by ozone, water vapour, CO_2 , dusts and clouds of the lower atmosphere, but the earth's surface is the prime absorber of solar energy heat. Thus, the troposphere is heated mainly by the earth but not by the sun. The main processes of heat transfer in the troposphere viz. green house effect, the condensation- evaporation cycle, conduction and convection are dealt separately in different chapters. The radiation-energy balance is described in figure 5.2

5.6 WIND

On a macroscale, wind originates due to unequal distribution of atmospheric temperature and pressure over earth's surface and is significantly affected by earth's rotation. The direction is from high pressure to low, but the Coriolis force deflects air currents out of these expected patterns on the meso and micro scales. Topographical features have great significance exemplified by heat islands, sea and land breezes, windward precipitation systems, coastal fog, mountain valley winds, monsoons etc. Up-draft or up-mountain breezes during day time and down-draft during night time are peculiar to mountain valleys. Variance of conductive capacity of land and water accounts for another effect of topography on wind direction causing land and sea-breezes. Due to locally generated mechanical or thermal turbulence, winds are often gusty and changeable in the friction layer. In the friction layer, wind velocity changes as follows:

$$\frac{V_2}{V_1} = Z_2^k / Z_1 \text{ where } V_2 = \text{wind speed at height } Z_2, \text{ m/sec}$$

$$V_1 = \text{wind speed at anemometer level, } Z_1, \text{ m/sec}$$

$$k = \text{coefficient, approximately equal to } 1/7.$$

The wind speed, V_2 at an elevation of Z_2 above ground can also be calculated by the following empirical formulae.

1. SUTTON'S formula: $V_2/V_1 = \{Z_2/Z_1\}^{n/(2-n)}$ where

$n=0.20$ for highly unstable and $n=0.50$ for highly stable atmospheres.

2. SMITH'S formula: $V_2/V_1 = \{Z_2/Z_1\}^n$ where

$n=0.25$ for unstable and $n=0.50$ for stable atmospheres.

Velocity of air is measured by an instrument called anemometer, an instrument consisting of 3 to 4 hemispherical cups arranged around a vertical axis. If wind velocity is more, the cups rotate at a faster rate. When the data for wind speed and direction are placed on 'wind rose' they field a graphical picture of the direction, frequency and velocity of the winds in a particular location.

The velocity determines the travel time of a particulate to the receptor and also the dispersion rate of air contaminants. Typically, if wind speed is 1m/sec and the emission rate is 5 grams/sec, then concentration of pollutant is 5 g/m³. If wind velocity becomes 5 m/sec, concentration will be only 1 g/m³. Thus concentration is inversely proportional to wind velocity. Dispersion is a function of wind speed which is a function of friction forces which depend upon the terrain roughness. Wind speed is zero at surface of earth and raises to a gradient value at a height of 200-500m, depending on the terrain roughness. Wind velocities are normally recorded in open flat country at a height of 10m in meters per second. The horizontal component of velocity of air is called 'wind' and the vertical component is called 'current'. When the wind speed is 0.5m/sec, it is described as complete calm in which smoke rises vertically, when it is about 3.3 m/s, it is described as slight breeze with leaves rustling; when it is 10m/s it may be termed as strong wind with larger branches of trees moving and when it is 15-20m/s it is called gale, and when it is 30-50 m/s it is called hurricane. The Beaufort scale of wind-speed equivalents is presented in Table 5.2

The wind direction can be observed by an instrument called wind vane. The arrow, which turns freely about the vertical axis represents the wind direction. The wind vane is erected at a height of 10m above ground. If the arrow is motionless for 3 minutes, the wind is described as calm. The wind direction may also be noted by letting off bits of paper or by observing the direction of smoke of a cigarette! Directions are grouped into four main categories - North, East, South and West and into 8 or 16 sub categories like

TABLE 5.2 BEAUFORT SCALE OF WIND - SPEED EQUIVALENTS

General Description	Specifications	Limits of velocity 10m above level ground (Miles per Hour)*
Calm	Smoke rises vertically. Direction of wind shown by smoke drift but not by wind vanes.	Under 1 1 to 3
Light	Wind felt on face ; leaves rustle ; ordinary vane moved by wind.	4 to 7
Gentle	Leaves and small twigs in constant motion; wind extends light flag.	8 to 12
Moderate	Raises dust and loose paper ; small branches are moved.	13 to 18
Fresh	Small trees in leaf begin to sway : crested wavelets form on inland waters.	19 to 24
Strong	Large branches in motion : whistling heard in telegraph wires ; umbrellas used with difficulty.	25 to 31
Gale	Whole trees in motion ; inconvenience felt in walking against the wind.	32 to 38
	Breaks twigs of trees; generally impedes progress.	39 to 46
Whole gale	Slight structural damage occurs (chimney pots and slate removed).	47 to 54
	Trees uprooted ; considerable structural damage occurs.	55 to 63
Hurricane	Rarely experienced ; accompanied by widespread damage.	64 to 75 Above 75

* 1 mile / hour = 0.4444 m/sec.

NEW, SEN etc. A Kata thermometer is used to measure very low air velocities of the order of 5 cm/second.

Wind Belts: Wind belts are formed by streams of air moving over the surface of the globe. These movements are caused by differences in atmospheric pressures, which are themselves caused by differences in temperature. The hotter the gas the lighter its density, the colder the gas the higher the density. Thus where the air is warm and ascending low pressure systems are created and where it is cold and descending high pressure areas come into being. As like as, water flows from high altitude to low, air flows from high pressure to low pressure regions. But such a straight flow of air is prevented by the rotation of the earth. As the earth spins west to east, air motions are deflected and assume rather rotatory patterns. In the northern hemisphere, air circles low pressure system in a counter-clockwise rotation and it is the clockwise in high pressure systems. The rotation of air in low pressure system is called cyclonic, and that around high pressure areas, anticyclonic. Cyclonic and anticyclonic winds rotate in opposite direction.

According to the World Meteorological Organisation, jet streams are the winds of thousands of kilometers long, more than 150km wide and few kilometers deep with a minimum speed of 50m/sec. These jet streams originate from the differential temperatures of the polar air and tropical air. When these two systems of air meet, their differing temperatures produce corresponding pressure changes and set the jets in motion. When the difference is the lowest, the wind speed remains at the minimum and the latitudinal area shifts towards the poles and when the difference is very high, wind speeds increase and the jets edge towards the equator.

The main importance of the jet streams are (i) They are the over-all regulators of weather conditions on earth i.e. cyclonic - clouds, rains, and foul weather and anticyclonic, namely fine dry weather (ii) The vertical air motions induced by jet streams cause rapid and incessant churning and mixing of air between the troposphere and stratosphere. This mixing is beneficial in maintaining the chemical composition of the atmosphere uniform over the globe. Thus it dilutes the pollutants thrown up by the modern civilization and distributes to a much wider area. This keeps pollution within tolerable limits and lastly (iii) They control monsoon rains over the entire tropical belt.

Wind Rose: For accurate estimation of the dispersion of pollutants in the atmosphere, a knowledge of the frequency distribution of wind direction as well as wind speed is essential. This type of information varies significantly

from city to city and varies considerably for a given city from month to month. The wind data, i.e. direction, duration and intensity are graphically represented by a diagram called 'wind rose'. The wind data should usually be collected for a period of atleast 5 years and preferably of 10 years, so as to obtain an average data with sufficient accuracy. As far as possible, these observations should be taken at or near the site selected, since the wind conditions may vary considerably with location particularly in hilly regions.

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 the lines. The length of each line is proportional to the frequency of wind from that direction and the frequency of calm conditions is entered in the centre. There are many variations in the construction of wind roses. Some indicate the range of wind speeds from each direction and some relate wind direction with other meteorological conditions.

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, it is necessary to keep in mind, the meteorological convention that wind direction refers to the direction from which the wind is blowing. A line or 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 etc. to represent various wind speeds.

Some times, special wind roses called 'Pollution Roses' are constructed 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 precipitation, smoke, SO_2 , hydrocarbons, particulates etc. instead of wind speed. Wind rose diagrams can be plotted in two types as follows:

Type 1 Wind Rose: This type of wind rose is illustrated in figure 5.15. 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 year during which the wind blows are plotted along the corresponding directions. All the plotted points are then joined by straight lines giving the maximum wind blowing direction. The maximum wind blowing direction is usually along the direction of the longest line on the wind rose diagram. This type of wind rose does not account for the effect of cross wind component.

Type II 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 year during which the wind, having particular intensity, blows from the respective direction. The procedure for plotting the wind rose is described in the solved problem.

5.7 PRESSURE

Electrical storms, location of continents, the differences in surface roughness and radiation, wind energy and global circulation patterns all combine to force development of high and low pressure systems.

High Pressure Systems: They are related to clear skies, light winds and stable atmospheres. Weather changes are gradual and temperature and humidity vary little over great areas. Dispersion of pollutants is restricted and undesirable levels are built.

Low Pressure Systems: They are associated with cloudy skies, gusty winds, atmospheric instability and the formation of fronts. Air pollution problems are minimal as dispersion is good due to unstable atmosphere.

Fronts: When air masses having different properties come together they do not mix easily. Warmer, less dense air tends to over-slide the colder denser air. The zones of transition between two air masses of different densities are called "fronts".

In case of warm fronts, warm air, being lighter, rises over the cold air, and a wide band of precipitation results. The precipitation is heavy in the beginning but decreases as the warm air progresses. When cold air advances on a cell of warmer air, the resulting weather is called 'cold front'. Here, the cold, denser air pushes under the warm air in its path. Typically cold fronts are associated with brief, but intense storms followed by clearing, cooling and a drop in humidity. When the transition zone between warm and cold air does not move one way or the other, it is called 'stationary front'.

Air has a specific weight of about 1.2 kg/m^3 at NTP conditions and hence the whole atmosphere presses down upon the earth beneath it. The absolute pressure of atmosphere can be measured by using a barometer. The atmosphere at a latitude of 45° and at a temperature of 0°C exerts a pressure of 1.03 kg/cm^2 which is equivalent to 1 bar and this pressure is called "ONE STANDARD ATMOSPHERE". Thus Standard Atmospheric Pressure = $1.03\text{kg/cm}^2 = 10.3 \text{ m of water} = 760 \text{ mm Hg} = 1030 \text{ millibars} = 12.88 \text{ m of kerosene}$. Isobars are the lines connecting points of equal atmospheric pressure. These isobars delineate high and low pressure regions that

influence the development of major weather systems. The atmospheric pressure decreases with increase in altitude. At an altitude of about 30 km above MSL the pressure is hardly 10mm of Hg. The pressure increases at the rate of 1 kg/cm^2 i.e. 760mm of Hg for each 10m depth under water below sea level! Pressures cause cyclones. Cyclone is the circulation of air around a core of low pressure. It spins clockwise below the equator and anti-clockwise above the equator. Cyclones have circular speed of about 120 kmph to 400 kmph. A fully developed cyclone may cover an area of 400 to 650 km. They may last for 1 to 30 days. In a single day, a moderately intense cyclone may release as much heat energy of 400 twenty-megaton hydrogen bombs. If converted to electricity, that amount of energy would be sufficient to supply all the electrical needs of India for more than one year!

Between the great trade winds of the north and south lie the Doldrums, a place of calm but not of peace. Here during summer, columns of moisture-laden air rise from the sea. They spiral around a hollow centre which marks the start of cyclone. The distinguishing feature of a cyclone is the eye or the storm centre.

Around the central eye, winds converge in circles. The circular motion of the air around the storm's eye is due to the rotation of the earth, which deflects winds north of the equator to the right and those of the south to the left. Towering clouds build up very high walls around the centre at about 12000m to 15,000 m. The storm's heaviest rainfall, highest speeds and maximum turbulence are concentrated in these cloud walls. The wall clouds themselves are surrounded by active rain bands, which spiral in from the outside towards the centre. It is the latent heat in this moist air that powers a tropical cyclone.

As the winds form, there is a very deep calm - the proverbial calm, before the storm. For perhaps half an hour the calm persists. Then from far away in the sea comes a quiet humming sound. Clouds creep over the sea and spread across the land. They become darker and darker and as the clouds turn pitch black storms lash out at terrific speeds. Torrential rains driven by gusty winds lay waste the land. High waves pummel the shore battering down everything in their way.

The Bay of Bengal in the Indian Ocean is one of the cyclone centres. Bangladesh and the eastern coast of India are hit by cyclones, almost every year. The 1970 cyclone in Bangladesh is the worse on record.

The cyclone damage results from three principal factors: (1) Destructive force of the wind (2) The storm surge or the rise of the water level as the cyclone moves in-land and (3) The floods caused by torrential rains, which can average 6 to 12 inches in a period of 24 hours or less.

5.8 MOISTURE AND HUMIDITY

Humidity is a measure of water vapour in atmosphere. The amount of moisture which air can hold depends on temperature. If the air is cooled, the excessive moisture precipitates for the particular temperature. This is called 'dew point'. Humidity is normally measured as absolute humidity or relative humidity . Absolute humidity is the weight of water vapour in a unit volume of air . It is expressed in grams per kg of air or grams per m³ of air. Relative Humidity is the percentage of moisture present in the air, complete saturation being taken as 100. The greater the RH, the nearer the air to saturation. If RH exceeds 65%, air inside the room feels sticky and uncomfortable. Better ventilation serves to lower such humidity. RH below 30% also is unpleasant. Permanent exposure to such low humidities can cause drying of the nasal mucosa which may predispose to infection, exemplified by sore throat and cough. Dry and wet bulb hygrometers, sling psychrometer and the Assamann psychrometers are the mostly employed instruments for the measurement of humidity.

Humidity or moisture is always present in the atmosphere. The continuous evaporation from water bodies transfers moisture from the earth's surface to the atmosphere. This water vapour condenses and forms clouds which precipitates finally as rain, hail, snow or sleet. Usually coastal regions and areas adjacent to huge water bodies are humid.

Topography has a great impact on humidity. Mountains tend to force the rise of moisture-laden air, resulting in heavier precipitation on the windward side. Humidity acts as a catalyst in the reaction of air pollutants like SO₂, NO₂ and particulates on materials. Moisture indicates the potentiality for fog formation in relation to the degree of air pollution.

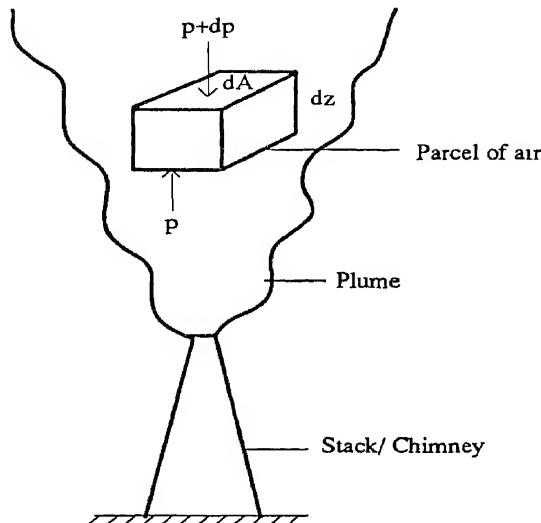
5.9 RAINFALL AND PRECIPITATION

Precipitation has a two-fold cleansing action on the pollutants discharged into the atmosphere. It helps remove the gaseous pollutants that are soluble in water. It also acts as a scrubbing fluid for the removal of gaseous pollutants, air-borne radio-active wastes and particulate matter from the atmosphere. Thus it accelerates the deposition of pollutants on the ground. However, precipitation in the form of fog does not allow the pollutants to disperse easily and brings the pollutants downwards forming a thick blanket that finally sinks onto the ground, leading to very high ground level concentrations. Precipitation can be measured by using various types of rain gauges.

5.10 TEMPERATURE LAPSE RATE

For the static equilibrium of a dry parcel (element) of air of area dA and height dz , released from a chimney, $\sum F = 0$ i.e. Net force acting on the element = 0. If 'w' is the specific weight of air (1.2 kg/m^3) at NTP and if dP is the net elemental pressure acting in the downward direction, then

$$\sum F = 0 \Rightarrow w \cdot dA \cdot dz + dP \cdot dA = 0 \Rightarrow dP = -w \cdot dz \quad \dots \dots \dots (1)$$



(since w is always + ve, pressure decreases with increase in Z , the elevation)

$$\text{Now } PV = RT \text{ or } P = wRT \text{ or } dP = -P/RT \cdot dZ \quad \dots \dots \dots (2)$$

In any atmosphere, $PV^n = \text{constant}$ ($n=1$ for isothermal i.e. constant temperature and $n = 1.4$ for isentropic i.e. constant entropy conditions)

$$\therefore P_1 V_1^n = P_2 V_2^n$$

$$(P_1/P_2)^{1/n} = V_2/V_1 = (RT_2/P_2)/(RT_1/P_1) = P_1 T_2 / P_2 T_1 \quad (\because PV = RT)$$

$$T_2/T_1 = (P_1/P_2)^{(1/n)-1} = (P_2/P_1)^{(-1/n)+1} = (P_2/P_1)^{(n-1)/n}$$

This may be written as,

$$T = T_1 (P/P_1)^{(n-1)/n} \quad \dots \dots \dots (3)$$

$$\therefore dT = T_1 \cdot (n-1)/n \cdot P^{(n-1/n)-1} / P_1^{(n-1)/n} \cdot dP$$

$$\therefore dT/dZ = - (n-1)/nR \quad \dots \dots \quad (\text{Substituting eqn. 2 and eqn. 3 in the above})$$

This dT/dZ is the rate at which the temperature changes with elevation in a dry adiabatic plume and is called 'Dry Adiabatic Lapse Rate, DALR'.

$$\therefore \text{Dry Adiabatic Lapse Rate, DALR} = -0.4/1.4 \times 29.3 \text{ m/}^{\circ}\text{K}$$

$$= -0.01^{\circ}\text{K/m} = -0.01^{\circ}\text{C/m}$$

However in the environment surrounding the plume the lapse rate may be different. This lapse rate is known as 'Environmental Lapse Rate, ELR', which may vary from time to time, and from place to place as shown in figure 5.3.

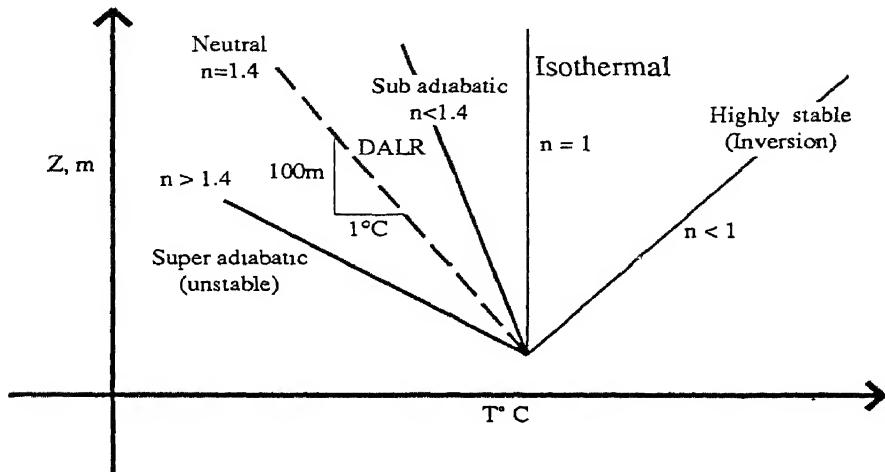


Fig. 5.3 Different Types of Environmental Lapse Rates

Inversion: The rate at which temperature changes with elevation is called lapse rate and is given by $dT/dZ = -(n-1)/nR$. The lapse rate in a dry and adiabatic atmosphere is called DALR and is equal to $-1^{\circ}\text{C}/100\text{ m}$ and such atmosphere is called neutral atmosphere. If dT/dZ is negative it is called inversion. Inversion occurs when $n<1$ i.e. dT/dZ is + ve i.e. when the temperature of atmosphere increases with elevation instead of decreasing. There are different types of inversions as shown in figures 5.4(a),(b) and (c).

1. Radiation Inversion: It occurs usually at night when the earth loses heat by radiation and cools the air in contact with it. If the air is moist and its temperature is very less, fog will form. The cool air stratum is covered by warmer air and the vertical movement of plume is stopped until the sun warms the lower air, next morning. This type of inversion, called RADIATION INVERSION, is common during winter because of the longer nights. Valleys are prone to such radiation inversions due to the restriction of horizontal air movement by surrounding high ground. Due to the simulta-

neous occurrence of fog and high concentrations of mists, such inversions are prolonged as sun rays cannot reach the earth easily. Thus radiation inversion is a phenomenon arising from the unequal cooling rates of earth and the air above the earth. It may extend few hundred meters into the friction layer and is characteristically a nocturnal phenomenon that breaks up easily in the early morning by the sun rays.

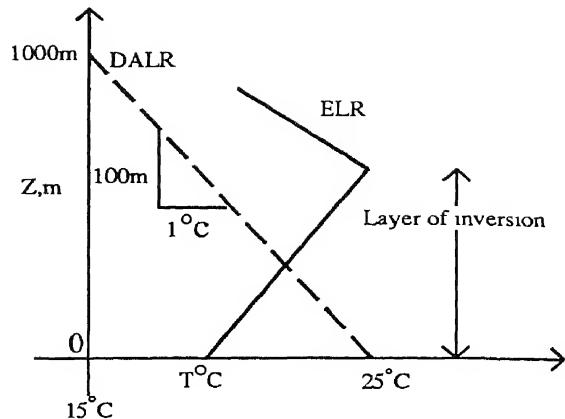


Fig 5.4 (a) Radiation Inversion

Due to longer inversion periods, gases and particulates are easily trapped, creating excess concentrations of pollutants.

2. Subsidence Inversion: It occurs due to a high pressure system. When air circulates around a stationary high, such as a mountain, it descends slowly. At lower elevations the pressure is more and due to this high pressure zone the descended air gets compressed and heated forming a blanket of warm air. Thus a zone of warmer air is trapped between two cooler zones forming 'subsidence inversion'. This warmer layer acts as a lid and prevents

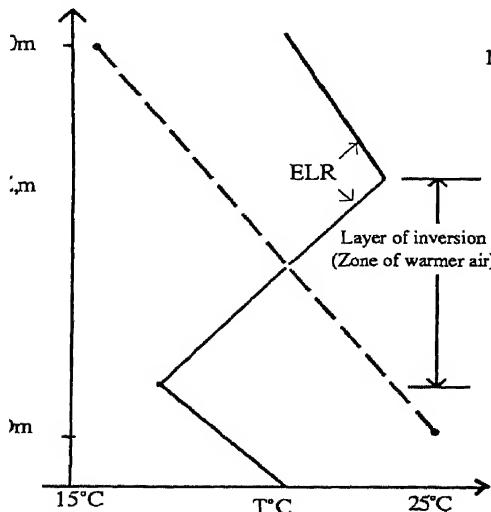


Fig 5.4 (b) Subsidence Inversion

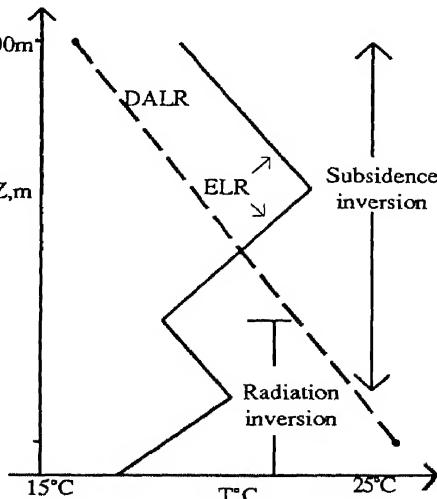


Fig.5.4(c) Double Inversion

the movement of contaminants to the cooler air above. Hills and valleys are prone to such inversions due to restricted air movement . Sea breezes also cause such inversions often. Normally they do not contribute short-term pollution problems but when they occur they remain for 5,6 days continuously, thusby accumulating all the pollutants released into the atmosphere. In the west coast of United States this occurs almost 365 times per year. For most of the Air Pollution Disasters, subsidence inversion was the culprit as such inversions may extend through the friction layer to heights of over 1500m also and when it drops to less than 200m, extreme pollution occurs. Thus the subsidence inversion occurs at modest altitudes due to the sinking or subsiding of air in anticyclones (high pressure areas surrounded by low pressure areas). The circulating air descends slowly at a rate of about 1 km per day and forms a blanket of 'warm layer'. Sometimes a combination of these two inversions occurs and such phenomenon is called 'DOUBLE INVERSION' as shown in fig. 5.4 (c).

5.11 MAXIMUM MIXING DEPTH (MMD)

Once air pollutants are released into the atmosphere their subsequent fate i.e. dispersion is entirely dependent on the weather conditions. The vertical extent to which the mixing takes place varies diurnally, from season to season, and is also affected by topographical features. The greater the vertical extent , the larger the volume of the atmosphere available to dilute the pollutant concentration. Thermal buoyancy effects determine the depth of the convective mixing layer, which is called the Maximum Mixing Depth (MMD). The MMD values available as an average for a period of 1 month are known as Mean Maximum Mixing Depths (MMMD).

When an air parcel is heated by solar radiation at the earth's surface, its temperature rises above that of the surrounding air. After heating, the air parcel will continue to rise within the local atmosphere until its temperature equals the local atmospheric temperature. At that point the air parcel and its surroundings will be in equilibrium and that height defines the limit of the convective mixing layer or the maximum mixing depth. The concept of MMD for different stability conditions is explained in figures 5.5 a, b, c, d.

In practice, the MMD is determined with the aid of the temperature profile of the actual atmosphere for several kilometers above the earth's surface. A balloon is sent aloft and temperature values at various altitudes are transmitted back. These are known as radiosonde measurements and are plotted versus height. A dry adiabatic temperature line, starting at the maximum surface temperature for that month , is also drawn on this plot. The altitude at which this dry adiabatic line intersects the radiosonde measure-

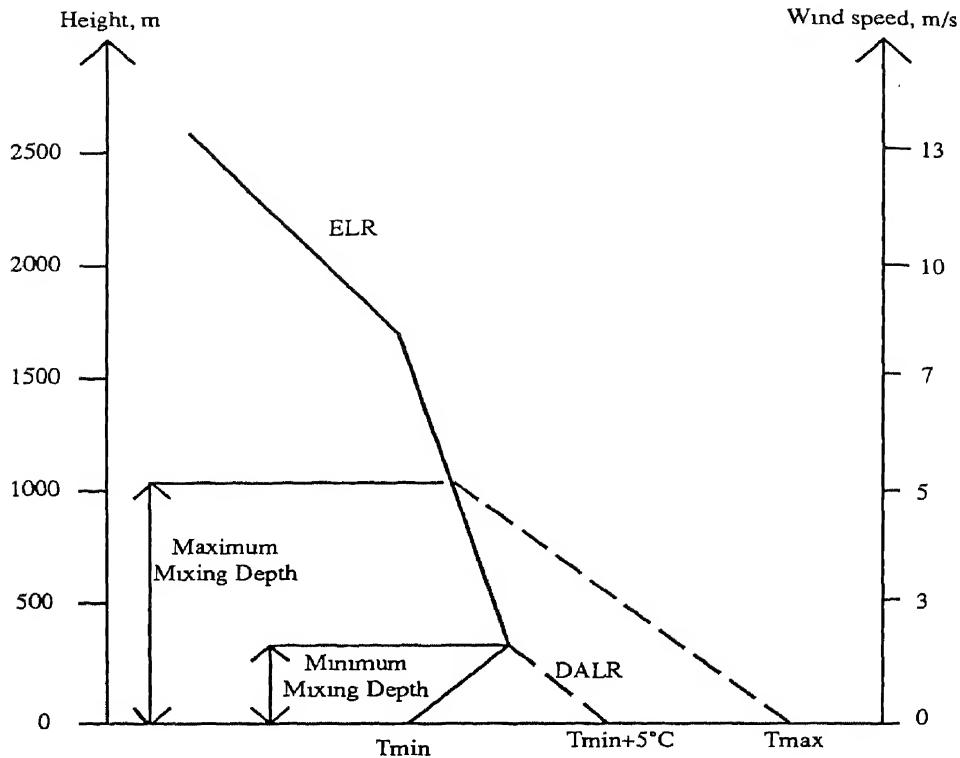


Fig.5.5(a) Computation of Mixing Depth in a Typical Environment

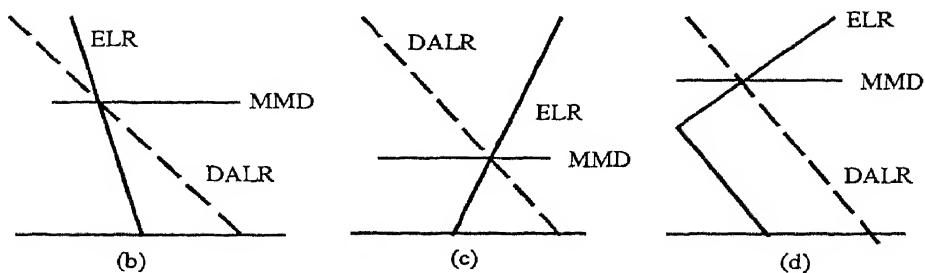


Fig.5.5(b) (c) (d) : Maximum Mixing Depth in Different Environments

ments is taken as the MMD. Temperature sounding data are usually taken at night but morning data are also frequently measured.

The values of the MMD are usually low at night and increase during the day light hours. Under a severe inversion at night, the value may be essentially zero while values upto 2000 and 5000m are common in the day time. On a seasonal basis the mean MMD is at a minimum in the winter (December and January) and at a maximum during the summer (May and June). It has been noted that extensive urban air pollution episodes frequently occur when the MMD value is less than 1500m. Since values less than this are quite common in many urban areas, the potential for air pollution episodes is often high. Before locating an industry, it should be seen that the MMD values are not less than 2000m. On similar lines the minimum mixing depth, which normally occurs before sun rise is obtained by adding 5°C to the minimum surface temperature as shown in figure.

5.12 PLUME BEHAVIOUR

The geometric forms of stack plumes are a function of the vertical temperature and wind profiles; vice versa, by looking at the plume one can state stability condition and the dispersive capacity of atmosphere. The behaviour and dispersion of a plume entirely depend on the environmental lapse rate, ELR. A parcel of air released from a stack into the atmosphere follows the

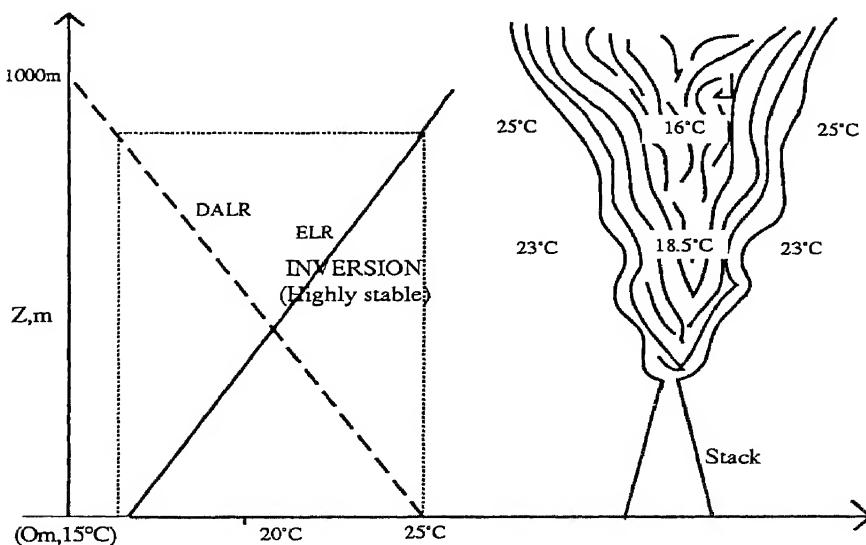


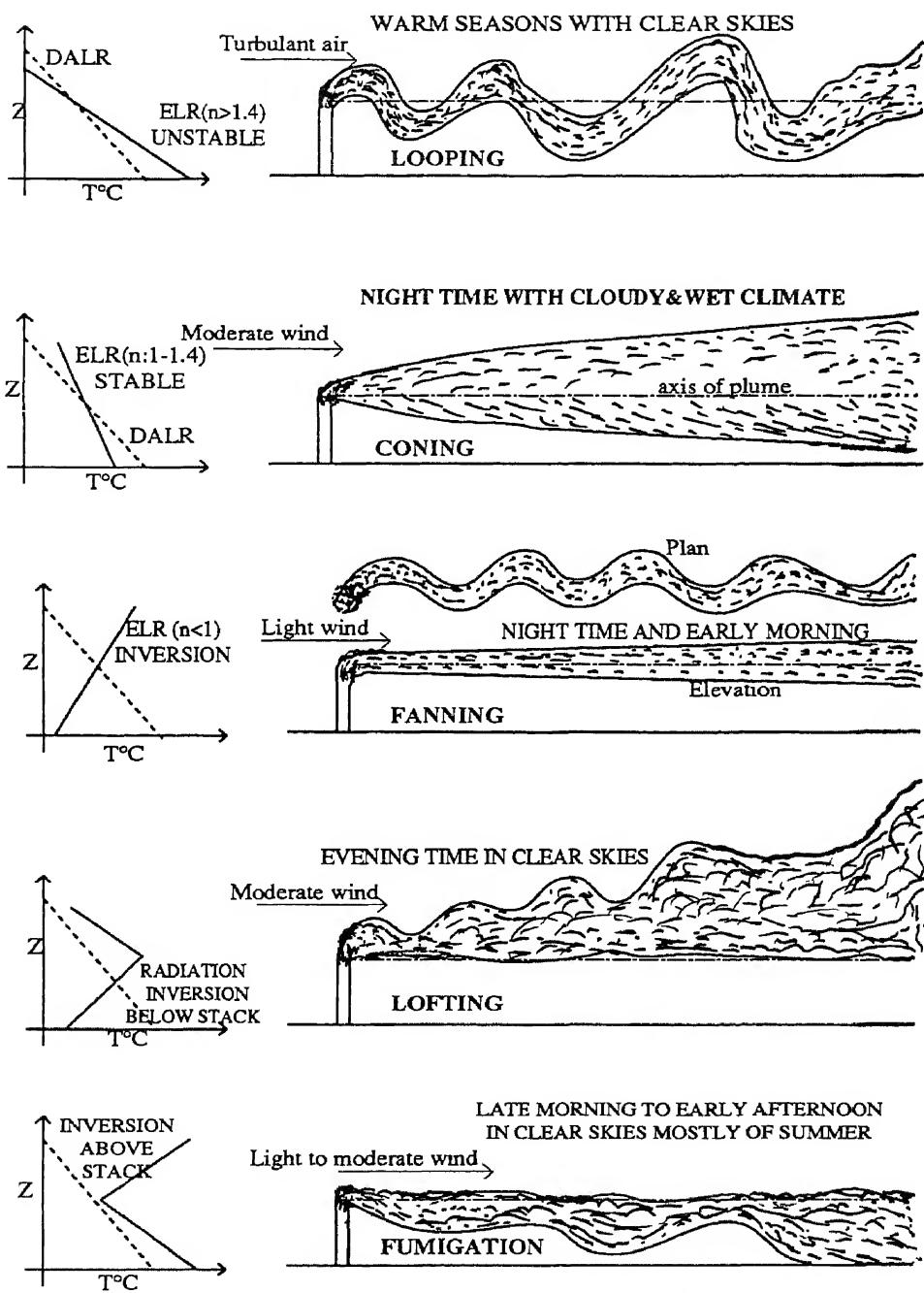
Fig. 5.6 Effect of Inversion on Plume Behaviour

dry adiabatic lapse rate, DALR and attains a temperature of about 16°C , as explained in figure 5.6(depending on surface temperature and altitude). But the surrounding environmental temperature will be about 25°C . Thus the denser parcel of air cannot raise upwards in the warmer and lighter atmosphere. Thus, inversion is the most unfavourable condition for the dispersion of pollutants in atmosphere. Similarly, in superadiabatic atmospheres ($n > 1.4$) the temperature in the environment would decrease at a faster rate of say $1.5^{\circ}\text{C}/100\text{ m}$ whereas the plume temperature would be decreasing at the standard rate of $1^{\circ}\text{C}/100\text{ m}$. Due to this, a plume or parcel of air released from a stack is at a higher temperature than its surrounding environmental temperature. Thus, the parcel of air owing to its lower density is continuously buoyed upwards. Such atmosphere is called unstable atmosphere in which the pollutant dispersion is good and ground level concentrations are less. The plume behaviour is shown in figure 5.7. The plume behaviour in a given environment may be different for stacks of different heights.

Looping: It is associated with turbulent air during warm seasons with clear skies. It occurs under super-adiabatic ($n > 1.4$) conditions and during day time with clear or partly cloudy skies and intense solar heating. In this, irregular loops dissipate in patches and relatively rapidly with distance. It occurs due to light to moderate wind speeds on a hot summer afternoon when large scale thermal eddies are present. These eddies carry portions of the plume to the ground level for short time periods, carrying momentary high surface concentration of pollutant near stack. Though looping occurs in unstable atmospheres which are favourable for thorough mixing, higher stacks may be needed to prevent premature contact with the ground.

Coning: When the ambient lapse rate is sub-adiabatic the atmosphere is neutral (or) slightly stable. Under such conditions, there is limited vertical mixing and the probability of air pollution problems in the area increases. The typical plume in such situation is called coning. The visible plume is cone shaped roughly 10 degrees with a horizontal axis . It dissipates further down wind than a looping plume. In this, small scale mechanical turbulence dominates since the thermal heating effect is much lower than in the case of looping plumes. Coning occurs when skies are overcast during either the day or night with moderate to strong winds. Unlike in looping, in coning, the major part of the pollutant concentration is carried fairly far downwind before reaching ground level in significant amounts. This is an especially good condition for estimating pollutant dispersion by the diffusion models. Dispersion is slower than looping and the pollutant touches at a large distance.

Fanning: A 'fanning plume' occurs in the presence of large negative lapse rates (inversion and isothermal lapse rate), so that a strong surface inversion



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Fanning: A 'fanning plume' occurs in the presence of large negative lapse rates (inversion and isothermal lapse rate), so that a strong surface inversion

takes place at a considerable distance above the stack height. The atmosphere is extremely stable, with very little turbulence and light winds. The typical occurrence of the plume is at night and in early morning conditions when the earth is cooled by outgoing radiation. A fanning plume may appear as a narrow horizontal fan without any vertical spreading for several kilometers downwind. If the effluent is warm, plume rises slowly and then drifts horizontally. The dispersion of plume is very slow, and concentration aloft high at relatively great distance downwind. A small probability of ground contact exists, though turbulence can result in considerable ground contact.

Lofting : 'Lofting' prevails in the late afternoon and early evening under clear skies. In the evening (sun sets) radiation from the surface leads to an inversion layer near ground level. As the inversion layer deepens, a lofting plume will change to a fanning plume. Due to the inversion, adiabatic lapse rate forms at stack top which makes the lower layer stable and the upper layer neutral or unstable. The plume is in the form of loops or cone with well defined bottom and diffuses to top. In the upper layer, the winds are of moderate and considerable turbulence and they have very little influence in the layer below. In lofting, probability of ground contact is small unless inversion layer is shallow. It is considered to be the best condition for dispersion since pollutants are dispersed in upper air with small probability of ground contact.

Fumigation: Fumigation plumes occur when a stable layer of air lies a short distance above the release point of the plume and an unstable air layer lies below the plume. It occurs during changes from inversion to normal condition and also with sea breeze in late morning or early afternoon. It stays temporarily for maximum 30 minutes except in case of sea-breeze conditions, in which case it stays for several hours. The morning sun heats the ground, which in turn leads to the development of a negative temperature gradient from the ground upward. Once the newly formed unstable layer reaches the height of the stack, large concentrations of stack gas will be carried downwind to the surface. The winds are light to moderate aloft and light below, but thermal turbulence is observed in lower layer only. The ground level concentrations are high especially when plume has stagnated aloft. Fumigation is formed usually under clear skies and light winds, and is more prevalent in the summer. It usually starts when a fanning plume breaks up into a looping plume.

Trapping: It occurs in a stable atmosphere, both above and below stack with an unstable atmosphere in between the two inversion layers and can diffuse only in the limited vertical height. It may occur at any time of the day in any season. If associated with subsidence inversion it may persist for months as in Los Angeles and if associated with warm frontal inversions it lasts for less

than a day. It is probably one of the worst pollution situations.

Neutral Plume: It tends to raise directly into the atmosphere until it reaches air of density similar to that of plume itself. It is often converted to coning if wind velocity is greater than 10m/sec and when cloud cover blocks the solar radiation by day and terrestrial radiation by night.

5.13 EFFECT OF TOPOGRAPHY ON POLLUTANT DISPERSION

Geophysical land forms like mountains, valleys, oceans and other large water bodies and continents over which air masses travel have a great effect on weather, meteorological conditions and finally on the dispersion of air pollutants in the atmosphere, as follows:

(A) Effect of Water Bodies on Pollutant Dispersion

During day time land gets heated up by solar rays very easily due to its conductance. The temperature over waters raises very slowly since water does not reradiate solar energy quickly and also since the heat energy received by water penetrates to greater depths. Thus during day time warm air over earth rises upwards and this zone is replaced by colder air over water bodies. This is typically exemplified by the 'Sea Breeze Condition'. This is an example of inversion as temperature increases with elevation. The effect is maximum during afternoons and during summer. The reverse i.e. offshore breeze may also occur during winter nights but the intensity is very less.

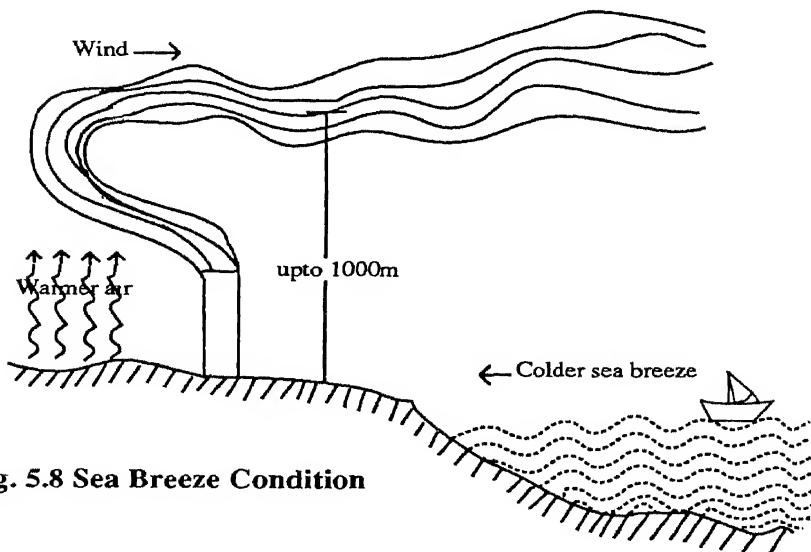


Fig. 5.8 Sea Breeze Condition

(B) Effect of Ridges/Buildings on Plume Dispersion

Both the above cases may cause dense ground level concentrations .

- Solutions:
1. Increase in stack height by 50% or more may be necessary.
 2. Process reduction during unfavourable wind conditions.
 3. Permanent stack cleaning devices.

The problem is more severe in coastal regions. When hills surrounding a coastal area form a basin, an intense pollution problem may be created. The cool air blows inland pushing the air pollutants towards the mountains where they are trapped because the cool air moving over the polluted air acts like a lid that prevents dispersion and dilution. In the presence of fog, smog is formed and this is the perennial air pollution problem of Los Angeles. Similarly taller buildings also interfere with the dispersion of air pollutants. If the height of chimney is less than about 2.5 times the height of surrounding buildings, eddy currents set up by the wind while blowing past the building may engulf the flue gases and bring them quickly to ground levels.

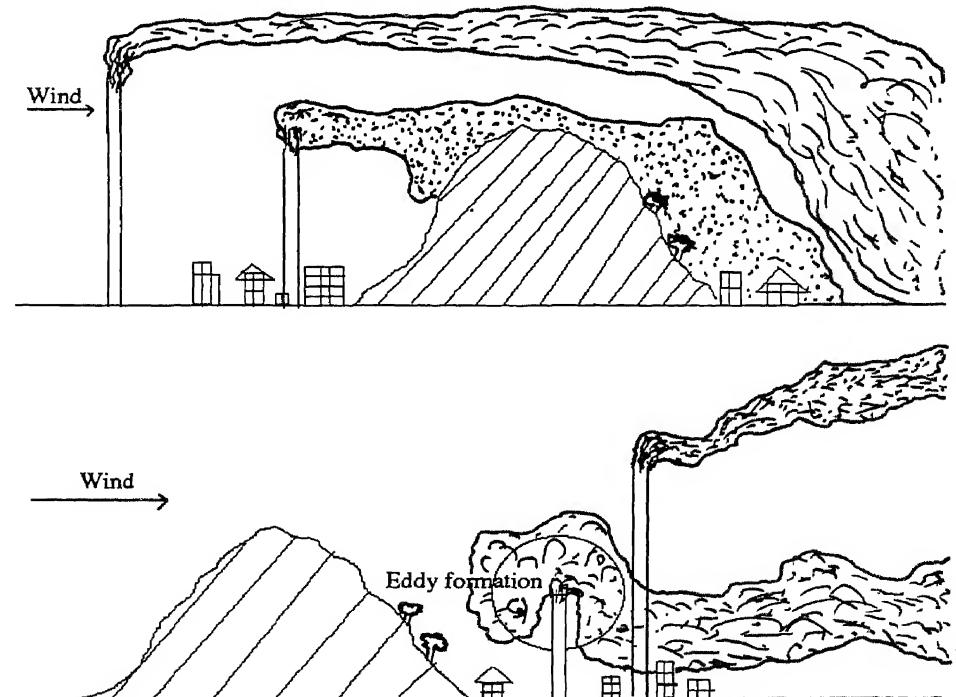


Fig.5.9 Effect of Ridges/Buildings on Dispersion

(C) Effect of Valleys on Pollutant Concentration

A valley tends to channel wind flow along the axis. In valleys, during day time, ground gets heated and warmer air starts ascending both up the valley and along the slopes. Thus the plume from the stack is forced to fan out. The problem is severe during nights when the reverse condition occurs. During nights, the air flows into the valley bringing and depositing the pollutants in the valley leading to high ground level concentrations. When winds are light, the air in the valley becomes stagnant and the problem is acute, especially during winter nights.

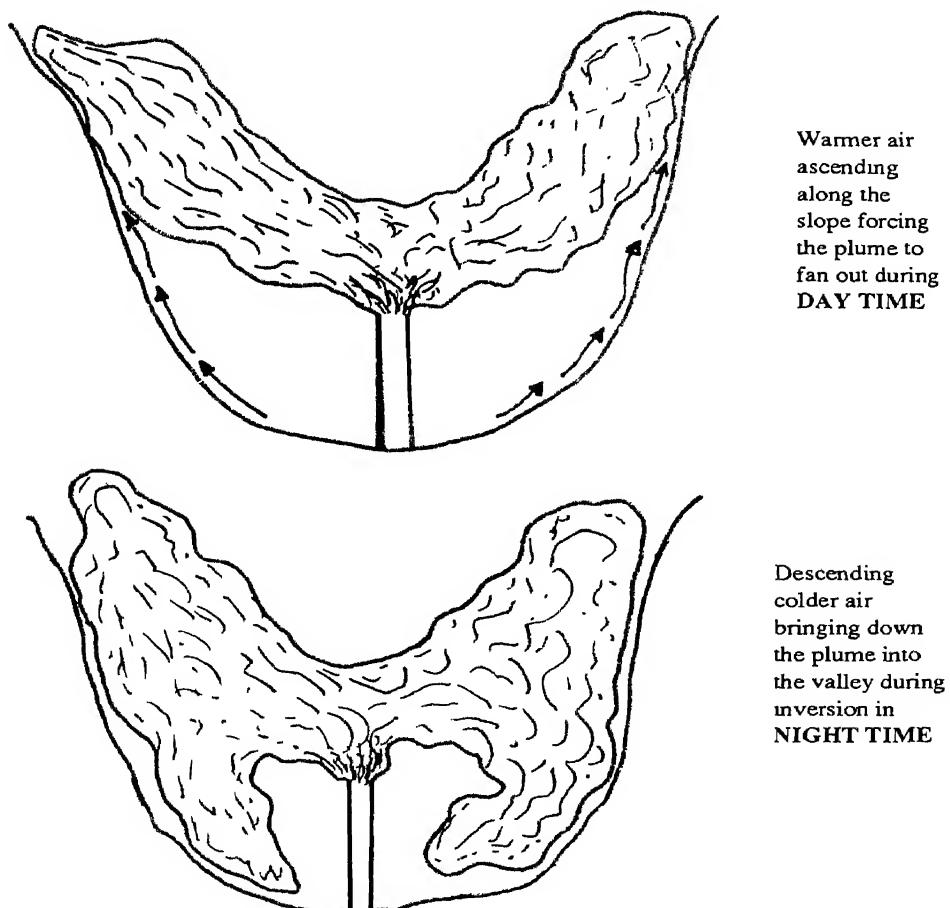


Fig. 5.10 Effect of Valleys on Dispersion

(D) Effect of Terrain Roughness on Dispersion

Pollutant dispersion is a function of wind speed which in turn is a function of friction forces which depend upon the terrain roughness. Wind speed is zero at earth's surface and then rises to a gradient value at a height of few hundred meters. If terrain roughness is more, as in case of urbanised and industrialized areas due to high-rise buildings and industries, the wind velocity profile is steeper and reaches deeper into the atmosphere and as the roughness decreases as in rural areas, the depth of the affected layer is less. Thus, dispersion of pollutants is good in rural areas where maximum wind speed is attained in lesser heights. The wind speed, in general, varies as:

$$U_2/U_1 = (Z_2/Z_1)^n \text{ where } n = 0.25 \text{ for unstable atmospheres and}$$

$$n = 0.50 \text{ for stable atmospheres.}$$

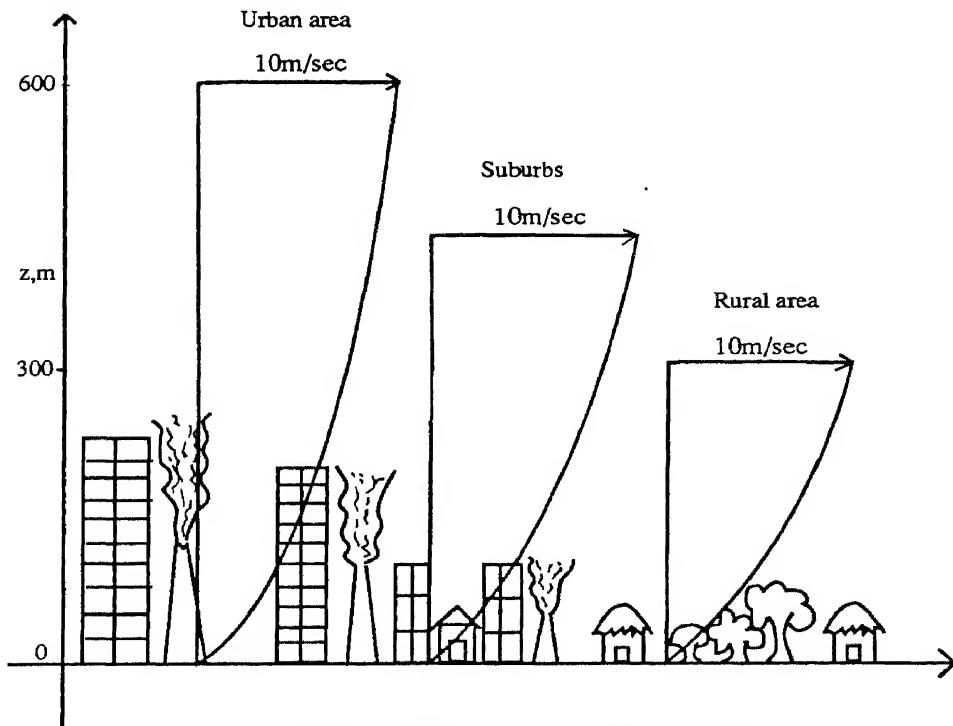


Fig. 5.11 Effect of Terrain Roughness on Dispersion

5.14 EFFECT OF AIR POLLUTANTS ON METEOROLOGY

Meteorology has significance on the dispersions of air pollutants. In a similar way, the air pollutants released into the atmosphere by man also have an impact on the atmosphere. They are :

1. Reduced Visibility: Visibility is a measure of the transparency of the atmosphere. Reduced visibility presents safety hazards and is aesthetically displeasing. Particulates of size 0.38 to 0.76 μm and gas molecules, especially sulphur dioxide, are the major contaminants to reduce visibility. These pollutants absorb and scatter light. Scattering reduces visibility by decreasing contrast between the object and the background sky. Scattering of light by small particles is also responsible for the reddish haze of sunsets.

2. Increase in Precipitation: Small particulates act as nuclei, inducing the formation of raindrops from condensation. Due to massive emission rates of particulates into the atmosphere from urban areas, they are fogger and rainier than their rural surroundings. The occurrence of fog over cities is double the incidence of fog over rural areas. Similarly, cloud formation provides 10% more cover in skies over cities than in those over countryside. High concentrations of SO_2 and NO_2 , increase the formation of fog and photochemical smog and are linked to acid rains.

3. Urban Heat Islands: Refer to 'Global Effects of Air Pollution'.

Thus, these three effects may cause cumulative global effects like increase in earth's ambient temperature, increase in Mean Sea Level etc.

5.15 AIR POLLUTION MODELING

Models give answers to many questions concerning pollution and are an important tool for making decisions concerning air pollution. The fundamental of air pollution modeling is to calculate air concentrations of one or more species in space and time as related to the independent variables such as emissions into the atmosphere, the meteorological variables, and parameters which describe removal and transformation processes. This is achieved by a system which quantitatively relates the concentrations to other parameters by mathematical or physical methods. Such a procedure is called the modeling.

The selection of appropriate model depends upon their use and purpose. Having determined the need for and purpose of a model, it is necessary to consider model attributes. An ideal model should be physically realistic and accurate, suitable for various meteorological and topographical conditions, suitable for various emission sources (point, area, line) and suitable for various air pollution species. But unfortunately such an "Ideal" model does

not exist because some of its features are mutually exclusive. Also, a universal model will not be easy to use and efficient. That is why each model is a compromise between simplicity and sophistication, accuracy and practicality.

Models are developed to address various atmospheric problems. The variety of existing models may be classified according to the different attributes of a model. The models are 1. Eulerian grid model 2. Lagrangian trajectory model and 3. Gaussian plume model.

These models represent deterministic modeling. Such models calculate the concentrations from any emission inventory and other independent, mostly meteorological, variables according to the solution of various equations which represent the relevant physical processes. In most cases, they are solutions of the following assumptions.

The Eulerian grid model employs a coordinate system which is fixed with respect to the ground. The region of interest is sub-divided into a two or three dimensional array of grid cells and the polluted air is simulated as it passes from cell to cell. In principle, the Eulerian grid model is capable of incorporating more physical relations than other model types.

A Lagrangian trajectory model attaches its coordinate system to a fictitious vertical air column, which moves horizontally with the advective wind. That is why the trajectory model is often called the moving cells or moving ordinate model. The Lagrangian model is based on the assumptions of 1. No vertical advection 2. Vertical variability of the horizontal wind is suppressed (i.e. no wind sheer) and 3. The horizontal diffusion term is either highly parameterized or neglected. In general, this model approach has the major advantages like: relatively inexpensive, easy to keep track of pollutant mass balances, no artificial dispersion and individual sources or receptors can be run separately, etc. However, the main disadvantage is that horizontal and vertical diffusion are neglected or highly parameterized and errors can be introduced in interpolating the results.

5.16 GAUSSIAN PLUME MODEL

There are several models available for predicting the concentrations downwind of a single source, but most of them are numerical methods. However, under a set of simplifying assumptions, the analytical closed form solution can be obtained. The first formulation for the steady - state concentration downwind from a continuous point source was presented by Sutton and further developed by Pasquill and Gifford. This solution is commonly known as the Gaussian Plume Model. The concentration distribution perpendicular to the plume axis is assumed to be Gaussian. The plume travels with a

uniform wind velocity (u) downwind from the source.

Gaussian Model (equation) is given by

$$X(x,y,z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \text{Exp}(-y^2/2\sigma_y^2)[\text{Exp}(-(z-H)^2/2\sigma_z^2 + \text{Exp}-(z+H)^2/2\sigma_z^2]$$

$X(x,y,z)$ = Concentration of pollutant at the point (x,y,z) in space g/m³

Q = Source strength i.e. pollutant emission rate, g/sec

u = Horizontal wind speed at the source level (at stack height) m/sec

$H = h + \Delta h$, where h = Physical height of stack, m

Δh = Plume rise, m and

H = Effective stack height, m.

The origin of the coordinate system is $(0,0,0)$ which is the base of the stack/chimney.

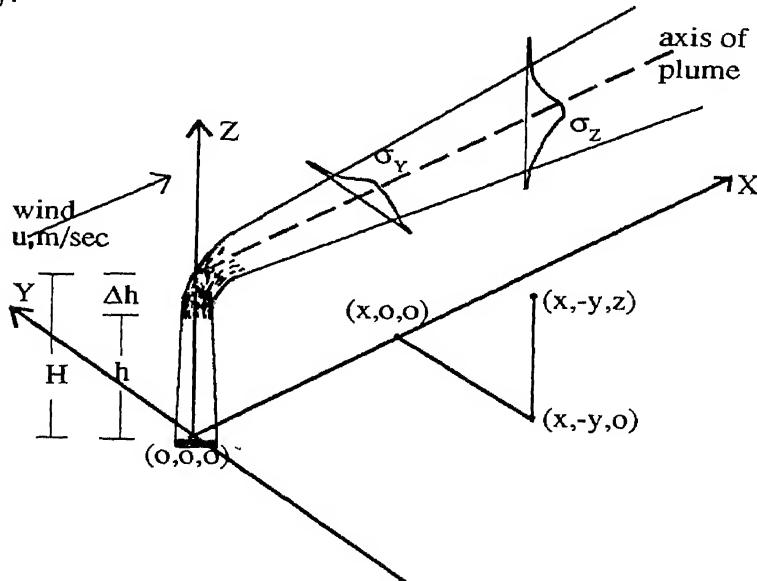


Fig 5.12 Gaussian Plume Model

σ_y and σ_z are the standard deviations of the concentration of the pollutant at 'x' in the horizontal cross-wind and vertical directions respectively. These called dispersion coefficients vary with the time of sampling, the basic time of sampling being one hour. σ_y and σ_z increase with down wind distance, x signifying that the dilution increases with distance. The rate at which σ_y and σ_z increase depends on the wind speed and stability condition of atmosphere. These values are found experimentally and given in the table. The values can be obtained from the graphs also.

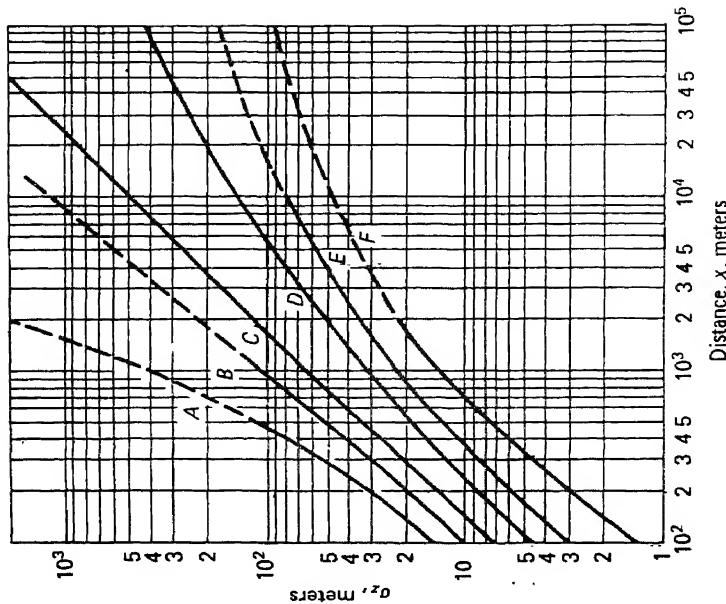


Fig. 5.14 σ_z as a Function of Downwind Distance and Stability

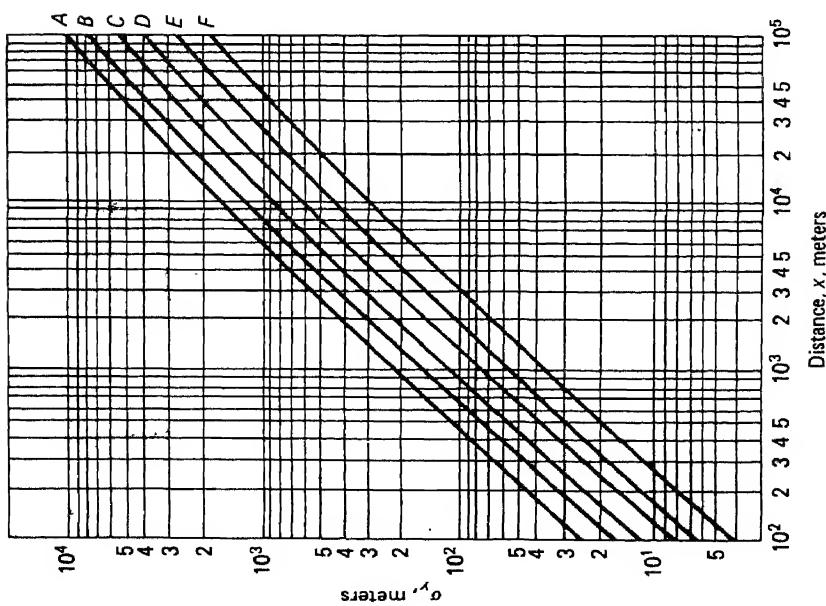


Fig. 5.13 σ_y as a Function of Downwind Distance and Stability

At any point on the ground ($z = 0$), the concentration is given by

$$X(x,y,0) = \frac{Q}{2\pi u \sigma_y \sigma_z} \cdot \frac{\text{Exp}(-y^2/2\sigma_y^2)}{2\text{Exp}(-H^2/2\sigma_z^2)}$$

Differentiating the above w.r.t. downwind distance, x , we get

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

At the point of maximum concentration, assuming $\sigma_y = \sigma_z$, it can be derived that $\sigma_z = H/\sqrt{2}$

In the direction of plume, ground level concentration, G.L.C. first increases and then decreases with the downwind distance, x and is given by

$$X(x,0,0) = \frac{Q}{\pi u \sigma_y \sigma_z} \text{Exp}(-H^2/2\sigma_z^2)$$

Further for ground level source, with no significant plume rise ($H=0$),

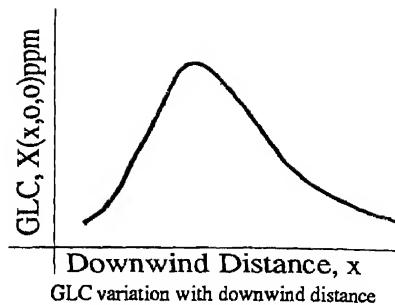
$$X(x,0,0) = \frac{Q}{\pi u \sigma_y \sigma_z}$$

Assumptions

1. The plume has a 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 horizontal crosswind and vertical directions respectively.
2. The mean speed affecting the plume is u , which is the wind speed at the source level i.e. at the point where dispersion starts.
3. Uniform and continuous emission of Q g/sec of pollutant takes place.
4. Diffusion of pollutant in 'x' direction is negligible compared to diffusion in cross-wind direction. This is true if emission is continuous and if wind speed is more than 1m/sec.
5. Total reflection of the plume takes place at the earth's surface i.e. there is no deposition or reaction on the pollutants at the surface. Also the pollutants are inert and passive so that there is no gravity fallout and there are no atmospheric chemical reactions.
6. Parameters governing the diffusion of the pollutant do not change in space and time i.e. steady-state conditions prevail.
7. The terrain underlying the plume is flat.

Limitations

1. It does not consider the existence of various stability layers at different heights in the atmosphere.
2. It does not consider the change in stability characteristics with time.
3. It does not consider the terrain characteristics such as terrain roughness, existence of mountains and valleys, distribution of land and water masses



4. It does not consider the existence of free convection regions and strong wind shears like change of wind directions and change of wind speed with height.
5. It can be applied only for shorter distances (upto 10km) and of shorter travel time (order of 2 hours).

Gaussian plume equation is derived for the sampling time of a few minutes only. If it is necessary to estimate the concentrations from a single source for larger time intervals, the best estimate can be obtained from

$$C_s = C_k \left(t_k / t_s \right)^p \text{ where}$$

C_s = desired concentration estimate for a sampling time, t_s

C_k = concentration estimate for the shorter sampling time, t_k (say 10 minutes) and 'p' is a constant between 0.17 and 0.2. The short-term models are used to calculate concentration for time periods of 30 minutes to one day.

During inversion conditions, diffusion of plume is restricted to a limited layer. The vertical pollutant concentrations of the plume in the mixing layer become uniformly distributed at large downwind distances and are given by:

$$X(x, y, 0) = \frac{Q}{\sqrt{2} \pi \sigma_z L_u} \text{Exp}[-y^2/2\sigma_y^2]$$

where L = height of the mixing layer.

For an infinite line source such as a series of industries located along a river or a harbor or heavy traffic along a long stretch of a national highway the ground-level downwind concentration is given by

$$X(x, 0, 0) = \frac{2q}{\sqrt{2} \pi \sigma_z u \sin \beta} \text{Exp}[-H^2/2\sigma_z^2]$$

where $q = Q/L$ = source strength per unit distance (units/sec.m) and β = angle between wind direction and line source. The above equation should not be used if β is less than 45° . When $\beta = 90^\circ$, the above equation can be simplified ($\sin \beta = 1$).

The ground level concentration from area source is obtained by summing up the concentrations from all elements upwind from the receptor. The equation thus obtained is further simplified by Gifford's "narrow plume hypothesis", which states that spacial distances between variations in area-source emission rate are large compared with horizontal distances. So the cross wind variation in $Q(x, y)$ also may be ignored.

Dispersion Coefficients: Dispersion coefficients (σ_y , σ_z) are defined as parameters which describe the growth of the dimensions of a Gaussian plume as a function of travel distance or travel time and atmospheric stability. They

also depend on the source height and the surface roughness. For estimating the concentration downwind resulting from a continuous plume, the values of dispersion coefficients σ_y , σ_z and wind speed are necessary besides the physical data such as coordinates x,y and z, emission rate Q, effective height H etc. In fact, dispersion coefficients are standard deviations of plume concentration distribution in the cross wind (σ_y) and vertical (σ_z) directions. σ_y and σ_z are a function of downwind position x as well as the atmospheric stability condition. Many experimental measurements in the atmosphere have led to the evaluation and correlation of σ_y and σ_z . There are several sets of charts for estimating the values of these two parameters. Most commonly used method for estimation of plume dispersion coefficients is the empirical method proposed by Pasquill and Gifford and later modified and described by Turner. The widely accepted set of charts is presented in fig. 5.13 and 5.14

However these correlations have some restrictions like:

1. The concentrations estimated from the use of these charts should correspond to sampling time of approximately 10 minutes..
2. The horizontal and vertical deviations are based on a terrain of open, flat grass land.
3. The estimated concentrations more nearly represent only the lowest hundred meters of the atmosphere.
4. Concentration measurements were at downwind distances less than 1km from source.

Turner has also prepared a list of atmospheric conditions which aids in determining six stability classes, A to F. In general, stability classes A to C represent unstable conditions, class 'D' represents nearly neutral conditions and classes E and F represent stable conditions.

While estimating gaseous dispersion from a given source one normally would choose that stability class typical of the region which would lead to the worst possible air pollution episode.

Due to the reduced size of graphs, it is difficult to read σ_y and σ_z values accurately from these graphs. Table 5.2 lists σ_y and σ_z values for the six stability classes for some arbitrarily chosen downwind distances. Some analytical expressions have been derived for dispersion coefficients instead of curves. The most common formulae are given as power functioned .

$$\sigma_y = ax^b \text{ and } \sigma_z = cx^d + f$$

Values for four of the stability dependent constants are given in table 5.3.

Note that the constants are different when x is less than or greater than 1 km. The value of b is always 0.894 and x must be expressed in kilometers.

TABLE 5.2 APPROXIMATE VALUES OF σ_y AND σ_z AS A FUNCTION OF DOWNWIND DISTANCE FOR VARIOUS STABILITY CLASSES IN METERS

Distance (km)	Stability Classes and σ_y Values						Stability Classes and σ_z values					
	A	B	C	D	E	F	A	B	C	D	E	F
0.1	27	19	13	8	6	4	14	11	7	5	4	2
0.2	50	36	23	15	11	8	29	20	14	8	6	4
0.4	94	67	44	29	21	14	72	40	26	15	11	7
0.7	155	112	74	48	36	24	215	73	43	24	17	11
1.0	215	155	105	68	51	34	455	110	61	32	21	14
2.0	390	295	200	130	96	64	1950	230	115	50	34	22
4.0	550	370	245	180	120		500	220	77	49	31	
7.0	880	610	400	300	200		780	360	109	66	39	
10.0	1190	840	550	420	275		1350	510	135	79	46	
20.0	2150	1540	1000	760	500		2900	950	205	110	60	

Source : D.B. Turner, Workbook of Atmospheric dispersion Estimates.
Washington, D.C. HEW, Rev., 1969.

TABLE 5.3 VALUES OF CONSTANTS TO BE USED IN EQUATION AS A FUNCTION OF DOWNWIND DISTANCE AND STABILITY CONDITION

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

Source: D.O.Martin, J. Air Pollution Control Assoc. 26, no. 2(1976):145.

More recently, many research projects have been undertaken to develop a technique that relates diffusion directly to turbulence but are seldom applied in air pollution models. Inspite of their disadvantages arising from accepted assumptions the Gaussian plume models are still the most commonly applied for calculating dispersion of pollutants emanated from point sources. Following are the advantages of the model:

- Much experience has been gained since first model formulations (particularly in the field of estimation of dispersion coefficients, σ_y and σ_z).

- b. Model is easy to understand and use, is efficient with reference to computer running time and the results agree with the experimental data quite well.

5.17 PLUME RISE

Because of the inertial force and the buoyancy, the plume released from a stack rises to a certain height and then gets dispersed by the wind. This height is called 'Plume Rise', Δh . It is a function of exit gas velocity, temperatures of ambient air and stack gas, emission rate, wind speed, atmospheric stability and shear of the wind speed, du/dz .

Plume rise typically increases the effective stack height by a factor of 2 to 10 times and can reduce the maximum ground level concentration of pollutants by a factor of as much as 100.

Most of the formulae available for the computation of plume rise are empirical due to the lack of theoretical formulae. These empirical formulae are mostly in the form :

$$\Delta h = k \cdot Q^\alpha / u^\beta \text{ where}$$

α , β and k are constants and Q is the heat emission rate from the stack. In the CCRL (Canadian Combustion Research Laboratory) equation, the values are: $\alpha = 1/4$, $\beta = 1$ and $k = 66.4$ when Q is expressed in Kcal/sec and u in m/sec. ' k ' is observed to be a function of the height of the source of emission. The plume rise is due to momentum and buoyancy and may be given as,

Plume Rise, $\Delta h = \Delta h_{\text{buoyancy}} + \Delta h_{\text{momentum}}$

As per Moses and Carson,

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

Q_H = Heat emission rate, K cal/sec and

C_1 and C_2 are plume rise regression coefficients which depend on the atmospheric stability.

Thus, as per the above equation, plume rise is inversely proportional to wind speed, directly proportional to the emission rate and the square root of the heat content of the gas. Almost all these formulae contain atleast one constant which must be evaluated experimentally.

Formulae for computation of plume rise:

1. Rupp's Formula : $\Delta h = 1.5 \times V_s / u \times D$

2. Brigg's Formula : $\Delta h = 3.0 \times V_s / u \times D$

3. Smith's Formula : $\Delta h = (Vs/u)^{1/4} D$, where

V_s = stack gas velocity, m/sec

u = mean wind speed, m/sec

D = inner diameter of the stack at exit, m.

(These three empirical formulae do not consider the 'buoyant force' and hence are applicable only for plumes of low temperature).

4. Davidson and Bryant Formula : $\Delta h = (Vs/u)^{1/4} \left(1 + \frac{T_s - T_a}{T_s}\right)$

5. Holland's Equation:

$$\Delta h = Vs \cdot d / u [1.5 + 2.68 p \left(\frac{T_s - T_a}{T_s}\right) d] \text{ where}$$

V_s = Stack gas exit velocity, m/sec.

d = Inner diameter of the stack at exit, m

u = Wind speed, m/sec

p = Atmospheric pressure in kg/cm² (at N.T.P, $p = 1.03$ kg/cm²)

T_a and T_s are the absolute temperatures of the ambient air and stack gas respectively, °K and 2.68 is a factor with units of cm²/kg.m

6. The Bureau of Indian Standards has suggested that the following Brigg's formula be used for the computation of plume rise (IS :8829).

a) For effluents with heat release of $> 10^6$ cal/sec.

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

b) For effluents with lesser heat contents i.e. for effluents with momentum as the dominant contributor, $\Delta h = 3W_oD/u$

where,

Q_H = Heat release rate, calories/sec

W_o = Efflux velocity, m/sec and

D = Inner diameter of stack at exit, m

It should be stated that these plume rise formulae may not be recommended for tall chimneys of height in excess of 300 m.

5.18 MINIMUM STACK HEIGHT

If the physical height of the stack is more, the effective stack height also will be more and a better dispersion is possible. Smaller stacks lead to higher ground level concentrations, the maximum concentration is usually inversely proportional to the square of the effective stack height . According

to the Bureau of Indian Standards (Central Board for Prevention and Control of Water Pollution, New Delhi) a minimum stack height of 30m is to be provided. The minimum stack height, H_{min} be arrived at by using the following formulae:

$$(i) H_{min} = 30m$$

$$(ii) H_{min} = 74 Q^{0.27} \text{ where } Q \text{ is particulate emission rate in tonnes per hour}$$

$$(iii) H_{min} = 14 Q^{0.3} \text{ where } Q \text{ is } SO_2 \text{ emission rate in kg/hour.}$$

The physical height of stack to be provided is the maximum of the three H_{min} values obtained.

A minimum stack height of about 2.5 times the height of the surrounding building would prevent the formation of eddies and reduce the maximum ground level concentrations. Usually, the maximum ground level concentration occurs downwind at a distance of about 10 chimney heights from the base of the chimney. Thus increasing stack height would reduce appreciably the concentrations of pollutants at places within about ten chimney heights only while there will not be significant changes in concentrations at larger distances.

If the maximum ground level concentration of a pollutant should not exceed $X \text{ mg/m}^3$ then the minimum effective stack height, H required is

$$H = (2.71 Q / uX)^{1/2} \text{ where } Q = \text{pollutant emission rate in kg/day.}$$

Problem 1 : An anemometer measures a wind speed of 5m/sec at a height of 10m above ground. Find the wind speed at a height of 150m if the change in temperature is (a) $-15^\circ\text{C}/1000\text{m}$ and (b) $+5^\circ\text{C}/1000\text{m}$.

Answer : The wind speed V_2 at elevation, Z_2 is given by Smith's formula as:

$$V_2/V_1 = (Z_2/Z_1)^n$$

a.) Since lapse rate is $-15^\circ\text{C}/1000\text{m}$ i.e. $-1.5^\circ\text{C}/100\text{m}$, the environmental lapse rate is super-adiabatic i.e. unstable atmosphere.

$$\therefore n = 0.25 \quad \therefore V_2 = 5 \text{ m/sec } (150/10)^{0.25} = 9.84 \text{ m/sec}$$

b.) As the lapse rate is $+5^\circ\text{C}/1000\text{m}$, it represents inversion that is highly stable atmosphere $\therefore n = 0.50 \quad \therefore V_2 = 5 \text{ m/sec } (150/10)^{0.5} = 19.36 \text{ m/sec.}$

Problem 2 : Find the effective stack height if a 40 m stack releases SPM at a rate of 1.25 grams / sec. The atmospheric pressure is 10.8 m of water. The temperatures of ambient air and gas are 27°C and 400°C . The stack diameter is 2.3 m. Stack gas velocity is 6.0m/sec and the wind velocity is 1.8 m/sec.

Also find the ground level concentrations at 1 km, 5 km and 10 km distances in the direction of wind.

Answer:

Applying Holland's equation,

$$\Delta h = V_s \cdot d / u [1.5 + 2.68 p (T_s - T_a / T_s) d] \text{ Where}$$

$$V_s = 6.0 \text{ m/sec; } d = 2.3 \text{ m; } u = 1.8 \text{ m/sec}$$

$$p = \text{Atmospheric pressure} = 10.8 \text{ m of water} = 1.08 \text{ kg/cm}^2$$

$$T_s = 400^\circ\text{C} = 673^\circ\text{K}; T_a = 27^\circ\text{C} = 300^\circ\text{K}$$

$$\Delta h = 6 \times \frac{2.3}{1.8} [1.5 + 2.68 \times 1.08 (673 - 300 / 673) \times 2.3] = 39.78 \text{ m}$$

$$\therefore \text{Effective Stack Height, } H = h + \Delta h = 40 + 39.78 = 79.78 \text{ m}$$

The values of σ_y and σ_z for various stability conditions are as follows:

Moderately Stable Conditions (condition F)

x, km	1	2	3	4	5	6	7	8	9	10
σ_y	4	133	180	275	300	325	400	450	490	510
σ_z	30	50	65	85	95	105	115	125	135	150

Highly Unstable Conditions (condition A)

x, km	1	2	5	10
σ_y	200	400	900	1500
σ_z	600	3500	∞	∞

Assuming conditions for poor dispersion i.e. stable atmosphere,

$$X(1,0,0) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp[-\frac{1}{2} (H/\sigma_z)^2] = \frac{1.25}{\pi x 1.8 \times 4 \times 30} \exp(-\frac{1}{2} (79.8/30)^2) \\ = 5.36 \times 10^{-5} \text{ g/m}^3 = 53.6 \mu\text{g/m}^3$$

$$X(5,0,0) = \frac{1.25}{\pi x 1.8 \times 300 \times 95} \exp[-\frac{1}{2} (79.8/95)^2] = 5.45 \times 10^{-6} \text{ g/m}^3 \\ = 5.45 \mu\text{g/m}^3$$

$$X(10,0,0) = \frac{1.25}{\pi x 1.8 \times 570 \times 150} \exp[-\frac{1}{2} (79.8/150)^2] = 2.25 \times 10^{-6} \text{ g/m}^3 \\ = 2.25 \mu\text{g/m}^3$$

Problem 3

A stack of height 50m releases 450mg/sec of SO_2 with a velocity of 4.9m/sec in summer. The stack diameter is 1.5m. The stack gas temperature is 300°C .

Atmospheric pressure is 1005 millibars and wind speed is 1.833 m/sec. Find G.L.C. at different points downwind.

Answer :

$$\text{Plume Rise, } \Delta h = V_s d / u [1.5 + 2.68 p d (T_s - T_a / T_s)]$$

$$V_s = 4.9 \text{ m/sec; } d = 1.5 \text{ m; } u = 1.833 \text{ m/sec}$$

$$P = \text{atmospheric pressure} = 1005 \text{ millibars} = 1.005 \text{ bars} = 1.005 \text{ kg/cm}^2$$

Assuming an ambient temperature of 37°C (being summer) $T_a = 310^\circ \text{K}$

$$\therefore \Delta h = \frac{4.9 \times 1.5}{1.833} [1.5 + 2.68 \times 1.005 \times 1.5 (573 - 310 / 573)] = 13.45 \text{ m}$$

$$\therefore \text{Effective stack height, } H = h + \Delta h = 50 + 13.45 = 63.45 \text{ m}$$

$$X(x, o, o) = \frac{Q}{\pi u \sigma_y \sigma_z} \exp[-\frac{1}{2} (H/\sigma_z)^2]$$

$$\therefore X(1, 0, 0) = 0.450 / \pi \times 1.833 \times 4 \times 30 \times \exp[-\frac{1}{2} (63.45/95)^2] \\ = 6.956 \times 10^{-5} \text{ g/m}^3.$$

$$X(2, 0, 0) = 0.450 / \pi \times 1.833 \times 133 \times 50 \times \exp[-\frac{1}{2} (63.45/50)^2] \\ = 5.25 \times 10^{-6} \text{ g/m}^3$$

$$X(5, 0, 0) = 0.450 / \pi \times 1.833 \times 300 \times 95 \times \exp[-\frac{1}{2} (63.45/95)^2] \\ = 2.194 \times 10^{-6} \text{ g/m}^3$$

$$X(10, 0, 0) = 0.450 / \pi \times 1.833 \times 510 \times 150 \times \exp[-\frac{1}{2} (63.45/150)^2] \\ = 9.34 \times 10^{-7} \text{ g/m}^3$$

Problem 4

A 100m stack of diameter 5m releases a gas at 13.5 m/sec, with a temperature of 145°C. Calculate the plume rise assuming a wind speed at stack height of 4m/sec and an ambient temperature of 15°C if the environmental lapse rate is a) 1.5°C / 100 m b) 0.5°C / 100m.

Answer:

$$\Delta h = 150 F/u^3 \text{ for unstable and neutral atmospheres and}$$

$$\Delta h = 5 F^{1/4} / S^{3/8} \text{ for stable atmospheres, where}$$

$$F = g V_s (T_s - T_a / T_s) \times d^2 / 4 \text{ and}$$

$$S = g / T_a [(dT / dZ) - (dT/dZ) \text{ adiabatic}] \text{ i.e. } g/T_a [\text{ELR} - \text{DALR}]$$

$$V_s = \text{Stack gas exit velocity, m/sec}$$

T_a and T_s are temperatures of ambient air and stack gas respectively, °K.

d = inner diameter of stack, m

$$\therefore F = 9.81 \times 13.5 [418 - 288 / 288] \times 5^2 / 4 = 375 \text{ m}^4 / \text{sec}^3$$

$$S = 9.81 / 288 [(0.5^\circ\text{C}/100 \text{ m}) - (1^\circ\text{C}/100 \text{ m})] = 0.000511/\text{sec}^2$$

a) (dT/dZ) adiabatic = DALR i.e. Dry Adiabatic Lapse Rate = - 1°C/100m.

However, the environmental lapse rate, ELR is -1.5°C/100m i.e. the atmosphere is super-adiabatic or unstable.

$$\therefore \Delta h = 150 F / u^3 = 150 \times 375 \text{ m}^4 / \text{sec}^3 \div 4^3 \text{ m}^3 / \text{sec}^3 = 878 \text{ m}$$

b) Since, ELR = +0.5°C/100m, the atmosphere is highly stable and the condition is 'Inversion'.

$$\therefore \Delta h = 5F^{1/4}/S^{3/8} = 5 \times 375^{1/4} (0.000511)^{3/8} = 377 \text{ m.}$$

Problem 5

Compute the plume rise for the stack in problem 2, using Davidson and Bryant formula.

Answer

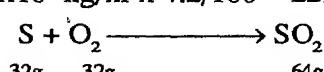
$$\begin{aligned} \text{Plume Rise, } \Delta h &= D (V_s/u)^{1.4} (1+T_s-T_a/T_s) \\ &= 2.3 (6.0/1.8)^{1.4} (1+673-300/673) = 19.29 \text{ m} \end{aligned}$$

Problem 6

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/sec. The atmosphere is slightly to moderately stable. Find a) Maximum G.L.C. and the corresponding distance b) G.L.C. at 3km downwind and 0.4 km cross wind distance.

Answer

$$\text{Sulphur emission} = 5.45 \times 10^3 \text{ kg/hr} \times 4.2/100 = 229 \text{ kg/hr.}$$



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

$$\text{SO}_2 \text{ emission rate} = 229 \times 64 / 32$$

$$= 458 \text{ kg/hr}$$

$$= 127 \text{ grams/sec.}$$

a) Maximum GLC occurs when $\sigma z = 0.707 H$, provided $\sigma z/\sigma y$ ratio is a constant with downwind distance. For the moderately stable class i.e. for class 'C', $\sigma z/\sigma y$ is constant upto a distance of 1km.

$$\text{Now } \therefore H = 75\text{m}, \sigma z = 0.707 \times 75 = 53\text{m}$$

The corresponding distance is 850m and the corresponding $\sigma y = 88$

$$\therefore \text{max GLC} = 127/\pi \times 6 \times 53 \times 88 \times \exp[-1/2(75/53)^2] = 5.31 \times 10^{-4} \text{ g/m}^3$$

b) At 3km distance, $\sigma z = 170$ and $\sigma y = 280$

(to be taken from graph)

$$\begin{aligned} \text{a) } X_{(3\text{km}, 0, 0)} &= 127/\pi \times 6 \times 170 \times 280 \times \exp[-\frac{1}{2}(75/170)^2] \\ &= 1.28 \times 10^{-4} \text{ g/m}^3 = 128 \mu\text{g/m}^3 \end{aligned}$$

$$\begin{aligned} \text{b) } X_{(3000, 400, 0)} &= \frac{Q}{\pi u \sigma y \sigma z} \exp[-\frac{1}{2}(y/\sigma y)^2] \exp[-\frac{1}{2}(H/\sigma z)^2] \\ &= \frac{127}{6\pi \times 280 \times 170} \exp[-\frac{1}{2}(400/280)^2] \exp[-\frac{1}{2}(75/170)^2] \\ &= 4.62 \times 10^{-5} \text{ g/m}^3 = 46.2 \mu\text{g/m}^3 \end{aligned}$$

Problem 7

A thermal power plant burns 100 tonnes 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.

Answer

$$\text{SO}_2 \text{ release/day} = 100 \times 1000 \text{ kg/day} \times 5.5/100 \times 64/32 = 11,000 \text{ kg/day}$$

$$\text{SO}_2 \text{ release/hr} = 458.3 \text{ kg/hr}$$

Minimum stack height required, as per CPCB (Central Pollution Control Board) of India,

$$= H = 14 \times Q^{0.3} = 14 \times 458.3^{0.3} = 87.99 \text{ m say 88m}$$

Similarly, particulate emission rate

$$= 20 \times 3600 \text{ m}^3/\text{hr} \times 8 \text{ g/m}^3 = 576 \times 10^3 \text{ g/hr} = 0.576 \text{ tonnes/hour}$$

$$H_{\min}, \text{ based on particulate emission} = 74 Q^{0.27}$$

$$= 74 \times 0.576^{0.27} = 63.76 \text{ m}$$

The minimum stack height to be provided is the maximum of 30m, 88m and 63.76m ie. 88m.

Problem : 8 Draw wind rose diagram for the following data :

Wind Direction	Duration of wind, percent		
	6.4-25 kmph	25-40 kmph	40-60 kmph
N	7.4	2.7	0.2
NNE	5.7	2.1	0.3
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
SSW	6.3	3.2	0.5
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

Answer

Total wind duration in a particular direction in percent are : N: 10.3, NNE 8.1, NE 3.9, ENE 1.8, E 1.0, ESE 0.4, SE 7.1, SSE 8.7, S 14.3, SSW 10.0, SW 5.7, WSW 1.6, W 0.5, WNW 0.3, NW 7.2, NNW 5.6, the gross total of which is 86.5 percent.

Therefore percentage of time during which wind speed is less than 6.4 kmph 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 percent. 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 5.15. This type of wind rose does not account for the effect of cross wind component.

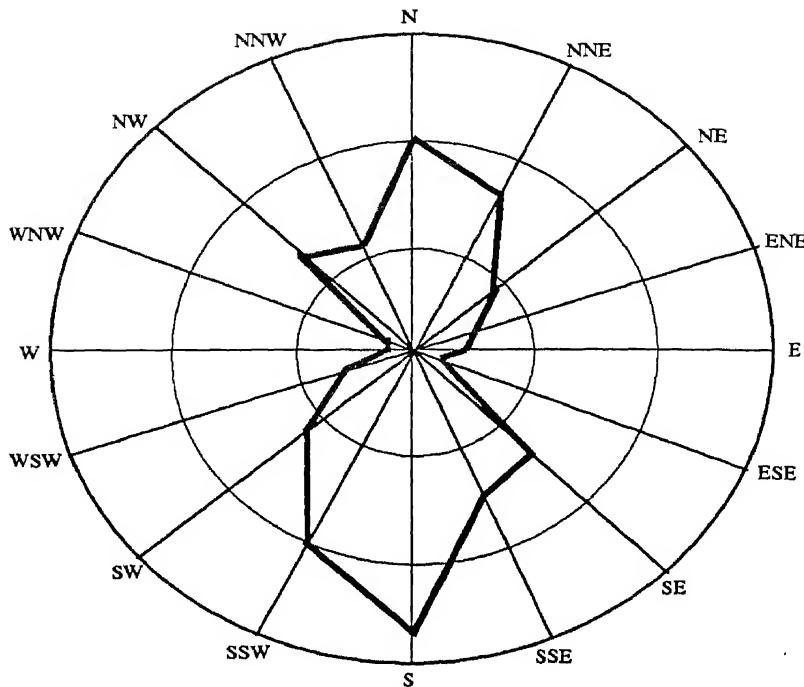


Fig. 5.15 Wind Rose Diagram

Problem 9 : The traffic density along a straight national highway is 4000 vehicles/hour and the average speed is 50 KMPH. The average vehicle emission rate of HC's is 40mg/sec. Find the concentration at a point 300m downwind on an overcast day if wind is blowing perpendicular to the road at 5m/sec speed.

Answer :

$$\text{Vehicles/m} = 4000 \text{ vehicles/hour} \div 50,000 \text{ m/hour} = 0.8 \text{ vehicles/m}$$

$$\text{Source strength/m, } q = 0.8 \text{ vehicles/m} \times 40 \text{ mg/vehicle.sec} = 32 \text{ mg/m.sec}$$

Assuming stability class 'D' (being an overcast day),

$$\sigma z = 12 \text{ m at } x = 300 \text{ m (obtained from graphs/tables)}$$

$$X(x, o, o) = \frac{2q}{\sqrt{2\pi}\sigma z u \sin\beta} \exp[-H^2/2\sigma z^2] \text{ for infinite line source}$$

$$X(300, 0, 0) = \frac{2 \times 32}{\sqrt{2\pi} \times 12 \times 5} = 0.4255 \text{ mg/m}^3$$

CHAPTER - 6

THERMODYNAMICS AND AIR POLLUTION

Thermodynamics is the science of energy transfer and its effect on the physical properties of substances. The applications of the laws of thermodynamics are found in almost all fields of air pollution, from formation to control. The principles of thermodynamics, as such, are the basics in the fields of energy technologies notably in steam and nuclear power plants, internal combustion engines, gas turbines, air conditioning, refrigeration, gas dynamics, jet propulsion, compressors, chemical process plants and direct energy conversion devices.

Today energy conservation is the main consideration in an effective project management. Sun is the basic source of energy (sufficient for 10 billion years) and any reduction in the amounts of incoming solar energy would be detrimental to life on earth. Air pollution control devices could result in an overall gain of energy and in the short-term evaluation, the control mechanism that provides the most effective emission reduction at a minimum expenditure of energy is usually used. A thorough study of the role of thermodynamics reveals that the techniques to improve energy conservation can also be the techniques to control air pollution. The study of thermodynamics is useful not only in controlling the emissions of pollutants in the plant but also in reducing the concentrations of pollutants after their discharge into the atmosphere from chimneys. The thermodynamics of formation of CO, SO_x and NO_x and combustion are described in detail in this chapter.

6.1 THERMODYNAMICS OF FORMATION OF CO

CO is formed as an intermediate product of the combustion reaction between carbonaceous fuels and oxygen rich mixtures i.e. insufficient quantities of oxygen lead to the formation of CO as the final product. Lean Mixtures (excess oxygen) also may form CO due to either poor mixing of fuel and air or dissociation of CO_2 to CO due to the high-temperature regions of the combustion zone. The CO_2 -CO equilibrium is shown in Table 6.1

TABLE 6.1 : EQUILIBRIUM CONSTANTS FOR CO-CO₂ OXIDATION

$\text{CO} + \frac{1}{2} \text{O}_2 \rightleftharpoons \text{CO}_2$	T°K	K _p
$K_p = \frac{p \text{CO}_2}{p \text{CO} (p\text{CO}_2)^{1/2}}$	298	1.2×10^{45}
	500	1.1×10^{25}
	1000	1.7×10^{10}
	1500	2.1×10^5
	2000	766
	2500	28
	4000	0.2

Thus, it can be observed that if the temperature is more than 2000°K, value of K_p will be very less indicating that CO_2 dissociation to CO is significant. Hence rich mixtures, poor mixing of air and fuel and high temperatures may lead to significant formation of CO especially in the hot combustion zones. This can be clearly observed in the following table 6.2

TABLE 6.2 : DISTRIBUTION OF CO, CO₂ AND O₂ WITH TEMPERATURE

C/O ratio	T°K	X _{CO}	X _{CO₂}	X _{O₂}
1/3.12	298	traces	0.637	0.362
"	1000	0.001	0.637	0.362
"	2000	0.003	0.635	0.363
"	3000	0.198	0.378	0.425
"	4000	0.437	0.063	0.501
1/2	3000	0.363	0.454	0.182
1/5	3000	0.113	0.264	0.623

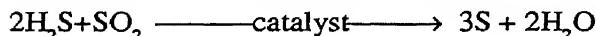
Thus all the combustion processes should operate at excess-air conditions, to avoid the formation of CO. However, too much of excess air causes other problems like formation of NO_x and hence optimum excess air values must be maintained.

6.3 THERMODYNAMICS OF FORMATION OF SO_x

Coal contains 0.5 to 4% of sulphur. If it contains less than 0.5% sulphur it may be considered as a very-low sulphur coal. Residual fuel oils also contain 1-4% sulphur. Thus all the fossil-fired combustion processes release significant quantities of oxides of sulphur. The overall, reaction for the formation of sulphur dioxide from sulphur in fossil fuels is : S+O₂ → SO₂

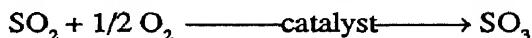
The reaction is highly exothermic with a heat release of about 300,000 kJ/mole at 25°C. In addition to SO₂, traces of SO₃ also are formed in the combustion reaction. In the combustion of fossil fuels the SO₂/SO₃ ratio is typically 40:1 to 80 : 1

SO₂ can act both as a reducing agent and an oxidizing agent at normal atmospheric conditions. For example,

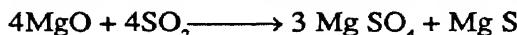


where SO₂ acts as an oxidizing agent

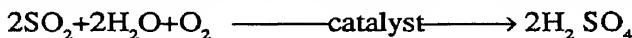
Other thermodynamic reactions of importance are:



(Here particulate matter and NO_x act as the catalysts)



In the presence of humidity SO_x forms acid mists as below



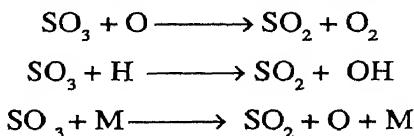
Metal salts such as sulphates and chlorides of iron and manganese are the noted catalysts for these reactions. The acid mists are corrosive and reduce visibility and are responsible for the formation of acid rains.

The thermodynamic equilibrium relationship between SO₂ and SO₃ is given in table 6.3

TABLE 6.3 : EQUILIBRIUM CONSTANTS FOR SO₂- SO₃ REACTION

SO ₂ + 1/2 O ₂ ⇌ SO ₃	T°K	K _p
K _p = $\frac{p \text{ SO}_3}{p \text{ SO}_2 (p \text{ O}_2)^{1/2}}$	298	2.6×10^{12}
	500	2.6×10^5
	1000	1.8
	1500	3.8×10^{-2}
	2000	5.6×10^{-3}

From the values of K_p it can be observed that SO_3 formation is favored only at low temperatures and that SO_2/SO_3 ratio is very high at higher temperatures. Thus SO_3 concentrations are very small in the actual flame zone and very large in the cooled flue gases. However, the concentrations of SO_3 in power plant furnaces, were observed to be altogether different. The anomalous behaviour of SO_3 is due to the role of kinetics in determining the rate of formation of intermediate products like SO and SO_2 . The equilibrium reaction of SO with oxygen to form SO_2 is thought to be the reason for the deviation in measurement of SO_3 concentration in flue gases. The main concern with reference to impact of air pollution on man and material, is the removal of SO_3 . The major SO_3 removal processes are :

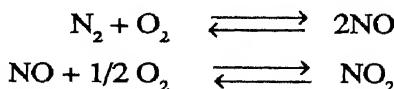


In the hot reaction zone, where high levels of "O" atoms occur it is quite reasonable to assume that SO_3 concentrations are less. Practically it was observed that the SO_3 concentration is about 1 to 5% of the SO_2 concentration. The SO_3 concentration is further suppressed under fuel rich conditions.

Thus it may be concluded that SO_2 is the main oxide of sulphur formed in combustion and that the conversion of SO_2 to SO_3 in the atmosphere is a slow process. However SO_2 is converted to SO_3 easily in the presence of particulates and humidity. This leads to an increase in sulphate aerosol formation that is dangerous to man and material.

6.3 THERMODYNAMICS OF FORMATION OF NO_x

The main sources of NO_x emission are (i) Nitrogen present in the fuel itself and (ii) Nitrogen present in air used for combustion. If excess air is not used, CO, hydrocarbons and other undesirable intermediate air pollutants may be formed. If excess air is used to control their emission, NO_x emissions increase as surplus oxygen combines with nitrogen. The two main reactions of concern in air pollution are:

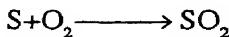
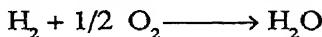


The thermodynamics of formation and control of NO_x is discussed in detail in chapter 10. It may be outlined that NO_2 emission can be reduced by reducing the peak combustion temperature and by reducing excess air available for combustion.

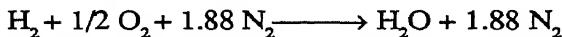
6.4 THERMODYNAMICS OF COMBUSTION

'Combustion' is the main process responsible for both generating air pollution and controlling air pollution. For example, odours generated through combustion processes are controlled mainly by destruction which is again achieved by combustion only.

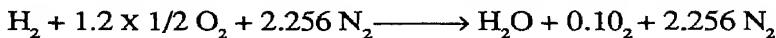
Combustion is an exothermic reaction in which thermal energy is released when the reaction occurs. Some of the common combustion reactions are:



Thus oxygen is the main element required for combustion. Normally air is supplied to the fuel to supplement the oxygen requirement instead of supplying pure oxygen for combustion. Air contains about 21% of oxygen and 79% of nitrogen by volume and hence for every one mole of oxygen present in air there will be 3.76 (0.79/0.21) moles of nitrogen. Thus, the actual combustion equations may be written as



These equations are the theoretical or stoichiometric equations of combustion which represent complete combustion of fuel which can be achieved only if every fuel molecule mates perfectly with every oxygen molecule. Such a condition requires an infinite time at very high temperature and perfect mixing. Thus the 3Ts that are very essential for an efficient combustion are: Temperature, Time and Turbulence. Practically it is not possible to allow perfect mixing to take place. Hence excess air i.e. air that is more than theoretical/ stoichiometric air, is supplied, to enable complete combustion to take place. For example, in 20% excess air, the actual combustion reactions would be:

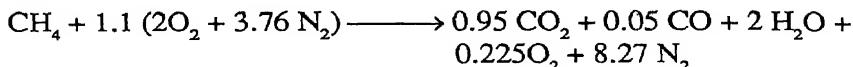


If excess air is not employed every oxygen molecule may not come in contact with every molecule of fuel resulting in the formation of some undesirable intermediate products. This incomplete combustion may be exemplified by



If the oxygen (or air) availability is considerably less than the theoretical requirement, there may be some hydrocarbons also in the products of combustion.

The excess air to be provided is a function of the fuel characteristics, combustion temperature and the turbulence or mixing provided. For example, even a 10% excess air produces the undesirable intermediate product of CO, as follows, if mixing is not proper :



The amount of oxygen (or air) provided for combustion is mostly represented by a parameter called AFR, the Air Fuel Ratio.

Air - Fuel Ratio

The ratio of mass of air to the mass of fuel is called Air-Fuel Ratio, AFR and is given by :

$$\text{AFR} = \frac{\text{Ma}}{\text{Mf}} \frac{\text{Na}}{\text{Nf}} \text{ where}$$

$$\text{Ma} = \text{Molecular weight of air } (21\% \text{ O}_2 + 79\% \text{ N}_2)$$

$$= 0.21 \times 32 + 0.79 \times 28 = 28.97$$

$$\text{Na} = \text{Number of moles of air}$$

$$= \text{No. of moles of O}_2 + \text{No. of moles of N}_2$$

$$\text{Mf} = \text{Molecular weight of fuel}$$

$$\text{Nf} = \text{Number of moles of fuel.}$$

Mixture strength, which is the ratio of stoichiometric AFR to the actual AFR, is most significant parameter that governs the products of combustion. Higher mixture strengths ($> 100\%$) cause incomplete combustion and hence undesirable products such as CO are formed. Usually boilers operate at about 20% weak mixtures; gas turbines at 300% weak mixtures whereas there is a wide variation in the operation of petrol-Engines. If excess air is more, nitrogen reacts with the excess oxygen forming NO_x emissions. Hence optimum mixture strengths must be provided to minimise emissions of air pollutants.

Combustion of fuels

There are two large reservoirs of organic material from which simple organic compounds can be obtained - petroleum and coal, and are known as fossil

fuels. Being the products of the decay of plants and animals, these simple organic compounds are used as the "building blocks" from which larger and more complicated compounds can be made. These fossil fuels particularly petroleum are being consumed at an alarming rate to meet man's greedy demands for power. 90% of petroleum is simply burned to supply energy and only 10% is used in making chemicals. The alternative sources of power - solar, geothermal and nuclear energy are being tried but only on experimental basis. The only alternative to these conventional fuels may be the origin of the fossil fuels itself, the biomass, which is renewable and can last for millennia if used properly.

Carbon atoms attach themselves to one another to an extent not possible for other atoms. They can form chains thousands of atoms long or rings of all sizes; the chains and rings can have branches and cross-links. To these are attached other atoms mainly hydrogen but also fluorine, chlorine, bromine, iodine, oxygen, nitrogen, sulphur, phosphorous etc. Each different arrangement of atoms corresponds to a different compound and each compound has its own characteristic set of physical and chemical properties. Nearly one crore compounds of carbon are known today and this number is increasing by about five lakhs a year. The most significant fuels and their potential for air pollution problems are described as follows.

6.5 COMBUSTION OF COAL

Coal is the most readily available energy source. Technologies to produce clean gas and liquid fuels from coal may spur increased use of this energy source. It is predicted to be sufficient for the next 600 years. It is extensively used inspite of its two limitations - (i) Comparatively it is difficult to handle and use especially in smaller installations (ii) When burned it releases uncontrolled air pollution emissions.

A variety of coals are available, all over the world. 'As received' analysis of a typical bituminous coal sample could be 3.0% moisture; 21% volatile matter; 70% fixed carbon and 6.0% ash. It has a heat value of about 7330 cal/gram (13,200 Btu/Lb). However, the ultimate analysis for this sample is 79.90% carbon; 4.85% hydrogen; 0.69% sulphur; 1.30% nitrogen; 6.50% ash and 6.76% oxygen. It has a true specific gravity of 1.40-1.70 for anthracite and 1.25-1.45 for bituminous. The specific gravity of loose-packed coal is about 0.64.

When coal is heated volatile matter is produced. After heating the fixed carbon and ash remain. Fixed carbon can be burned off leaving the ash. The non-combustible mineral matter in coal produces the bottom ash and some of

the fly ash particulates. Coal contains both inherent and extraneous mineral matters. The inherent matter, originated as a part of the growing plant life that produced the coal is uniformly distributed and makes up about 3% of the coal. Extraneous mineral matter is the inorganic material originated from the strata surrounding the coal seam.

During combustion the mineral matter becomes hard or melts forming the ash. The quality of ash produced depends on the furnace conditions and the composition of coal. Another unwanted element present in coal is sulphur. It is available in three forms - pyrites, organic or sulphates. About 50% of sulphur is constituted by pyrites or iron sulfide. Organic sulphur consists of complex organic molecules. Sulphates are present to a small extent and are present only in fresh coal. Coal washing processes can remove more than 50% of pyrites and mineral matters. Coal also contains significant concentrations of boron, cadmium and selenium. Coal is basically burned as fuel placed in a bed, in suspension or in a fluidised state. The fluidized bed combustion of coal is gaining significance as it produces less NO_x and reduces volatilization of sodium and potassium from the ash. With this high heat transfer rates and large combustion efficiencies are possible. In addition, high SO_2 removal also can be obtained.

The main air pollutants from the combustion of coal include particulates, SO_x , CO , HC , NO_x and aldehydes. The concentrations of these pollutants depend on the type of coal, combustion process and the operational characteristics such temperature, turbulence, mixing, excess air etc. The particulates consist mostly of ash particles and the unburned coal blown during the turbulent combustion.

More than 95% of sulphur present in the fuel is converted into SO_2 . Presence of rare metals such as platinum and vanadium present in the ash can catalyse the conversion of SO_2 to SO_3 . Presence of excess air further increases the formation of SO_3 . In the presence of water vapour SO_3 forms acid mists, which are highly dangerous.

NO_x is produced if the combustion temperature is high. The two basic sources of nitrogen are (1) nitrogen present in the fuel itself and (2) nitrogen present in the air used for the combustion. Excess air increases NO_x concentrations. Large coal-fired boilers emit more NO_x than any other combustion source. If excess air is more NO_x concentrations are more but the concentration of CO and hydrocarbons will be very low. Thus an optimum excess air must be maintained to control the air pollutants. Coal combustion emission may also include materials such as arsenic, beryllium, lead, mercury and radio active materials.

6.6 COMBUSTION OF OIL

Oil is the most versatile energy source. It is easy to transport, burns relatively clear, is safe to use and has a high energy to volume ratio. Natural fuel oils are obtained from crude oils. The typical composition of a diesel oil is 0.2% sulphur, 13% hydrogen, 87% carbon, < 0.1% nitrogen and 0.01% ash. It has a specific gravity of 0.84 and has a heating value of 11.19 kcal/gram. Kerosene also has more or less the same properties. However it has a sulphur content of less than 0.05%. Kerosene has a molecular formula of $C_{12}H_{26}$.

For combustion of oil, they must first be atomized by oil burners to produce drops of sizes less than 50μ diameter. Oil is then sprayed into the boilers to mix with combustion air. Oil burners usually operate at 5-10% excess air.

Properly operated oil burners produce less air pollution compared to coal combustion. Horizontal and tangential firings are the two basic arrangements in firing. The oil is directed towards the centre of the furnace in a horizontal firing system resulting in a hotter flame and hence the formation of NO_x . Similarly, large boilers burn hotter and hence produce more NO_x than smaller ones. In an oil fired boiler about only 0.65% of SO_2 is converted to SO_3 .

6.7 COMBUSTION OF GAS

Gases are the cleanest burning fuels and hence are the best suited for minimum air pollution generation. Of all gases, natural gas is the most available fuel. It has a significantly high gross heating value of 8900-9800 kcal/Nm³. It has a relative density of about 0.57, when referred to air. Artificial gas, also known as manufactured gas or city gas is a mixture of water gas, coal gas and others. Carburetted gas (or water gas), producer gas and coke oven gases are made from coal or coke. LPG, the liquefied petroleum gas is a gasoline refining by product and consists mainly of butylene and propane and trace amounts of butylene and propylene. Although it is distributed as a liquid under pressure it reverts to gaseous state before burning. LPG commonly known as bottled gas has a heating value of 6000-6400 Kcal/Nm³. Different fuels have different applications. Gasoline is used in internal combustion engines that require a fairly volatile fuel. Kerosene is used in tractor and jet engines and gas oil is used in diesel engines. During the combustion of gaseous fuels, both gaseous fuels and air are forced together through nozzles and the flame is sustained. The residence time near the tip of burners is about 0.25 to 3 seconds, depending upon whether the temperature is high or low. Gas burners typically operate at 3-15% excess air. A gas burner may be compared with an old-style gas stove where gas enters the flame through a number of holes and mixes with air. As majority of gaseous fuels contain insignificant amounts of sulphur, the SO_x emissions resulting from

the combustion of gases is almost negligible. As gases can easily mix with air, minimum excess air is sufficient for an efficient combustion. Thus gases can be burnt with minimum NO_x emissions.

Of all the fuels, natural gas is the most promising fuel. Its origin and significance are discussed in detail.

6.8 NATURAL GAS

Natural gas is one of the most important fuel resources in the world. The transportation of natural gas to multiple consumers started as early as in 1880 itself. Since the second world war the expansion of the natural gas industry was spectacular throughout the world. Currently, the amount of natural gas depositions in the world are of the order of 80, 450 Gm³. The best endowed country is the erstwhile Soviet Union with 40.0% of world reserves while the second is Iran with 14% of world's reserves, followed by USA (7%).

Composition of Natural Gas

At normal temperature and pressure, the contents of commercial natural gas are mainly methane (CH_4), ethane (C_2H_6) and varying amounts of propane (C_3H_8) and butane (C_4H_{10}). An average composition of natural gas indicates methane - 83.0%, ethane-7.2%, propane-2.3%, butane-1.0%, N_2 -5.8%, CO_2 -0.2% etc. There may be traces of helium, oxygen, hydrogen and other substances. The main impurities are N_2 , CO_2 and H_2S . If H_2S is more than 10 grains/m³, it is removed commercially and converted to elemental sulphur by Clauss process. If concentration of H_2S is less, it is removed by the process called 'sweetening'. Natural gas containing H_2S is called 'SOUR GAS'. It has an unpleasant odour and H_2S dissolved in water forms a mild acid which is corrosive to pipes and valves. Some sources of natural gas contain helium upto 8% also. As such, natural gas is the main source of helium.

Origin of Natural Gas

According to one theory, when earth was born, it was surrounded by methane, water, ammonia and hydrogen. Energy radiation from the sun and lightning discharges, broke these simple compounds to a large number of organic compounds like 'amino acids' which form proteins, the 'stuff of life'. In 1953, Nobel prize winner Harold C. Urey and Stanley Miller showed that electric discharge converts a mixture of methane, water, ammonia and hydrogen into complicated organic compounds that are responsible for making up living organisms. Thus methane generated in the final decay of dead organisms may well be the same substance from which the organism was derived. After the escape of hydrogen, oxidation of methane and breaking up of water, O_2 and N_2 remained in the earth's atmosphere. The methane is found most often, with

or near the oil deposits, which indicates a major method of its formation. The gas could be considered to be the product of the microbial decomposition of organic matter in the absence of oxygen. The methane gas also escapes from decaying vegetation in swamp lakes mixed with little H_2S and CO_2 . The gas also occurs in fire damps in coal mines creating explosion hazards. Methane is present in some gold and uranium mines of South Africa mixed with helium gas. Methane is also produced by the biological treatment of sewage or solid organic wastes under anaerobic conditions. These areas could be important sources of methane based on renewable resources.

Properties of Natural Gas

Since most of the natural gases contain methane over 90%, natural gas becomes synonymous to methane. It is the simplest form of hydrocarbon-'alkanes'. The melting point of methane is $-183^{\circ}C$ and its boiling point is $-161.5^{\circ}C$. Natural gas can also be liquefied and Liquefied Natural Gas (LNG) is ideally transported across the sea in specially designed tankers. Density of LNG is 425.0 kg/m^3 . The critical point of LNG is $82.1^{\circ}C$ at 48.0 kg/cm^2 . The atmospheric boiling point of LNG is $-161.5^{\circ}C$. Comparative analysis of properties of methane and natural gas are discussed in the following. The gross calorific value of natural gas is $1000\text{ (k.cal/cu.m.)}$, for methane it is 995 kcal/m^3 . The net calorific value for natural gas is 902 kcal/m^3 whereas for methane it is 859 kcal/m^3 . The specific gravity of natural gas is 0.59 whereas for methane it is around 0.555. The stoichiometric air requirement (vol air/vol gas) is 9.6 for natural gas, whereas for methane it is 9.52. The inflammability limits for both the gases are 5-15% gas. The spontaneous ignition temperature for natural gas is $700^{\circ}C$. Methane is a colourless gas and less dense than water. Methane is a gas at ordinary temperature, slightly soluble in water, but highly soluble in organic liquids like gasoline. Under ultraviolet rays or at $250-400^{\circ}C$, methane and chlorine combine to yield HCl and CH_3Cl called chloromethane or methyl chloride. This is called chlorination which may lead to the formation of CH_2Cl_2 (dichloromethane or methylene chloride), $CHCl_3$ (trichloromethane or chloroform) and CCl_4 (tetrachloromethane or carbon tetrachloride). Methane reacts with fluorine even in the dark at room temperatures. Methane affects skin, throat and lung. Being malodorous it presents an unpleasant atmosphere. It retards the growth of vegetation.

Sources of Natural Gas

There are mainly two sources of natural gas. It occurs in gas fields i.e. underground reservoirs similar to oil reserves and is recovered by drilling gas wells. In addition, large quantities of gas are produced in association with the

production of crude oil. Oil normally contains alkanes from methane upwards. In the reservoir the lower gaseous alkanes are in solution under considerable pressure. When the oil is brought to the surface, the pressure is released forming 'associated gas'. In some oil fields, particularly those in inaccessible regions, this gas is burnt. In other fields it is collected and used. Composition of a typical associated gas of the Zakum field of Abu Dhabi is 76% CH_4 ; 11.4% C_2H_6 ; 5.3% C_3H_8 ; 2.2% C_4H_{10} ; 1.3% C_5H_{12} ; 2.3% CO_2 and 0.3% H_2S .

Synthetic natural gas, a mixture of carbon monoxide and hydrogen is an ideal connecting link between a source of fossil fuel and substituted natural gas. The low grade coal is initially transformed into synthetic gas ($\text{CO} + \text{H}_2$) by gasification process followed by catalytic conversion to methane. The substituted natural gas can be used as a fuel or as a feed stock for chemical and allied industry.

Uses of Natural Gas

Natural gas is used in many ways. The global consumption of energy in the form of natural gas is presently equal to one half of the consumption of energy in the form of petroleum. Natural gas is used in energy sector, in gas turbines and in diesel engines. Natural gas is also used in the compressed form for road transport. It is the main energy resource in chemical and fertilizer industries. Natural gas is used extensively in petrochemical, metallurgical and sponge iron manufacturing units.

Natural Gas Scenario in India

India with its huge growing population and constant commitment to industrial and agricultural development is indeed a power hungry country. The main resources are its huge coal deposits much of which is low grade. India is presently meeting a large part of its demand of energy and chemical feed by importing crude oil at an enormous drainage of foreign exchange. India is situated in between international trade routes of 'NG' and there is availability of natural gas from Bombay High, Hazira field, Krishna Godavari fields and Assam fields.

Natural gas is also available as mine drainage gas in coal mines. The typical analysis of the mine drainage gas is CH_4 - 98.04%, CO_2 - 0.10%, N_2 - 0.97%, and CO - 0.0015%. Methane is also available in the form of sludge gas from sewage digestion plants. Sludge gas also may be directly used for power generation. Other forms of organic wastes eg. garbage, animal wastes, market wastes can also be recycled back to produce biogas and fertilizer. Methane produced from farm yards also may be tried as a source of natural gas.

Exploration and Processing of Natural Gas

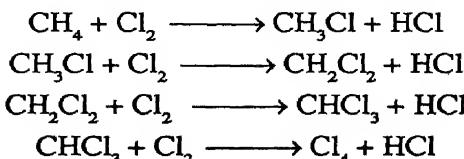
The conditions for natural gas exploration vary widely depending on geographical location and terrain. Seismic methods are the first choice for preliminary gas deposits. Such techniques are simple to apply on land and have now become routine, at offshore exploration. If the first exploration looks promising the next step is the drilling at a series of appraisal wells to get a more detailed picture of the size and quantity of the reservoir.

Combustion of Natural Gas

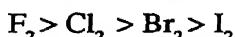
Combustion of methane is the principal reaction during the burning of natural gas. The important product of combustion is not carbon dioxide or water but heat. Burning of methane or any other hydrocarbon takes place only at high temperatures, as provided by a flame or a spark. Once started, however, the reaction gives heat which is often sufficient to maintain high temperatures and to permit burning to continue. The heat of combustion (i.e. the quantity of heat evolved when one mole of hydrocarbon is burnt to CO_2 and H_2O) for methane is 213 kcal.

Through controlled partial oxidation of methane and the high-temperature catalytic reaction with water, methane is an important source of products other than heat. It produces hydrogen, used in the manufacture of ammonia; it produces CO and hydrogen used in the manufacture of alcoholic products.

Under the influence of UV rays or at temperatures of 250–400°C, methane reacts with chlorine and yields HCl and CH_3Cl . Thus if methane undergoes chlorination, chloromethane or methylchloride, CH_3Cl is formed. This may further form CH_2Cl_2 i.e. dichloromethane or methane chloride. In a similar way chlorination may continue to yield CHCl_3 i.e. trichloromethane or chloroform and CCl_4 i.e. tetrachloromethane or carbon tetrachloride.



Methane also reacts with bromine at high temperatures or under UV rays to yield corresponding bromomethanes. Methyl bromide, methylene bromide, bromoform and carbon tetrabromide. It does not react at all with iodine. It reacts vigorously with fluorine even in the dark and at room temperature. Thus the reactivity of halogens may be expressed as :



Problem 1 : A ceramic industry releases $10 \text{ Nm}^3/\text{sec}$ of flue gases at 170°C . If this is to be utilized for boiling water at 30°C , find the quantity of water that can be boiled.

Answer :

The following assumptions may be made for the solution.

$$(i) \text{ Molecular weight of flue gas (air)} = 29$$

$$(ii) C_p - C_v = R$$

$$(iii) C_p - C_v/r = R \text{ i.e. } C_p(1 - 1/r) = R$$

Now, the gas flow rate is $10 \text{ Nm}^3/\text{sec}$ at 170°C i.e., 12.0 kg air/sec at 170°C (assuming specific weight of air = 1.20 kg/m^3)

$$\text{Heat lost} = m \cdot C_p \cdot dT$$

$$= \frac{1.20 \times 10^4 \text{ grams/sec}}{29 \text{ grams/mole}} \times \frac{8.3 \text{ joules}}{\text{mole}^\circ\text{K}} \times \frac{r}{r - 1} \times 140^\circ\text{K}$$

$$= 4 \times 10^5 \text{ calories/sec} = 400 \text{ k.cal/sec} = 40 \text{ k.cal/m}^3$$

• (taking r as 1.4 and 1 calorie as 4.2 joules)

If this heat lost by air is to be gained by water at 30°C ,

$$4 \times 10^5 = msdT = mx1x(100-30)$$

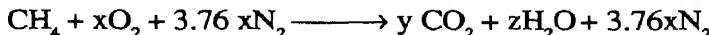
$$\therefore m = 5700 \text{ g} = 5.7 \text{ litres}$$

Thus $10 \text{ m}^3/\text{sec}$ of gas at 170°C can boil about 5.7 litres of water per second. However, there will be energy transfer losses in the system and hence the actual amount of water that can be boiled will be slightly less than 5.7 LPS.

Problem 2 : Find stoichiometric air fuel ratio for combustion of methane. If it is to be burnt in 150% stoichiometric air, write the equation and find AFR.

Answer:

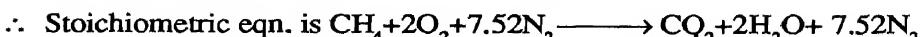
The stoichiometric equation for combustion of CH_4 is



Balancing for carbon 'C' and hydrogen 'H' atoms, we get

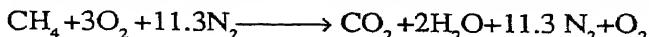
$$\text{C : 1} = y \text{ and H : 4} = 2z \quad \therefore z = 2$$

$$\text{O : } 2x = 2y + z \Rightarrow 2x = 2+2 = 4 \quad \therefore x = 2$$



$$\therefore \text{Stoichiometric AFR} = \frac{M_a N_a}{M_f N_f} = \frac{28.97(2+7.52)}{16(1)} = 17.25$$

If 150% air is used, the actual combustion equation would be



Problem 3 : Find AFR for formaldehyde if 100% excess air is used for its combustion.

Ans : $\text{CH}_2\text{O} + x\text{O}_2 + 3.76x\text{N}_2 \longrightarrow y\text{CO}_2 + z\text{H}_2\text{O} + 3.76x\text{N}_2$

$$\therefore y=1; 2=2z \Rightarrow z=1; 1+2x=2y+z=3 \quad \therefore x=1$$

$$\therefore \text{Stoichiometric eqn. is } \text{CH}_2\text{O} + \text{O}_2 + 3.76\text{N}_2 \longrightarrow \text{CO}_2 + \text{H}_2\text{O} + 3.76\text{N}_2$$

$$\therefore \text{AFR} = 28.97 (1+3.76)/30(1) = 4.60$$

If 100% excess air is used, total air used = 200%

$$\therefore \text{AFR with 100% excess air} = 4.60 \times 2 = 9.20$$

Problem 4: Find stoichiometric AFR for methyl mercaptan.

Ans : $\text{CH}_3\text{S} + x\text{O}_2 + 3.76x\text{N}_2 \longrightarrow y\text{CO}_2 + z\text{H}_2\text{O} + k\text{SO}_2 + 3.76x\text{N}_2$

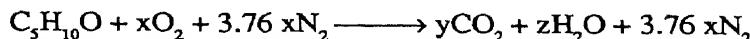
$$1=y; 4=2z \Rightarrow z=2; 1=k; 2x=2y+z+2k=2+2+2=6 \quad \therefore x=3$$

$$\therefore \text{Stoichiometric eqn. is : } \text{CH}_3\text{S} + 3\text{O}_2 + 11.3\text{N}_2 \longrightarrow \text{CO}_2 + 2\text{H}_2\text{O} + \text{SO}_2 + 11.3\text{N}_2$$

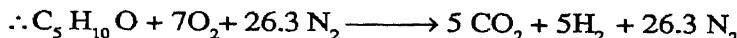
$$\text{AFR} = 28.97 (3+11.3)/48 \times 1 = 8.631$$

Problem 5: Find AFR if 150% excess air is used for combustion of diethyl ketone, $\text{C}_5\text{H}_{10}\text{O}$.

Answer:



$$\therefore 5=y; 10=2z; 2x+1=2y+z \quad \therefore 2x=10+5-1=14 \quad \therefore x=7$$



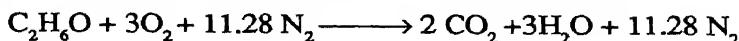
$$\therefore \text{Stoichiometric AFR} = 28.97 (7+26.3)/86 (1) = 11.22$$

$$\therefore \text{If 150% excess air is used, AFR} = 2.5 \times 11.22 = 28.05$$

Problem 6: Find the air - fuel ratio if (a) 90% and (b) 120% mixture strengths are used for the combustion of ethyl alcohol, $\text{C}_2\text{H}_6\text{O}$ in a motor vehicle .

Also find the exhaust gas analysis.

Answer: The stoichiometric equation of combustion is:



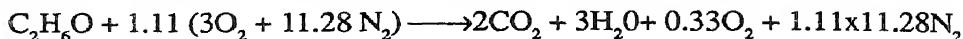
$$\text{AFR (stoichiometric)} = 28.9 (3+11.28)/46 \times 1 = 8.96 \text{ kg/kg fuel.}$$

(a) Mixture strength = stoichiometric AFR/actual AFR $\Rightarrow 0.90 = 8.96/\text{AFR}$

$$\therefore \text{Actual AFR} = 8.96/0.90 = 9.95 \text{ kg/kg fuel.}$$

Thus the mixture is weak and $9.95/8.96$ i.e. 11% excess air is used

\therefore The actual combustion equation will be



$$\therefore \text{Total number of moles of products} = 2+3+0.33+12.52 = 17.87$$

Hence wet and dry analysis of products of combustion are :

Product	No.of Moles	% Wet	% Dry
CO_2	2	$2/17.87 = 11.20$	$2/14.87 = 13.45$
O_2	0.33	$0.33/17.87 = 1.85$	$0.33/14.87 = 2.22$
H_2O	3	$3/17.87 = 16.8$	----
N_2	12.52	$12.52/17.87 = 70.2$	$12.52/14.87 = 84.40$

Total wet : 17.87 Total = 100.05% Total = 100.07%

Total H_2O : 3.00

Total dry : 14.87

(d) Mixture strength = 120% $\therefore 1.2 = \text{Stoichiometric AFR/Actual AFR}$

$$\therefore \text{Actual AFR} = 8.96/1.20 = 0.834 \times 8.96 = 7.47 \text{ kg/kg fuel}$$

Thus air availability is only 83.4% of the required quantity. Due to non-availability of oxygen, incomplete combustion takes place. H_2O is the first product formed as hydrogen has greater affinity for oxygen than carbon. Later carbon forms CO and CO_2 , the proportions of which can be calculated as follows.



$$\text{Carbon balance : } 2 = a+b$$

$$\text{Oxygen balance : } 1 + 0.834 \times 6 = 2a + b + 3$$

$$\therefore a = 1.004 \text{ and } b = 0.996$$

\therefore The final products are = 1.004 moles of CO_2 + 0.996 moles of CO + 3.0 moles of H_2O + 0.834×11.28 moles of N_2 = 14.41 moles.

\therefore The wet and dry analysis of products of combustion is

Product	No.of moles	% wet	% Dry
CO ₂	1.004	1.004/14.41=6.97	1.004/11.41 = 8.7
CO	0.996	0.996/14.41 = 6.90	0.996/11.41 = 8.7
H ₂ O	3.00	3.0/14.41 = 20.82	---
N ₂	9.41	9.41/14.41 = 65.30	9.41/11.41 = 82.5
Total wet	14.41	Total : 99.99	Total : 99.9
Total H ₂ O	3.00		
Total dry	<u>11.41</u>		

Problem 7: Calculate AFR if 20% excess supply of air is used for combustion of anthracite of composition 90% CO ; 3% H₂; 2.5% O₂; 1% N₂; 0.5% S and 3% ash. Find the dry and wet analysis of products of combustion.

Answer : The analysis of products of stoichiometric combustion is :

Element	Mass kg/kg	Reqd O ₂ kg/kg coal	Products
C	0.900 (C + O ₂ → CO ₂)	(0.9 × 32/12)=2.4	0.9 × 44/12 = 3.3CO ₂
H ₂	0.030(H ₂ +1/2 O ₂ →H ₂ O)	(0.03×16/2)=0.24	0.03×18/2 = .27 H ₂ O
O ₂	0.025	-0.025	
N ₂	0.010		0.010 N ₂
S	0.005 (S+O ₂ → SO ₂)	.005×32/32=.005	.005×104/32=.01SO ₂
Ash	0.030		
Total	1.000	2.620	

$$\therefore \text{O}_2 \text{ required/kg fuel} = 2.620 \text{ kg.}$$

$$\therefore \text{AFR} = 2.620/23.3 \times 100 = 11.25 \text{ kg (assuming that air contains 23.3\% O}_2 \text{ by weight)}$$

$$\therefore \text{Stoichiometric AFR} = 11.25 \text{ kg fuel}$$

If 20% excess air is used, actual AFR = 11.25 × 1.2 = 13.5 kg air/kg fuel

$$\therefore \text{O}_2 \text{ supplied} = 2.620 \times 1.2 = 3.144 \text{ kg/kg fuel}$$

$$\therefore \text{N}_2 \text{ supplied} = 0.01 + 3.144 \times 0.767/0.23 = 10.36 \text{ kg/kg fuel}$$

$$\therefore \text{Air supplied} = 3.144 + 10.36 = 13.5 \text{ kg/kg fuel}$$

\therefore Products of combustion with 20% excess air are:

$$1) \text{O}_2 : 3.144 - 2.620 = 0.524 \text{ kg/kg fuel} \quad 2) \text{N}_2 : 10.36 \text{ kg/kg fuel}$$

Product	kg/kg fuel	% by mass	M	moles / kg fuel	% vol wet	% vol dry
CO ₂	3.3	22.80	44	0.075	15.74	16.30
H ₂ O	0.27	1.87	18	0.015	3.16	—
N ₂	10.36	71.67	28	0.37	77.80	80.30
O ₂	0.524	3.60	32	0.0162	3.40	3.51
SO ₂	0.01	0.07	64	0.0002	0.03	0.03
Total :	14.646	100.01		0.4764	100.13	100.14
			-H ₂ O : 0.0150			
			Dry : 0.4614			

Problem 8 : Find AFR if 20% weak mixture is employed for the combustion of coal gas with 49.4% H₂; 18% CO; 20% CH₄; 2% C₄H₈; 0.4% O₂; 6.2% N₂ and 4% CO₂. Find the dry and wet analysis of products of combustion.

Answer:

Element	moles per mole of gas	combustion equation	required O ₂ moles/mole fuel	Products	
				CO ₂	H ₂ O
H ₂	0.494	H ₂ +1/2O ₂ → H ₂ O	0.247	-	0.494
CO	0.180	CO+1/2O ₂ → CO ₂	0.090	0.18	-
CH ₄	0.200	CH ₄ + 2O ₂ → CO ₂ + 2H ₂ O	0.400	0.20	0.40
C ₄ H ₈	0.020	C ₄ H ₈ + 6O ₂ → 4CO ₂ + 4H ₂ O	0.120	0.08	0.08
O ₂	0.004	-	-0.004*	-	-
N ₂	0.062	-	-	-	-
CO ₂	0.040	-	-	0.04	-
Total	1.000	-	0.853	0.50	0.974

(*-ve sign is used for O₂ as oxygen present in the fuel will supplement the O₂ required for combustion)

∴ Amount of O₂ required for complete combustion = 0.853 moles

∴ Amount of air required for complete combustion

$$= 0.853/0.210 = 4.06 \text{ moles / mole of fuel}$$

∴ AFR (on volume basis) = 4.06 moles/mol of fuel

$$\begin{aligned} \text{AFR (on weight basis)} &= 4.06 \times 28.85 / (0.494x2 + 0.18x28 + 0.2x16 + 0.02x56 \\ &\quad + 0.004x32 + 0.062x28 + 0.04x44) \\ &= 4.06 \times 28.85 / 13.976 = 8.4 \end{aligned}$$

∴ Actual AFR (on volume basis) = $4.06 \times 1.2 = 4.872 \text{ moles/mol fuel}$

$$\therefore \text{Excess oxygen} = 0.853 \times 0.2 = 0.1706 \text{ moles / mol}$$

$$\therefore \text{Oxygen present in products} = 0.1706 \text{ moles / mol}$$

$$\text{N}_2 \text{ present in products} = 0.062 + 4.872 \times 0.79 = 3.911 \text{ moles /mol fuel.}$$

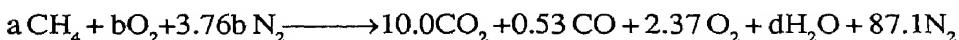
Thus the dry and wet analysis of products of combustion may be computed as follows.

Product	moles/mol fuel	% by vol dry	% by vol wet
CO ₂	0.500	10.90	9.00
H ₂ O	0.974	-	17.50
O ₂	0.1706	3.72	3.08
N ₂	3.911	85.40	70.40
Total wet :	5.557	100.02	99.98
H ₂ O moles :	0.974		
Total dry :	4.583		

Problem 9 : Natural gas (methane CH₄) is burned in atmospheric air. The analysis of products on a dry basis was found to be :

10.0% CO₂; 2.37% O₂; 0.53% CO and 87.10% N₂. Find AFR, % theoretical air and the combustion equation.

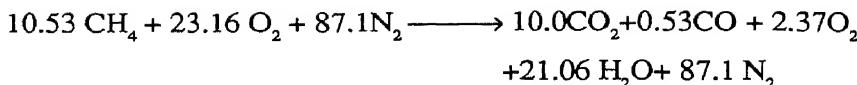
Answer: The equation for combustion may be written as:



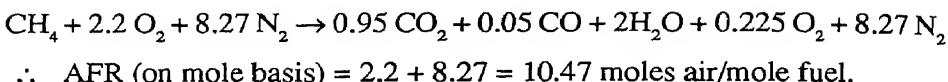
Balancing carbon, hydrogen, oxygen and nitrogen atoms,

$$b = 23.16; a = 10.53; d = 21.06$$

∴ The combustion equation is

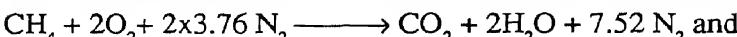


The combustion equation, per mole of fuel, may be written as:



$$\text{AFR (on mass basis)} = 10.47 \times 28.9 / 16.0 = 18.97 \text{ kg/kg fuel}$$

However, the theoretical combustion equation for methane is



$$\text{The theoretical AFR} = (2+7.52) 28.9 / 16.0 = 17.23 \text{ kg air / kg fuel}$$

$$\therefore \% \text{ Theoretical air employed} = 18.97 / 17.23 \times 100 = 110\%$$

Problem 10: The products of combustion of a fuel of unknown composition have the following composition on a dry basis :

8% CO₂; 0.9% CO; 8.8% O₂ and 82.3% N₂. Calculate the Air-Fuel Ratio, fuel composition on mass basis and the percent theoretical air employed.

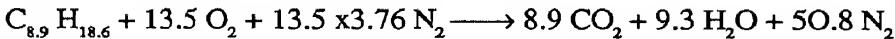
Answer: As the products contain only CO₂, CO, O₂ and N₂, the equation may be written as



Balancing the nitrogen, oxygen, carbon and hydrogen atoms,

$$d = 21.9; c = 9.3; a = 8.9 \text{ and } b = 18.6$$

Thus the composition of the fuel could be written as C_{8.9}H_{18.6}. The theoretical or stoichiometric combustion equation is:



$$\therefore \text{Theoretical AFR} = (13.5 + 50.8) 28.9 / (8.9 \times 12 + 18.6 \times 1) = 14.9 \text{ kg / kg fuel.}$$

However the actual equation of combustion is different . It is C_{8.9}H_{18.6} + 21.9O₂ + 21.9 × 3.76 N₂ → 8.0 CO₂ + 0.9 CO + 8.8 O₂ + 9.3 H₂O + 82.3 N₂

$$\therefore \text{Actual AFR} = (21.9 + 82.3) 28.9 / (8.9 \times 12 + 18.6 \times 1) = 24.1 \text{ kg air / kg fuel}$$

$$\therefore \% \text{ Theoretical air employed} = 24.1 / 14.9 \times 100 = 162\%$$



CHAPTER - 7

PARTICULATE CONTROL TECHNOLOGY

Everyday about half-a-million tonne of particulates (of sizes ranging from 100 to 0.1 microns and even less) are released into the atmosphere by anthropogenic sources. Particulates on a micro-scale cause severe effects on man, material and vegetation and on a macro-scale affect the earth-atmosphere heat balance by disturbing the evaporation-condensation cycle. Many cities all over the world are experiencing undesirable concentrations of particulates in the atmosphere. Particulates present in air in the form of aerosols, dusts, mist, smoke, smog, smaze or cloud, pose a potential pollution hazard and the already worsened situation demands an immediate relief by means of a proper particulate control technology. As particulates are more clearly seen, their removal from flue gases has assumed greater significance in the recent past. There are three broad approaches to the control of particulates - dilution in the atmosphere, control at source and control by using pollution control equipments.

7.1 DILUTION

Dilution of particulates and gases can be accomplished by the use of tall stacks. Pollutants released from taller stacks disperse easily and hence low ground level concentrations are observed. Till 1955 there were only two stacks in excess of 150m in USA. Today there are hundreds of stacks in excess of 150m. Tall stacks penetrate the inversion layer and disperse the contaminants easily so that the ground level concentrations are less harmful.

Thus, dilution is only a short-term control measure and tends to bring about highly undesirable long-range effects.

In India, a minimum stack height of 30m is to be provided. Similarly, the minimum height of stack, H required for an effective dispersion of particulates in air is given by $H=74Q^{0.27}$ where Q is particulate emission rate in tonnes per hour. This often demands, stack heights in excess of 400m, especially in cement industries and thermal power plants and hence may prove uneconomical compared to particulate control by treatment.

7.2 CONTROL AT SOURCE

The most effective means of dealing with the problem of air pollution is to prevent emission at the source itself. In the case of industrial pollutants, this can often be achieved by investigating various approaches at an early stage of process design and development, and selecting those methods which do not contribute to air pollution (or) have the minimum air pollution potential. It may be difficult to implement these methods in existing plants, but still some of the methods could be applied without upsetting the economy of the operation. Control of particulates at the source can be accomplished in several ways through raw material changes, operational changes, modification or replacement of process equipment and by more effective operation of existing equipment. Source locations through allocation of land usage i.e. proper planning and zoning of industrial areas is also one of the important means of control of pollutants. Some of the source correction methods are discussed briefly as follows.

Raw Material Changes

Some raw materials are primarily responsible for causing air pollution. Use of pure grade of raw material is often beneficial and may reduce the formation of undesirable impurities and by-products or may even eliminate the troublesome effluents. Ore handling operations usually result in the emission of large quantities of dust into the atmosphere. In steel industry, replacement of raw ore with briquetted (or) pelleted sintered ore has greatly reduced dust emissions during ore handling and also helped to reduce the blast furnace 'slips' which result in emission to the atmosphere of enormous amounts of uncleaned blast furnace gas when the safety dampers open and allow the gases to bypass the dust collectors.

Process Changes

Changing the process being used is still another important method of controlling emissions at their source. For example, petroleum/chemical industries have undergone radical changes in processing methods which

emphasize continuous automatic operations, often computer controlled and completely enclosed systems that minimise the release of materials to the atmosphere. The volatile substances from storage tanks etc. are recovered by condensation and the non-condensable gases are recycled for additional reactions such as polymerisation and alkylation of gaseous hydrocarbons to produce gasoline. Hydrogen sulfide, which was once flared in refineries, is now recycled and used in Clauss process to recover elemental sulphur.

Replacing open hearth furnaces with controlled basic oxygen furnaces or electric furnaces can reduce smoke, carbon monoxide and metal fumes while at the same time, conserving energy. Such changes, coupled with various combinations of gas cleaning devices, can be very effective in reducing air pollution.

In cement plants, rotary kilns are the major sources of dust generation. This can be reduced to some degree by adjusting operating conditions like reduction of the gas velocities within the kiln, modification of the rate and location of feed, introduction and employment of a dense curtain of light weight chain at the discharge end of the kiln etc.

Emissions of highly objectionable sulphurous materials are notorious for smelting and paper industries. These emissions are being curtailed by major process changes such as hydro-metallurgical separations of ores and avoiding the use of sulfides in paper making.

In the steel industry, a radically different process has been proposed to lower sulphurous emissions during combustion. In this process, the sulphur bearing fuel, limestone and air are injected into a molten bath. The combustibles in the fuel are partially oxidized to carbon monoxide within the molten iron bath, the gaseous CO comes off at the top of the molten iron and is burnt efficiently in a conventional manner. The sulphur is retained in the iron bath and forms a slag with the limestone, which is removed.

Other examples involving process changes include :

1. Reduction of the formation of nitric oxides in combustion chambers by low excess air combustion in two stages, fuel gas recirculation and water injection.
2. Washing the coal before pulverization to reduce the fly ash emissions.
3. Substitution of bauxite flux for fluorine - containing fluorspar in open hearth method.
4. The use of liquid and gaseous fertilizer chemicals like anhydrous ammonia, applied by injection into the earth instead of being spread across the surface as finely divided powders.

5. Reduction in oxidation of SO_2 to SO_3 , by reducing excess air from 20% to less than 1% when burning fossil fuels, has eliminated sulfuric acid emissions. However, care should be taken as absence of excess air tends to result in greater soot production.

Equipment Modification (or) Replacement

Another method of control of pollutants at the source involves the proper use of existing equipments, modification and replacement of equipments. For example, the unburnt carbon monoxide and hydrocarbons in the cylinders of an automobile engine, which are otherwise emitted into the atmosphere through the tail pipe, can be burnt by injecting air into the hot exhaust manifold of the engine. Similar results can be obtained by suitable modification in the carburetion and ignition systems.

Hydrocarbon vapours from petroleum refineries are released into the atmosphere from storage tanks due to temperature changes, direct evaporation and displacement during filling. These losses can be minimized by designing the tanks with floating roof covers or by pressurising the tanks.

In addition to the above mentioned source correction methods, air pollutants emitted from industrial operations can be reduced by proper equipment maintenance, handkeeping, and cleanliness in the facilities and premises. Often, changes in the design of local exhaust hood and proper installation can minimize the emission of pollutants to the atmosphere. Chemical process plants often have excessive leakage around ducts, piping, valves and pumps. Many such leaks can be prevented by checking the seals and gaskets routinely. Floors, decks, storage bins and silos, loading areas and material transfer conveyors must be kept clean to reduce dust pollution.

7.3 PARTICULATE CONTROL BY USING EQUIPMENTS

The most effective methods of particulate control are reduction at the source by the application of control equipment and process control. If air pollution problems are properly considered in an industry prior to its design, real economy can be affected. But unfortunately in most cases air pollution control is an after-thought and ways and means are derived and designed hurriedly in the eleventh hour to treat the polluted effluents.

To remove the particulate matter from gas streams, various types of control equipment are available. But to select the required equipment, certain basic data must be available. The required data is :

- (1) Quantity of gas to be treated and its variation with time.
- (2) Nature and concentration of the particulate matter to be removed.
- (3) Temperature and pressure of the gas stream.

- (4) Nature of the gas phase (for solubility and corrosive effects).
- (5) Desired quality of the treated effluent i.e. efficiency of removal of particulates required.

Objectives of Using Control Equipment

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

Particulate Control Equipment

As pollutants, originating from a variety of sources primarily from industrial processes, airborne particulates exert a significant influence on atmospheric phenomena, plants, property and on animals including man. In 1970, an estimated 18 million tonnes of suspended particulate matter was emitted to our atmosphere, with industry contributing about 50% of that total. Due to the progress made in control of particulates at their source, 60 percent overall reduction in particulates occurred between 1970 and 1980.

All control devices and physical principles involved in particulate control have been understood, developed and used for quite some time. Control devices are divided into five major groups.

1. Gravitational settling chambers
2. Cyclones
3. Fabric filters
4. Electro static precipitators
5. Scrubbers (or) wet collectors

Each of these devices is uniquely suited to specific applications and the proper choice of method depends upon careful considerations of several factors, as presented in table 7.5. Particulate emission rates for different sources are given in table 7.4. Such particle characteristics as size distribution, shape, density, stickiness, hygroscopicity and electrical properties and such carrier gas properties as flow rate and particle concentration must be taken into consideration. Such operational factors as continuous or intermittent emission, overall efficiency desired, available space, ultimate waste disposal methods required, and equipment limitations (i.e. pressure, temperature and corrosion) must be balanced against the economic considerations of installation, operation and maintenance costs. Various particulate control equipments are described as follows :

7.4 SETTLING CHAMBERS

The gravitational settling chambers are perhaps the simplest and crudest of all pollution control devices. Much of the motivation for studying settling chambers stems from their simplicity. Thus the study of settling chambers is as much anything a prelude to the study of other devices. Settling chamber is almost the cheapest device to construct, operate and maintain and often serves as a preliminary screening device. Where the mass of larger particles is huge, the settling chamber can remove much of the mass of the particulate distribution which would otherwise choke up other control devices, impairing their operation or requiring frequent cleaning. Thus in majority of the particulate control devices, the first unit is a 'gravity settling chamber'.

Gravitational force may be employed to remove particulates in settling chambers when the settling velocity is greater than about 0.12m/s. The application of Stoke's law and similar equations to settling operations involving particles in air streams is same as for particles in water streams. Like settling tanks in water systems, gravity settling chambers are provided with enlarged areas to minimize horizontal velocities and allow time for the vertical velocity to carry the particle to the floor.

The gravitational settling chambers usually operate with velocity between 0.5 and 2.5 m/s, although for best operating results the gas flow should be uniformly maintained at less than 0.3 m/s. Some settling chambers have simply enlarged conduits and some have horizontal shelves and baffles, spaced about 2.5 cm apart. The horizontal shelves shorten the settling path of the particles and thus improve removal efficiency of the device since the gas velocity in the chamber remains substantially the same and yet each particle has a much shorter distance to fall before reaching the bottom of the passage between the trays. The collection efficiency of the chamber depends upon the type of flow also. For both laminar and turbulent flows, the design considerations are given in the following.

Design Considerations

Generally, settling chamber design based on laminar flow requires either a very large size or an inordinately large number of trays with an awkward shape of chamber. The laminar chamber has the advantage of giving theoretically perfect collection efficiency for particles of the designated size, but is of little practical value since the efficiency drops off rapidly with smaller particles. It is virtually impossible to collect very small particles with reasonably good efficiency using a settling chamber.

The most practical flow in the settling chamber will probably be turbulent rather than laminar. The turbulent chambers offer a more practical design

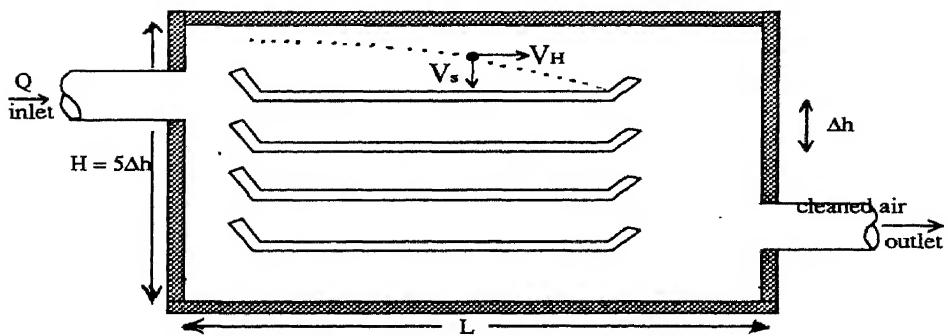
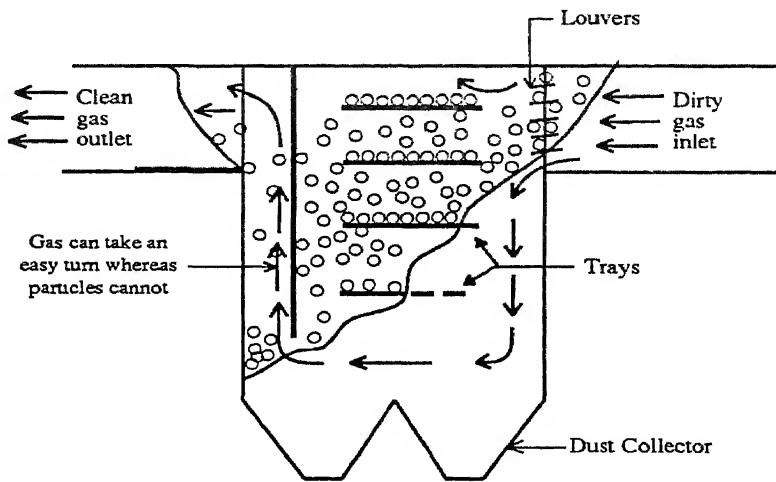
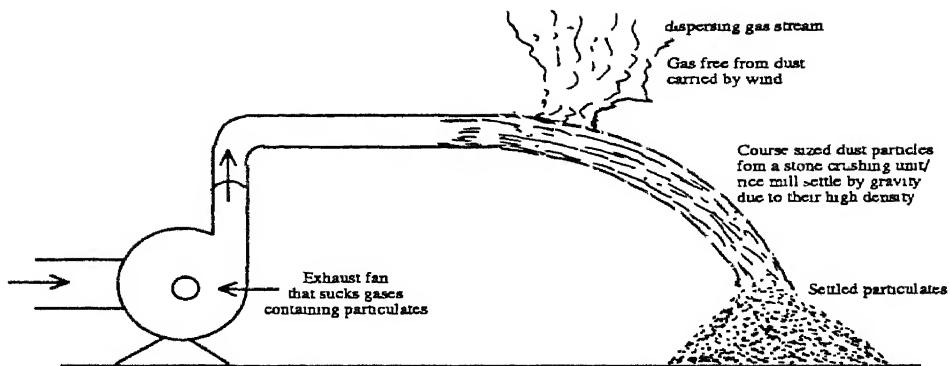


Figure 7.1 Gravity Settling Chambers

concept, although no matter how big it may be, theoretically the chamber will never collect all particles of a specified size. The chamber should be reasonably designed for the removal of 99 percent of the particles which are as large or larger than some specified diameter, for example 50 or 100 μm . The turbulent settling chamber's design is also made by two assumptions : first, there is a laminar layer adjacent to the bottom surface of the passage into which turbulent eddies do not penetrate, because any particle which crosses into this layer will be captured shortly. Second, in the remainder of the flow passage the eddying motion due to turbulence will cause a uniform distribution of particles of all sizes.

Consider a settling chamber having dimensions $L \times W \times H$, and containing 'n' number of trays including the bottom surface of the chamber as shown in fig. 7.1. In this section we shall assume the case of laminar flow in the passage ways between the trays ; this condition is less common but does sometimes occur. The criterion for laminar flow is that the Reynolds number, which is based on hydraulic diameter, should be less than 2300. The hydraulic diameter for flow passage between the trays is given by

$$D_h = \frac{2W\Delta H}{W + \Delta H} \quad \dots \dots \dots \quad (7.1)$$

The Reynolds number,

$$R_e = V D_h \rho / \mu \quad \dots \dots \dots \quad (7.2)$$

The velocity inside the chamber 'V' is given by

$$V = Q / nW \Delta H \quad \dots \dots \dots \quad (7.3)$$

where Q = flow rate of the gas stream.

Substituting for V and D_h in Eqn. (7.2)

$$Re = \frac{2Q\rho}{n\mu(W + \Delta H)} \quad \dots \dots \dots \quad (7.4)$$

If the thickness of the trays is neglected the distance between the trays is related to the height of the settling chamber as, $\Delta H = H / n$

Then Eqn. (7.4) becomes

$$Re = \frac{2Q\rho}{\mu(nW + H)} \quad \dots \dots \dots \quad (7.5)$$

It is to be noted that these equations hold good only when there is no dust layer collected in the trays. If a layer of dust of thickness H_d is present, then equation (7.5) becomes.

$$Re = \frac{2Q\rho}{\mu(nw+H-nH_d)} \quad \dots \dots \dots \quad (7.6)$$

For laminar flow conditions ($Re < 2300$) within the trays, particles of size d_p of a particular material will settle a distance 'y' with a terminal velocity V_t in time 't', given by, $t = y/V_t$

During this same time the particles are transported a distance L, with the velocity of the gas stream 'V' i.e., $t=L/V$

Equating these two,

$$y/V_t = L/V \quad \dots \dots \dots \quad (7.7)$$

The value of "y" can be found from a knowledge of the particle settling velocity. If the particles are assumed to be uniformly distributed over the incoming streams, the efficiency of collection for particles having the diameter used in calculating V_t is given as the ratio of y to ΔH .

$$\text{Efficiency, } \eta = y/\Delta H = \frac{LV_t}{V\Delta H} = \frac{nWLV_t}{Q} \quad \dots \dots \dots \quad (7.8)$$

\therefore For 100% η , length of chamber $L = Q/nWV_t$. When length is more or when $y \geq \Delta H$, all particles of that size (or larger) will be collected in the settling chamber.

The terminal settling velocity can be calculated by using the Stoke's law

$$V_t = gd_p^2 (\rho_p - \rho_g) / 18 \mu_s \quad \dots \dots \dots \quad (7.9)$$

Stoke's law is a reasonable approximation for calculating the settling velocity of particulates suspended in air also. This Stoke's law is accurate for particles smaller than $100\mu\text{m}$. The minimum particle size that can be removed with 100% efficiency can be found from the equation.

$$d_{p \text{ min}} = \sqrt{18 Q \mu_s / n W L g (\rho_p - \rho_g)} \quad \dots \dots \dots \quad (7.10)$$

The above equations should be used only as guides to the collection efficiency of the settling chamber, as several factors cause deviations. These include hindered settling at high particle concentrations, non-uniform gas velocity over the settling height and width, particle re-entrainment and turbulence. As a general rule, chamber velocities below 3 m/s are satisfactory for avoiding reentrainment of most of the materials. If the flow is turbulent, the collection efficiency of a settling chamber is given by:

$$\text{efficiency } \eta = 1 - e^{(-nLWV_t/Q)}$$

7.5 CYCLONES

This class of separators is the most common of a general group of separators that are classified as centrifugal (or) inertial separators. It depends upon centrifugal force instead of gravity to separate 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. Reverse Flow Cyclones, as shown in figure 7.2, consist of a cylindrical shell, a conical base, dust hopper and an inlet where the dust-laden gas enters tangentially. Under the influence of the centrifugal force generated by the spinning gas, the solid particles are thrown to the walls of the cyclone as the gas spirals upward at the inside of the cone. The particles slide down the walls of the cone and into the hopper. The operating (or) separating efficiency of cyclone depends on the magnitude of the centrifugal force exerted on the particles. The greater the centrifugal force, the greater the separating efficiency. The magnitude of the centrifugal force generated depends on particle mass, gas velocity within the cyclone and the cyclone diameter etc.

Design Concepts

1. Separation Factor : In a cyclone, the inertial separating force is the radial component of the centrifugal force and is a function of the tangential velocity. The centrifugal force, F_c , is given by

$$F_c = \frac{mv_o^2}{r} \text{ where}$$

m = mass of the particle

v_o = tangential velocity of the particle

r = radius of rotation

The magnitude of the centrifugal force is frequently described in terms of the number of times this force exceeds the force of gravity. The separation factor S is given by

$$S = \frac{V_o^2}{gr}$$

The separation factor varies from 5 in large, low velocity units to 2500 in small, high pressure units. Obviously, the higher the separation factor, the better is the performance of the cyclone.

2. Cut size : Cut size d_{pc} , is the size of those particles that are collected with 50% efficiency. The particles larger than d_{pc} will have a collection efficiency greater than 50% while the smaller particles will be collected with lesser efficiency.

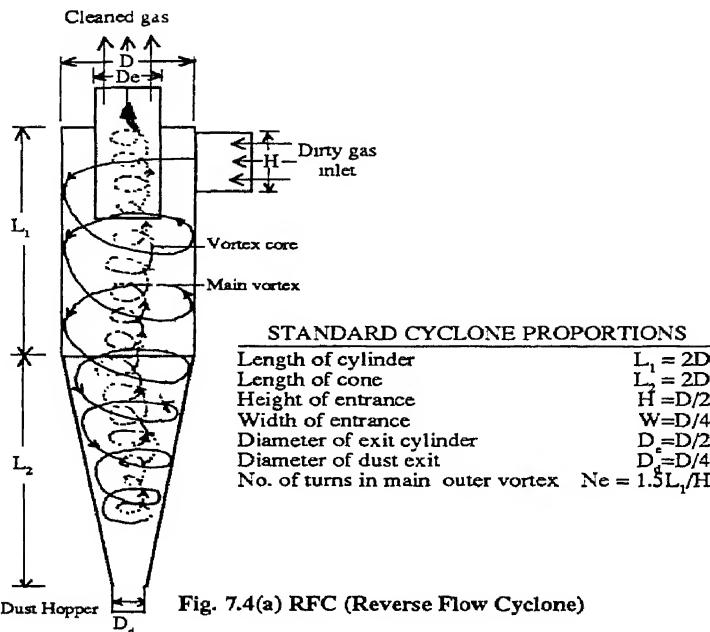


Fig. 7.4(a) RFC (Reverse Flow Cyclone)

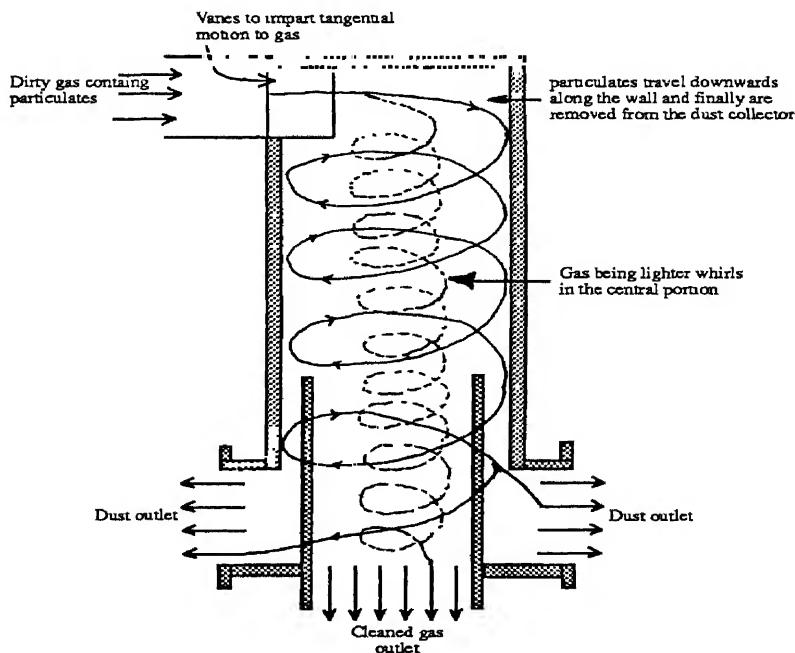


Fig. 7.4(b) Straight Flow Cyclone Separator

The cut size of particle given by Laplace is :

$$d_{pc} = \sqrt{9\mu_g b / 2\pi N_e V_i (\rho_p - \rho_s)} \quad \dots \dots \dots (7.11)$$

where μ = gas viscosity, (kg/m-sec)

b = width of cyclone inlet, m

N = number of effective turns within the cyclone (5 to 10 in most cases)

V_i = inlet gas velocity, m/s

ρ_p = density of the particulate matter, kg/m³ and ρ_g = gas density

3. Pressure Drop: In addition to collection efficiency, a correct estimate of the pressure drop across a cyclone is necessary, so that cost effectiveness may be calculated. The acceptable operating range is of magnitude 25 cm water or less. Pressure drop is proportional to the density of gas and square of the inlet gas velocity.

Many types of commercial cyclones have been developed and information on their performance for specific applications is generally available. Cyclones are divided into two classes - conventional and high efficiency. High efficiency cyclones merely have a smaller body diameter to achieve greater separating forces. The efficiency ranges of cyclones are shown in table 7.1

TABLE 7.1 : EFFICIENCY RANGES OF CYCLONES

Particle size range (microns)	Efficiency range % weight collected	
	Conventional	High effic.
Less than 5	Less than 50	50-80
5-20	50-80	80-95
15-40	80-95	95-99
40 and above	95-99	95-99

In general, efficiency will increase with increase in dust particle size or density, gas inlet velocity, cyclone body or cone length and ratio of body diameter to gas outlet diameter and decreases with gas viscosity or density, cyclone diameter, gas outlet diameter and outlet velocity. However, there is a limiting value of inlet velocity above which turbulence causes an increase in pressure drop and a decrease in collection efficiency.

In straight flow cyclone, the inner vortex of the air leaves at the bottom with initial centrifugal motion being imparted by vanes at the top. The chief advantages of this unit are low pressure drop and high flow rates. In the

impeller collector, gases enter normal to an impeller and are swept out by the impeller around its circumference while the particles are thrown into an annular slot around the periphery of the device. The main advantage of this unit is its compactness, but a drawback is plugging from solid buildup in the unit. For high efficiency at reasonable capacity, a battery of smaller cyclones operating in parallel is used in preference to a large unit that requires less space. Now a days, RFCs (Reverse Flow Cyclones) are mostly used in industrial operations for particulate control.

7.6 FABRIC FILTERS

One of the oldest and most widely used methods of separating particulates from a carrier gas is 'filtration'. A filter generally is a porous structure composed of granular or fibrous material which tends to retain the particulate and allows the gas to pass through the voids of the filter. Small particles are initially retained on the fabric by direct interception, inertial impaction, diffusion, electrostatic attraction and gravitational settling. 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. Fibrous and deep bed filters have large void spaces amounting from 97 to 99% of the total volume. Fabric filters are made in the form of tubular bags or cloth envelopes and are suitable for a dust loading of the order of 1 g/m^3 . They are capable of removing dust particles as small as 0.5 microns and will remove substantial quantities of particles as small as 0.1 microns also. A bag house consists of 2 to 6m long bags, the upper ends of which are closed and lower ends are attached to an inlet manifold. The hopper at the bottom serves as a collector for the dust.

The gas entering through the inlet pipe strikes a baffle plate, which causes the larger particles to fall into a hopper due to gravity. The carrier gas then flows upward into the tubes and then outward through the fabric leaving the particulate matter as a "cake" on the inside of the bags. The filter efficiency during pre-coat formation is low, but increases as the pre-coat (cake) is formed, until a final efficiency of over 99% is achieved. This precoat acts as a part of the filter medium, which helps in further removal of the particulates. Thus dust becomes the actual filtering medium. The bags , in effect, act primarily as a matrix to support the dust cake. The cake is usually formed in a matter of minutes or sometimes even seconds.

The accumulation of dust increases the air resistance of the filter and therefore filter bags have to be cleaned periodically. The cleaning can be done by rapping, shaking or vibration or by reverse air flow, causing the filter cake to be loosened and to fall into the hopper below. The gas is to be passed through

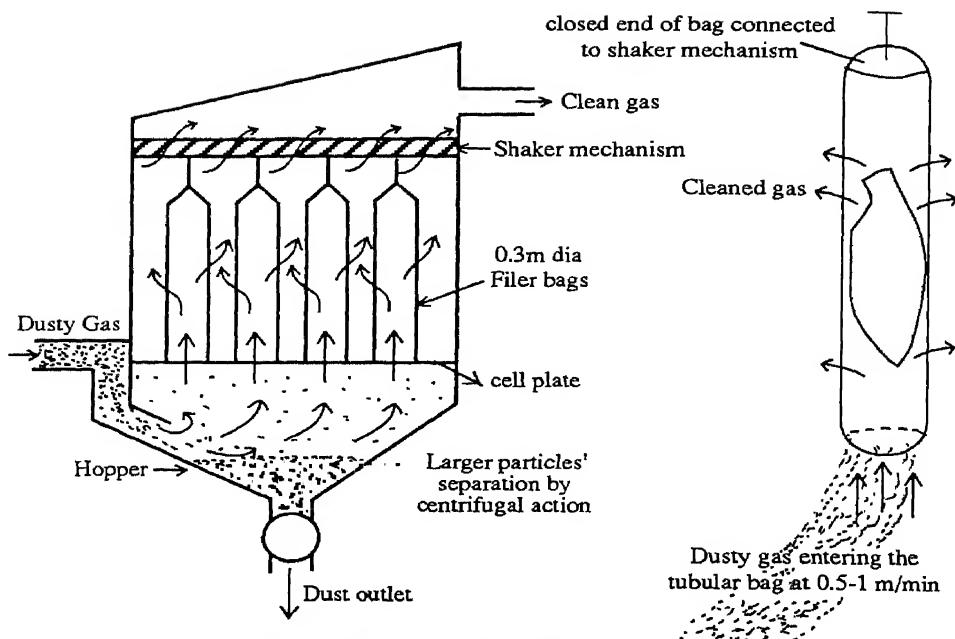


Fig. 7.3 Bag House (Fabric Filter)

the bags at a velocity of 0.4 to 1m/min. Efficiency of bag filters may decrease on account of the factors like excessive filtration and selection of filter media. The ratio of the carrier gas volume to gross filter area per minute flow of gas is termed as 'filter ratio'. Excessive filter ratio will lower the particulate removal efficiency and results in increased bag wear.

Operational Problems

Operational problems associated with the use of fabric filters are :

- 1) **Cleaning :** After few hours of operation, the filters get so clogged up with a covering of dust particles that the gas can no longer pass through them. 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 (i.e. shaking), the greatest problem inherent in cloth filters is rupture of cloth. It is often difficult to locate ruptures and when they are found the replacement time is often considerable.
- 3) **Temperature :** Generally, the filters are designed for about 250°C to 300°C . The temperature related problem occurs whenever the effluent contains a reactive gas such as sulphur dioxide which can form an acid

if the temperature in the bag house falls below the dew point. This can be prevented by having the bag house fairly well insulated. Sometimes, an auxiliary heater is used in winter season so that the temperature does not fall below the acid-gas dew point.

- 4) **Bleeding :** Bleeding is the penetration of fine particles through the filters. Bleeding occurs if the weave is too open or if the superficial filtration velocity (filter ratio) is too high. Generally, smaller particles only can penetrate through the fabrics and they only are responsible for primary human health hazard. The solution to bleeding problem is to use a double layer material of a thick woven fabric.
- 5) **Humidity :** Humidity control is a common and an important problem especially if a hygroscopic dust is involved. This problem can be overcome by taking suitable precautions.
- 6) **Chemical Attack :** Another problem associated with fabric filters is the possibility of chemical attack due to corrosive chemicals such as SO₂, present in the process effluents. Acid / Alkali Resistant filter cloths are to be used in such cases.

Filter Cleaning

Filter cleaning is one of the important operating problem in fabric filters. The filter cleaning can be done by the following methods.

- 1) Shaking 2) Reverse air flow (back wash) 3) Pulse jet
- 1) **Shaking :** Bag house units can range in size from those with only half a dozen bags that are shaken manually upto a very large system containing hundreds of bags that are shaken mechanically. The bags are joined to the shaker frame work by a rod and each shaker assembly consists of an electric motor, connecting arms and bearings. This method is not used for sticky dusts because the forces needed to remove the collected dust would probably cause tearing and rapping in the bags very quickly.
- 2) **Reverse Air Flow:** In this unit, the filter is cleaned by a high velocity air jet which is discharged from the inner side of a traversing ring that moves on the outside of the filter tube. The air jet passes through the fabric in a direction reverse to the normal flow and removes cake continuously from the filter surface. The main advantages of this method are (1) it requires no shut downs or programming for cleaning. Blow rings are a continuous cleaning mechanism in that some part of each bag is being cleaned at all times (2) The cloth resistance can be maintained at a nearly constant value (3) The filters work at higher velocity of 3 to

6m/min as compared to 0.5 to 2 m/min for the usual cloth filters. But, the main disadvantage of the blow rings are mechanical linkages and the individual air hose attachments required for each bag, resulting in increased maintenance costs.

- 3) **Pulse Jet:** Here, a jet of high pressure air is blasted periodically down the inside of the bag which is supported by a wire frame. During the filter cleaning, the air jet inflates the bag momentarily. When the bag is inflated the dust cake is loosened and falls into the hopper below. The two main advantages of this system are that there are no moving parts and continuous cleaning is possible. Also duration of the cleaning is insignificant compared to the length of filtering time between cleaning intervals. The pressure involved in operation is moderate to high. In general, while selecting the specific method of filter cleaning, we have to consider the cleaning mechanism, frequency and duration of cleaning and any undesirable effects on the bags.

Selection of Filter Medium

While selecting the filter medium for bag houses, we must consider the characteristics and properties of the carrier gas and dust particles such as (i) carrier gas temperature (ii) carrier gas composition (iii) gas flow rate (iv) size and shape of dust particle and its concentration.

As far as the fabric is concerned, its abrasion resistance, chemical resistance, tensile strength and permeability should be considered. Of course, the cost of the fabric is also an important consideration. Apart from fabrics, a wide variety of filter cloths are available commercially. Cotton fabrics are used extensively where gas temperature is below 80°C, and acid gases are absent. Wool fabrics are more resistant to acid than cotton and are used in the collection of metallurgical fumes and for fine and abrasive dusts such as cement. Other than this, many synthetic filter fabrics like nylons, polyesters are used in special applications. Table 7.2 gives the properties of different filter materials.

Advantages and Disadvantages of the Fabric Filters

Advantages

1. High collection efficiency for all particle sizes especially for particles smaller than 10 micron diameter
2. Simple construction and operation
3. Nominal power consumption
4. Dry disposal of collected material

TABLE 7.2 PROPERTIES OF THE FILTER MATERIALS

Filter Material	PHYSICAL CHARACTERISTICS				RELATIVE RESISTANCE TO ATTACK BY				Tensile strength kg/cm ²
	Relative Strength	Specific Gravity	Normal moisture content (%)	Max. usable temperature (°C)	Acid	Fluoride	Alkali	Abrasion	
Cotton	Strong	1.6	7	80	Poor	Poor	Good	Very Good	4920
Wool	Medium	1.3	15	100	Medium	Poor to Fair	Poor	Fair	1755
Nylon	Strong	1.1	5	100	Poor to Fair	Poor	Good to Excellent	Excellent	5625
Orión	Medium	1.2	1	120	Good to Excellent	Poor to Fair	Fair to Good	Good	5270
Dacron	Strong	1.4	0.4	140	Good	Poor to Fair	Good	Very Good	5625
Poly ethylene	Strong	1.0	0	120	Medium	Medium	Medium	Good	7730
Nomex	Strong	1.4	5	230	Poor to Good	Good	Good to Excellent	Excellent	5625
Fiber Glass	Strong	2.5	0	260	Fair to Good	Poor	Fair to Good	Fair	14000
Teflon	Strong	2.3	0	260	Excellent	Poor to fair	Excellent	Poor to Fair	1400

Disadvantages

1. Operating limits are imposed by high carrier gas temperatures, high humidity, etc.
2. High maintenance and fabric replacement costs (replacing of leaking bag)
3. Larger size of equipment
4. Problems in handling dusts which may abrade, corrode or blind the cloths.

Application of Fabric Filters

Fabric filters are extensively used in the following industries and operations.

1. Metallurgical industry
2. Foundries
3. Cement industry
4. Chalk and lime plants
5. Brick works
6. Ceramic industry
7. Flour mills etc.

7.7 ELECTRO STATIC PRECIPITATORS

The electrostatic precipitator is one of the most widely used devices for controlling particulate emissions from industrial installations ranging from house hold appliances to power plants, cement and paper mills and oil refineries. In most cases, the particulates to be collected are by-products of combustion. In others, they are dust fibres or other small particles such as acid mists from process industries. The electrostatic precipitators are particulate collection devices that utilize electrical energy directly to assist in the removal of the particulate matter. These are successfully used for removal of fine dusts from all kinds of waste gases with very high efficiency. The particles as small as a tenth of a micron also can be removed efficiently. The principle on which this equipment operates is that when a gas containing aerosols is passed between two electrodes that are electrically insulated from each other and between which there is a considerable difference in electric potential, aerosol particles precipitate on the potential electrode, which are subsequently removed.

There are various types of electrostatic precipitators used for different industrial purposes. They can also be used for air cleaning in public buildings, theatres, railways, cars etc.

Electrostatic precipitator consists of six major components viz.

1. A source of high voltage
2. Discharge electrodes and collecting electrodes
3. Inlet and outlet for the gas

4. An electronic cleaning system
5. 'Hopper' for collection and disposal of particulates
6. An outer casing (called shell) to form an enclosure around the electrodes.

Principle of ESP

Electrostatic precipitation is a physical process by which particles (solid or liquid) can be removed from the gaseous streams. The gas stream is passed between a pair of electrodes, across which high potential difference is maintained. The electrodes are discharge electrode at a high potential and an electrically grounded collecting electrode. Due to the high potential difference, a powerful ionising field is formed. Under the action of electrical field, gas ions formed in the corona move rapidly towards the collecting electrode and transfer their charge to the particles by collision with them. The electrical field interacting with the charge on the particles then causes them to drift towards, and be deposited on the collecting electrode. The particles deposited on the collecting electrode lose their charge and then are removed mechanically by rapping or vibration to a hopper below the electrical treatment zone and are collected for ultimate disposal. When the particles are liquid droplets, the collected droplets coalesce on the collecting electrode and drip off the bottom of that electrode into a collecting sump.

Types of Precipitators

The main electrical mechanisms for precipitation of particles are (1) supplying an electrical charge to the particles for gas ionisation and (2) supplying the electrostatic force that causes the charged particles to drift towards the collecting electrode (for collection of particles). In the usual industrial electrostatic precipitators both these charges are supplied simultaneously and the precipitator acts as a single stage unit. In some cases like air conditioning applications and a few industrial applications a two-stage precipitator is used in which the two mechanisms are separated. One set of electrodes supplies the electrical charge to the particles and a second set supplies the electrostatic force that precipitates the charged particles. Almost all industrial precipitators are of the single stage design. Depending on the electrode arrangements they may be classified as pipe type or plate type precipitators.

Pipe Type Precipitator : In the pipe-type precipitator, the nest of parallel pipes acts as the collecting electrode. The pipes may be of round, square or octagonal cross section. Generally the pipe is about 30 cm or less in diameter. The discharge electrode is a wire (2.8 mm dia) with a small radius of curvature, suspended along the axis of each pipe. The wires are suspended from an insulated hanger at the top and kept under tension by weights attached to their lower ends and strong enough to withstand rapping or vibrating for

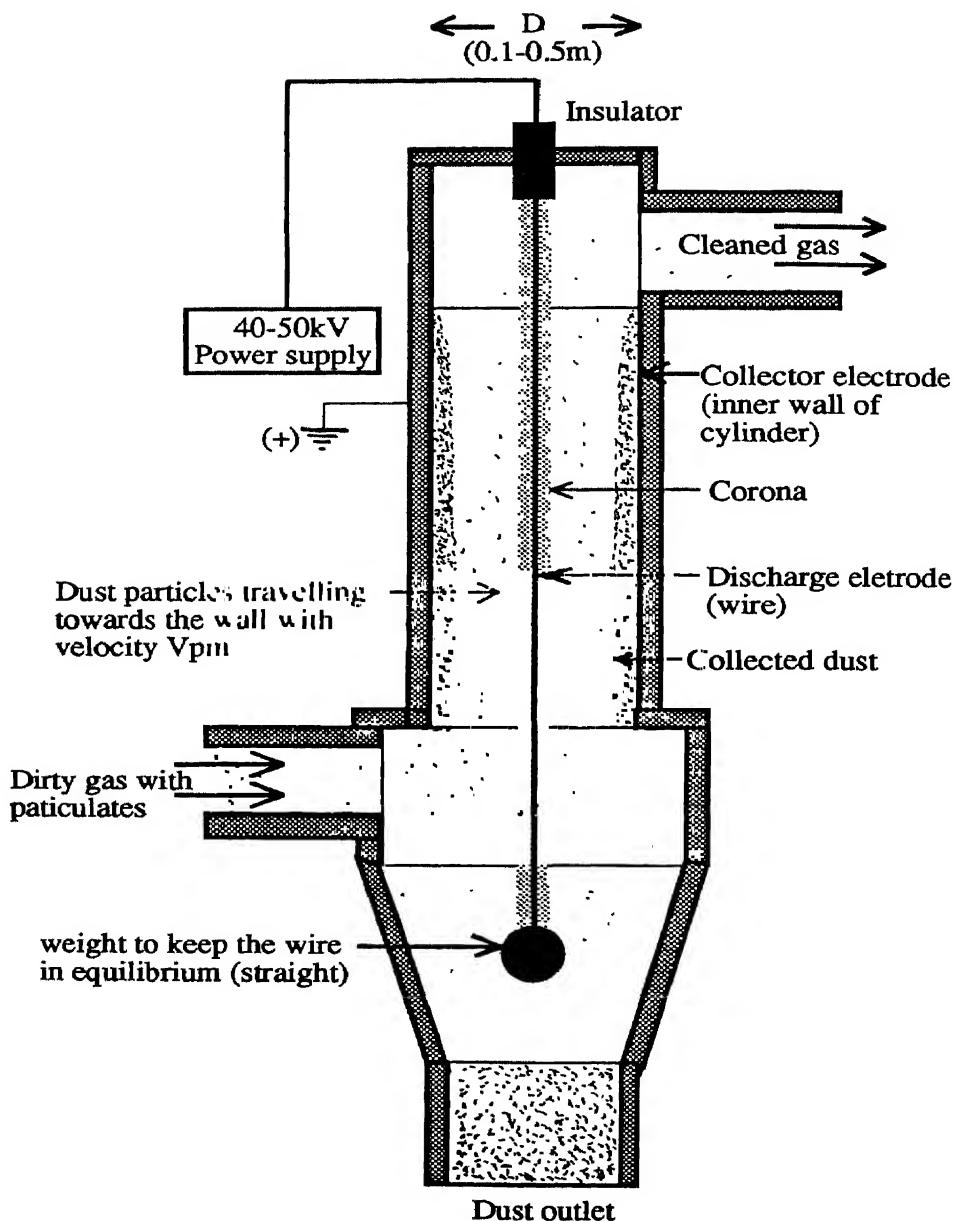


Fig. 7.4 Single Stage Cylindrical Electrostatic Precipitator

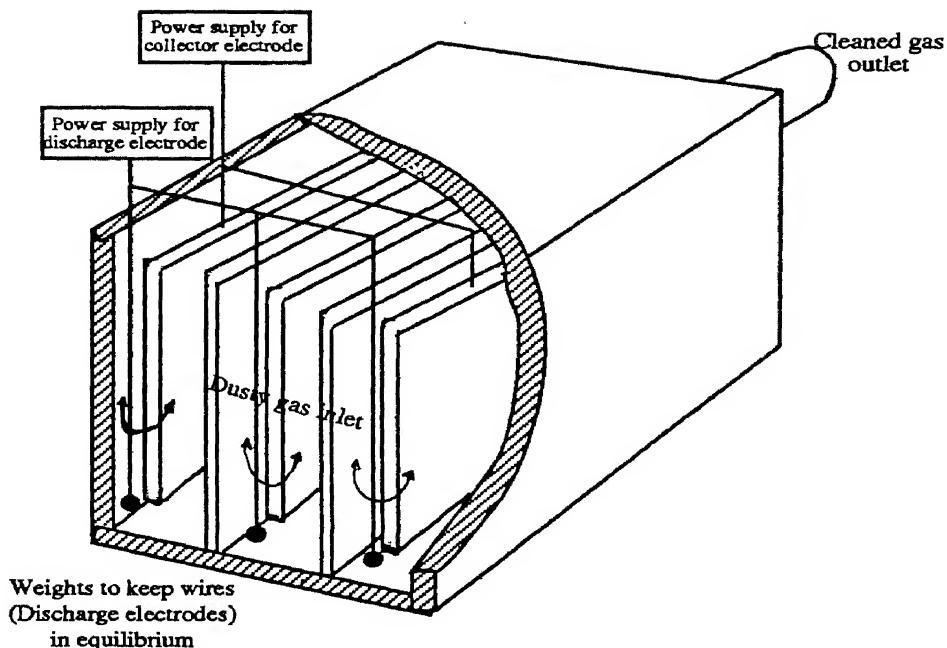


Fig. 7.5 (b) Parallel-Plate Two-Stage Electrostatic Precipitator

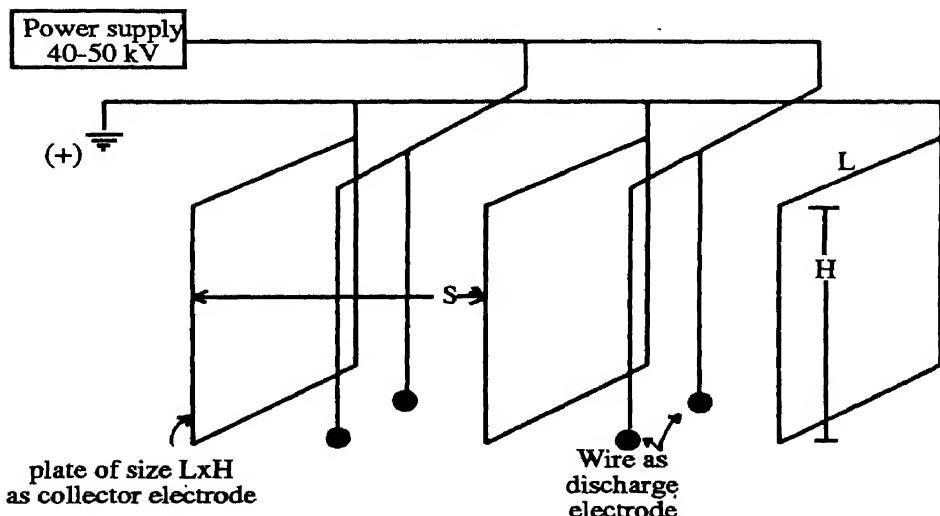


Fig. 7.5 (a) Parallel - Plate Single-Stage Electrostatic Precipitator

cleaning purposes. The gas flow path is down around the outside of the tubes and then up through the inside of the tubes. The pipe electrodes are 2 to 5 m in height/length.

As the gas flows upwards, electrostatic forces cause the dust particles to migrate to the collector electrode where they stick. The cleaned gas then emerges at the top. The collected dust (aerosols) is removed periodically from the collector electrodes by rapping it; this dust then falls to the dust hopper and is accumulated there for periodic removal. A power supply furnishes a large DC voltage on the order of 50 kV, which is either steady or pulsed; modern usage favours the pulsed DC voltage. Generally the pipe-type precipitators are used for the removal of liquid particles in which case no cleaning mechanism is required as the aerosols coalesce and fall into the hopper continuously.

Plate-Type Precipitators : In the plate-type precipitators, the collecting electrodes consist of parallel plates of size 1-2 m wide and 3-6 m high. These parallel plates are spaced at 20-30 cm. The number of plates in the precipitators depend upon the inlet flow, so that the inlet gas velocities are 1-2 m/s in each channel. The discharge electrodes are similar to those used in pipe-type precipitator. Sometimes electrodes of square rods (4 to 5 mm) and twisted square rods (3.2 to 6.4mm) are used. These discharge electrodes (i.e. wires), made from non-corrosive materials like tungsten, alloys of steel and copper are suspended from the top and hang free with a weight attached at the bottom to keep them straight. The collection of the aerosols takes place on the inner sides of the parallel plates. The dust material collected can be removed by rapping and vibrating periodically.

The plate-type precipitators are generally employed for the collection of solid particulates. The collection efficiency of the precipitator depends upon the collection surface, bulking resistance and resistance to corrosion of the collection electrode.

Collection Efficiency of the ESP

The electrostatic precipitator is a high efficiency collector. The objective of visually clear stacks has made it necessary for many installations to operate at efficiencies of 98-99% and in some cases in the 99.5-99.9% range. Some materials ionise more readily than others and are thus more adopted to removal by electrostatic precipitation. Acid mists and catalyst recovery units often have efficiencies in excess of 99%. Over 60% of the installed capacity of precipitators in United States is used for fly ash recovery and the remaining capacity is used mainly for the detarring of fuel gases and for carbon black recovery. Carbon black cannot be removed efficiently because of its agglom-

erating tendency. However, by proper combination of an ESP with a cyclonic collector, high efficiencies may be obtained in collecting carbon black.

The gas flow in a precipitator is normally turbulent because of electric wind effect. The "electric wind" is the motion of the gas at right angles to the main gas flow, induced by the motion of the gas ions streaming from the discharge electrode to the collecting electrode. As a result of the turbulence, the collection efficiency takes on an exponential form as determined by W.Deutsch in 1922. Rose and Wood modified the equation with the assumption that turbulent mixing effect is intense enough so that the particle concentration is constant over any cross-sectional area at right angles to the main gas flow. The given equation for efficiency of ESP is a function of gas flow rate and precipitator size and is applicable to both cylindrical and parallel plate type precipitation. The collection efficiency equation is

$$\text{Efficiency} = 1 - \exp\left(\frac{-A_c V_p}{Q}\right) \text{ where}$$

V_p = particle migration velocity, m/sec

A_c = collector surface area, m^2

Q = Volumetric flow rate of the gas, m^3/sec

Dust Removal : The dusts are deposited on the collector electrode during the operation of ESP. After sometime, the thickness of the dusts collected increase to 1 to 2 cms, which decreases the efficiency of the collection electrode. When the dust resistivity becomes more than $2 \times 10^{10} \text{ ohm-cm}$, the working of the system is stopped. A dust resistivity of 10^9 to 10^{10} ohm-cm is desired for ESPs. If resistivity increases it becomes difficult to maintain corona discharge and hence back-ionisation occurs decreasing the efficiency. Particles of high resistivity may be conditioned with moisture to bring them into the acceptable range. This can be achieved by spraying water or steam into the gas stream at inlet. If the resistivity is less, particles are charged easily but dissipate it so quickly that the particles are reentrained in the gas stream, again decreasing the efficiency. 'Dust resistivity' is a function of the composition of the dust, the continuity of the dust layer, operating temperature and the voltage gradient in the dust layer. Thus, when the dust resistivity is high, the collecting electrodes should be cleaned to 0.2 to 0.3 cm of dust thickness, by rapping or vibrating the collecting electrode. The dislodged particles are collected in the dust hopper. If the particulates are 'liquid droplets' they are automatically drained into the hopped bottom by gravity. Both collecting and discharge electrodes must be cleaned of dust to reduce electrical resistance of the dust layers and permit continued operation. Dust build-up on wires is difficult to be removed and occasionally the deposited dust resem-

bling 'dough nuts' or 'grape fruits' must be removed by hand cleaning or electrode rapping. The frequency and intensity of the rapping cycle have an important effect on the collection efficiency of the precipitator. A high collection efficiency requires that the dust, when rapped loose from the collecting plate, should fall as coarse aggregates, so that the dust is not redispersed into the gas stream. Cylindrical ESPs are preferred to collect liquid particles with high efficiency.

Reentrainment: In the derivations of collection efficiency equations, reentrainment of the deposited dust is usually neglected. The reentrainment has no effect on liquid droplets but for dry particles, reentrainment losses can markedly reduce the efficiency. There are number of different causes of reentrainment. Gas flow through the hoppers can sweep collected dust back into the gas stream. This can be minimized by providing baffles in the hoppers to reduce the circulation of gas.

TABLE 7.3 EFFECTIVE MIGRATION VELOCITIES, V_p

S.No.	Application	V_p (m/s)
1)	Pulverized coal fly ash	0.10 - 0.13
2)	Paper mills	0.08
3)	Open hearth furnaces	0.06
4)	Secondary blast furnaces	0.12
5)	Gypsum	0.16 - 0.20
6)	Sulphuric acid mist	0.06 - 0.08
7)	Hot phosphorous	0.03
8)	Cement wet process	0.10 - 0.11
9)	Cement dry process	0.06 - 0.07
10)	Catalyst dust	0.08

Advantages and Disadvantages of Electro Static Precipitators

Advantages:

1. High collection efficiency.
2. Particles as small as 0.1 micron can be removed.
3. Low maintenance and operating costs.
4. Low pressure drop (0.25 to 1.25 cm of water).
5. Satisfactory handling of large quantities of high temperature gas.

6. Treatment time is negligible (0.1 to 10 seconds).
7. Cleaning is easy by removing units of the precipitator from operation.
8. There is no limit to solid, liquid or corrosive chemical usage.

Disadvantages

1. High initial cost.
2. Space requirement is more because of the large size of the equipment.
3. Possible explosion hazards during collection of combustible gases or particulates. Well trained personnel are necessary to operate.
4. The poisonous gas, ozone is produced by the negatively charged discharge electrodes during gas ionization.
5. Precautions are necessary to maintain safety during operation (i.e. proper gas flow distribution, gas resistivity, particulate conductivity etc.).
6. Gases cannot be removed by ESPs.

Applications of Industrial Precipitators: The important applications of electrostatic precipitators in industries are given in the following table

S.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 oven 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 vapour state
5.	Petroleum industry	-Recovery of catalyst dust
6.	Carbon black industry	-Agglomeration and collection of carbon black
7.	Thermal power plants	-Collecting fly ash from coal fired boilers

Design Considerations of ESP : The efficiency of the ESP is given by

$$\eta = 1 - \exp \left(\frac{(-V_p A_c)}{Q} \right) \text{ where}$$

$Q = \text{Gas flow rate} = \pi D^2/4 \times V_g$ for a cylindrical ESP

and $HS \times V_g$ for a parallel plate ESP

V_g = Inlet gas velocity (about 1 to 3 m/sec)

D = Diameter of cylinder (0.1 to 0.5m)

S = Height of collecting electrode (2 to 6m)

A_c = Area of collecting electrode, m^2

= $2HL$ for parallel plate ESP

= πDL for cylindrical ESP where

L = Length of the collecting electrode

V_p = Drift velocity or migration velocity (0.05 to 0.2 m/sec)

Migration velocity is probably the most important parameter. It is a function of different operational quantities like electric field strength, particle size, viscosity of gas and dielectric and resistivity properties of the dust.

The drift velocity is normally given by $V_{pm} = a \times dp$

where, 'dp' is the diameter of the particle and 'a' is a constant. Thus V_{pm} is more if diameter of the particle is more. Normally, it ranges from 0.05 to 0.2 m/sec. 'a' is a constant for a given system and is a function of voltage applied, properties of gas and the ability of the particle to accept an electric charge. Normally, drift velocity is measured experimentally for a given system. The values of V_p are presented in Table 7.3

7.8 WET SCRUBBERS / WET COLLECTORS

Nature uses 'wet scrubbing' as the method of cleaning herself since the world began. Rain or precipitation scrubs the air containing dusts and gases, as a result of which fresh-air sensation is experienced by one and all after a rain.

Wet scrubbers are more universal in that they can function as either or both particulate and gas control devices. These particulate control devices utilize a liquid to assist in the removal of particulates from the carrier gas stream. In these devices water is the mostly used scrubbing liquid. In these wet collectors, the particulates are agglomerated with water and then separated into cleaned gas and contaminated liquid streams. For particulate matter, material transfer between the gas and liquid phases may be by a variety of mechanisms. For gaseous molecules, it is mainly diffusion. Particulate removal mechanism involves inertial, gravitational, electrostatic, thermal and diffusional phenomena. Wet scrubbers have the advantage of handling hot gases and sticky particulates and liquids. The disadvantages are that they require more operating energy and discharge wet gases and produce a wet

product which results in problems like corrosion. Huge quantities of water at the rate of 0.05 - 0.20 m³ of water per 100 m³ of gas are required, which in turn produce significant quantities of sludges.

Wet scrubbing method involves four major steps in collecting the particles. The stages are -transportation, collision, adhesion and precipitation. The particles are moved to the vicinity of the water droplets and collide with each other. The particles are adhered to the liquid media and precipitated to the bottom of the unit containing the dust particles from the gas phase. In addition to removing entrained particulate matter, scrubbers can also remove gases by absorption and adsorption. This capability of scrubbers is not possessed by any other type of particulate control equipment. Scrubbers can remove particles of size 0.1 to 200μm efficiently.

Collection Mechanism

Particulates are removed from the gas stream mainly by absorption and adsorption.

Absorption by Impingement and Interception : When gas containing dust is swept through an area containing liquid droplets, dust particles will impinge upon the droplets, adhere and are finally collected by them. In general, the efficiency of collection is more when the liquid droplet is approximately 100 to 300 times the size of the dust particle, in order to increase the number of inelastic collisions.

Interception occurs when the particles have less inertia and almost follow the stream lines. Particles that move with the gas stream may not impinge on the droplets and adhere to them. This interception mechanism is predominant for particles of diameter above 0.3 μm.

Adsorption by Diffusion or Condensation : Diffusion of the disper-soid onto the liquid medium helps in the removal of the particulate matter. This diffusion prevails for particles of diameter below 0.2 mm.

Similarly, condensation of the liquid medium vapours on the particulates increases the size and weight of particles, which exerts a force upon the particles and forces them to get deposited on the surface.

The applicability of each type of design is upto a certain range. Of these, the efficiency of a scrubber is dependent to a great extent upon impingement and Brownian diffusion. Thus, low energy scrubbers such as spray towers are most often used to handle particles largely above 5 - 10 μm in diameter, while high energy units such as the venturi scrubber are very effective with fine particles (< 3μm).

Types of Scrubbers

Presently, there are many scrubber designs available, where the contact between the scrubbing liquid and the particles is achieved in a variety of ways. The common and important types of scrubbers are as follows:

1. Spray towers
2. Venturi scrubbers
3. Cyclone scrubbers
4. Packed scrubbers
5. Mechanical scrubbers

Spray Towers : A spray tower is the simplest type of wet scrubber into which water is introduced by means of spray nozzles (Fig : 7.6). It can be either round or rectangular, in which gas is passed, counter-current to falling drops of liquid (usually water) from spray nozzles. The particle collection can be done by the mechanism of inertial impaction and interception on the droplets. Spray towers cause very little pressure loss (energy) and can handle large volume of gases. The towers are very effective in removing, particles in excess of $10\mu\text{m}$. 'Stairmand' found that collection efficiency by inertial impaction is independent of particle size, when droplets fall under gravity through air. The maximum efficiency occurs if droplets have a diameter of $800\mu\text{m}$ (0.8 mm). The efficiency of a spray tower depends upon the droplet size, flow velocity of the gas, velocity of liquid etc. Spray tower effectiveness varies with the size of particles. It is 94 percent for $5\mu\text{m}$ particles to 99 percent for $25\mu\text{m}$ particles.

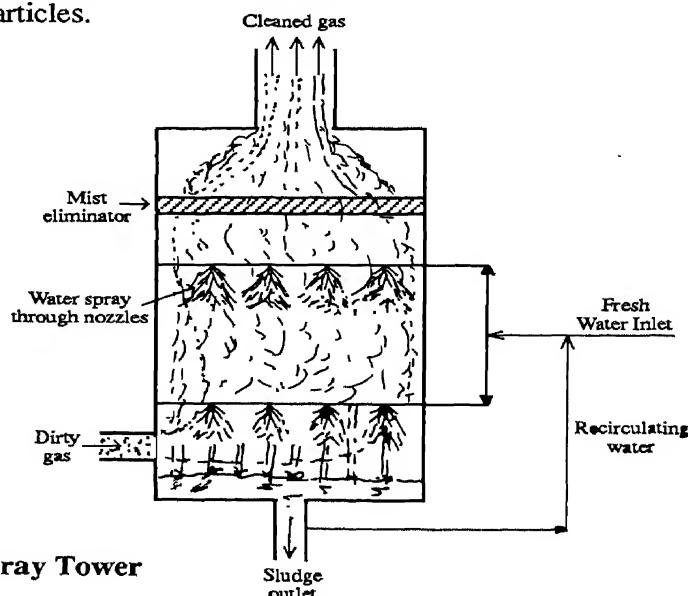


Fig. 7.6 Spray Tower

Venturi Scrubbers: Venturi scrubbers are high energy wet scrubbers with high performance collection of fine particles, usually smaller than 0.5 to 5 μm diameter. They are particularly suitable for submicron particulates associated with smoke, fume and also highly corrosive matter. Venturi scrubbers may have converging and diverging sections but usually the angles are greater to keep down the length. The high performance of the venturi scrubber is achieved by accelerating the gas stream to very high velocities, of the order of 60 - 180 m/s. Due to the high speed action, the feed liquid is atomized with a uniform fashion across the throat through several low pressure spray nozzles directed radially inward as shown in figure 7.7

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. The acceleration continues to some extent into the diverging section of the venturi. The gas liquid mixture is then directed to a separation device such as a cyclone separator where particulate matter is separated from the gas stream. The affecting mechanisms for collection of particulates in the scrubber are inertial impaction, diffusion, electrostatic phenomenon and condensation and agglomeration. But the principal mechanism is inertial impaction. The application of venturi scrubber is more oftenly in kraft mill furnaces, metallurgical furnaces, sulphuric acid concentrators etc. for removing mists and dusts from gases.

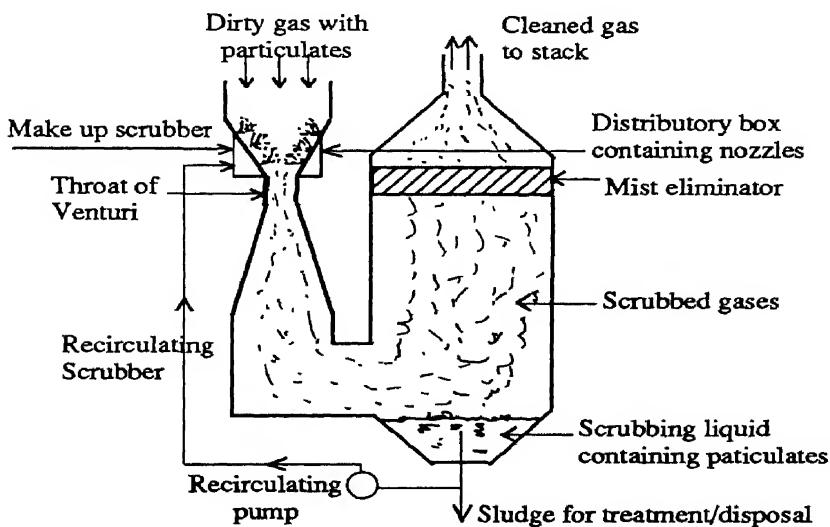


Fig. 7.7 Venturi Scrubber

Cyclone Scrubbers: It is the modification of the dry cyclone by the addition of liquid phase. In cyclone scrubbers, the gas is tangentially swirled around, same as in dry cyclone. Water sprays from the top of cyclone and outside the wall. These sprays assist in the collection of the dispersoid and prevent reentrainment. In cyclone scrubbers inertial impaction and separation are the main collection mechanisms. For droplets of $100\mu\text{m}$, efficiency approaches 100% and 90 to 98 percent removal is achieved for droplets between 5 and $50\mu\text{m}$. Generally, efficiencies slightly higher than those obtained with the spray tower or the dry cyclone can be expected.

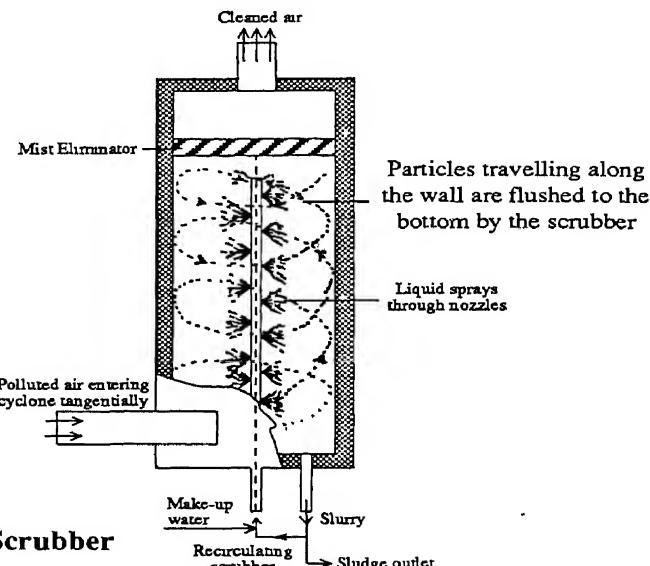


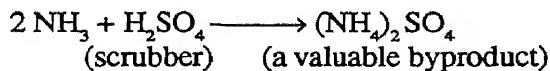
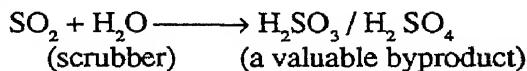
Fig. 7.8 Cyclone Scrubber

Packed Scrubber: In packed scrubber, fibre glass (fine glass filaments) or other packing (coke or broken stone) are used as the collection material. The polluted gas stream moves upward in a counter current-flow packed scrubber and comes in contact with the scrubbing liquid stream which is moving downward over the packing in a film. The gas stream passes through the packing pore spaces and captures the particles by the inertial impaction. Because of the good mass transfer characteristics of the packing, efficient collection of fine particles by diffusion is also possible. Smaller packing increases the efficiency of collection but its shape does not appear to affect the collection efficiency. Some times packing towers encounter plugging problems, which can be reduced by employing sprays to wash the packing or by using low density spheres etc. Recently a moist chemical foam packing has been employed, which drains slowly from the scrubber with captured particles and is replaced with fresh material.

Mechanical Scrubbers: Mechanical scrubber is the high energy scrubber, and has mechanical means of breaking up the scrubbing liquid into small droplets and simultaneously creating turbulence. It has internal rotating mechanical part, where the liquid dispersoid contact is achieved by the simultaneous introduction of the liquid medium and the gas stream. The scrubbing liquid drips down on the rotating part and is struck violently and disintegrated into fine droplets that are thrown radially by the centrifugal force and are removed quite easily. These scrubbers have a high initial cost, high operating cost and require considerable maintenance. The quantities of water required and wasted also are very high.

Advantages of Wet Collectors

1. Wet scrubbers have an additional advantage if some gases and particulates are to be removed simultaneously. For example, if SO_2 or NH_3 are the gases to be removed then,



H_2SO_4 and ammonium sulfate, $(\text{NH}_4)_2\text{SO}_4$ are valuable byproducts.

2. High removal efficiencies even for submicron sized particulates.

Disadvantages of Wet Collectors

1. High pressure losses and high operational costs.
2. Quantity of sludge developed is very high. Handling of such huge quantities of sludges is very difficult and costly. In a way air pollution is converted to water pollution. (This is something like 'law of conservation of pollution' that says that pollution can neither be created nor destroyed! While treating sewage often sludges are disposed off on land that converts water pollution to land pollution. Similarly, we see land pollution getting transformed to air pollution during the treatment of solid wastes by incineration).
3. Temperature of flue gases decreases significantly and hence the process may require after-burners. Otherwise, the wet plume would raise to a lesser height and may cause high ground level concentrations. Water vapour present in treated gas contributes to a visible plume under some atmospheric conditions.

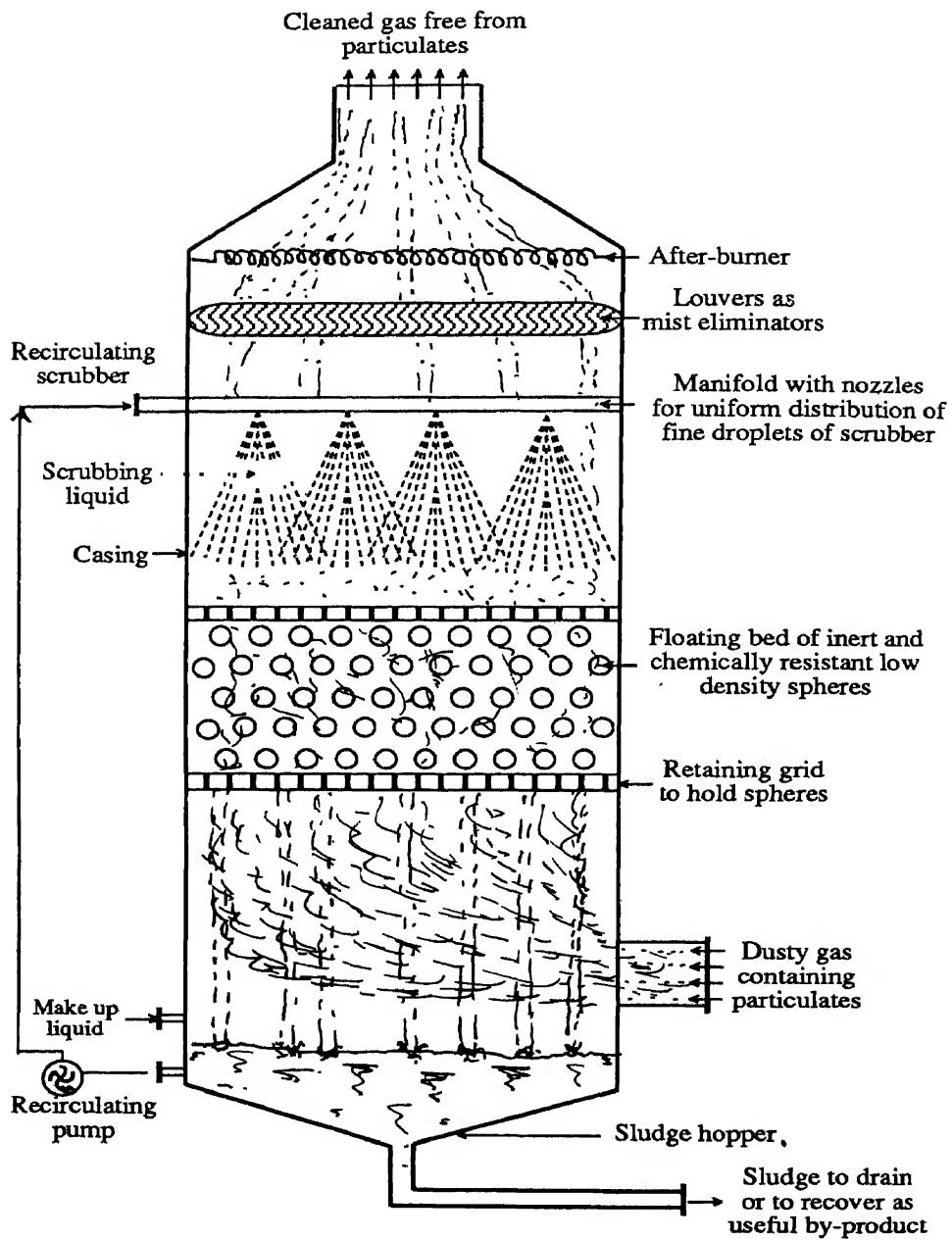


Fig. 7.9 Packed Tower

Device Name	Optimum Particle size(μm)	Optimum conc. g/m ³	Efficiency % by Wt	Limiting Temp. °C	Pressure drop 'cm' water	Power used kW/m ³ /sec	Face velocity m/sec	Applications	Limitations
1	2	3	4	5	6	7	8	9	10
SETTLING CHAMBERS									
Simple	>50	>175	<50	370	0.25-1.25	0.05-0.2	0.3-3	Low pressure loss; simplicity of design and maintenance; used as pre-cleaner in almost all industries to decrease load on the following secondary treatment units.	Large space required, low collection efficiency, difficult to clean, warpage problem.
Baffled (Multiple tray)	>30	>175	<50	370	0.25-1.25	0.05-0.02	5-10		
CYCLONES									
Single	>10	>35.5	<80	400	1.5-5.0	0.2-1.2	5-10	Low to moderate pressure loss, simplicity of design, inexpensive, most widely used, handles large particles, handles high dust loadings, temp. independent, little floor space required, continuous disposal of collected dry dusts. Mostly used in iron & steel mills and petroleum refineries.	Much head room required, low collection efficiency of small particles. Sensitive to variable dust loadings and flow rates, abrasion and plugging problems.
Multiple	>5	>35.5	<90	400	5.0-25	1.0-4.0	5-10		
FILTERS									
Cloth bag	>0.3	* >3.5	>99	300	5-15	1 - 3	0.05-0.15	Dry collection possible, decrease of performance is noticeable, collection of small particles possible, high efficiency possible, more compact, constant flow possible; mostly adopted in metallurgical, cement, glass and ceramic industries, floor mills, lime and chalk plants, brick works etc.	Sensitive to filtering velocity.
Cloth envelope	>0.3	* >3.5	>99	300	5-15	1 - 3	0.05-0.15		High-temperature gases must be cooled to 100-400 °C. Affected by relative humidity (condensation), susceptibility of fabric to chemical attack.

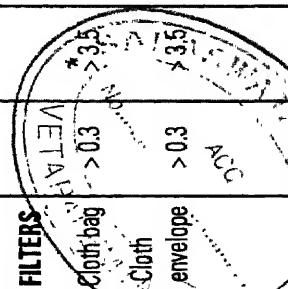


Table 7.5 SUITABILITY OF PARTICULATE CONTROL EQUIPMENT

TABLE 7.4 PARTICULATE EMISSION RATES

Emission Source	Emission Factor
1. Natural Gas Combustion Power plants Industrial boilers Domestic and commercial furnaces	240 mg/m ³ of gas burned 290 mg/m ³ of gas burned 310 mg/m ³ of gas burned
2. Distillate Oil Combustion Industrial and commercial furnaces Domestic furnaces	1.70 kg/m ³ of oil burned 1 kg/m ³ of oil burned
3. Residual Oil Combustion Power plants Industrial & commercial furnaces	1.10 kg/m ³ of oil burned 2.70 kg/m ³ of oil burned
4. Coal Combustion Cyclone furnaces Other pulverized coal furnaces Spreader stokers Other stokers	P kg/ton of coal burned 6P-7P kg/ton of coal burned 6P kg/ton of coal burned P-2.5P kg/ton of coal burned where P = % ash in fuel
5. Incineration Municipal, multiple chamber Commercial, multiple chamber Flue-fed incinerator Domestic, gas-fired Open burning of refuse	8.00 kg/ton of refuse burned 1.40 kg/ton of refuse burned 12.8 kg/ton of refuse burned 7.00 kg/ton of refuse burned 7.20 kg/ton of refuse burned
6. Motor Vehicles Gasoline - powered engines Diesel - powered engines	1.36 kg/m ³ of gasoline burned 12.5 kg/m ³ of fuel burned
7. Cement Manufacturing	17.2 kg/barrel of cement produced
8. Kraft Pulp Mills Lime kiln Recovery furnaces (with scrubbers)	43 kg/ton of dried pulp produced 70 kg/ton of dried pulp produced
9. Steel Manufacturing Open-hearth furnaces Electric arc furnaces	10 kg/ton of steel produced 7 kg/ton of metal charged
10. Sulfuric Acid Manufacturing	3 kg/ton of acid produced

Source : Control techniques for particulate air pollutants, Washington, D.C.

Problem 7.1

Calculate the settling velocity of fog with a particle size of $1\mu\text{m}$.

Solution : From Stoke's law,

$$V = \frac{g(\rho_p - \rho_a)d_p^2}{18\mu}$$

where ρ_p = density of particle i.e. fog = 1000 kg/m^3

ρ_a = density of air = 1.2 kg/m^3 ; $\rho_p >> \rho_a$ ($\therefore \rho_a$ can be neglected)

d_p = diameter of particle = $1 \times 10^{-6}\text{m}$

μ = viscosity of medium (i.e. air) in which the particle is settling
 $= 1.8 \times 10^{-5} \text{ kg/m.sec}$

$$\therefore V = \frac{9.81 \frac{\text{m}}{\text{sec}^2} \times (1000-1.2) \frac{\text{kg}}{\text{m}^3} \times (1 \times 10^{-6})^2 \text{m}^2}{18 \times 1.85 \times 10^{-5} \text{ kg/m.sec}} = 3 \times 10^{-5} \text{ m/sec}$$

However, Stokes law is applicable only if $Re < 1$

$$Re = \frac{\rho V D}{\mu} = \frac{1.2 \text{ kg/m}^3 \times 3 \times 10^{-5} \text{ m/sec} \times 1 \times 10^{-6} \text{ m}}{18 \times 1.8 \times 10^{-5} \text{ kg/m.sec}} = 0.111 \times 10^{-6}$$

\therefore Stoke's law is applicable and hence settling velocity = $3 \times 10^{-5} \text{ m/sec}$.

(This is very very less. That is why fog appears to float in air. Particles with $< 0.1\mu$ are affected by Brownian motion. They collide with the surrounding particles, coagulate and flocculate and then finally settle down.)

Problem 7.2

Calculate the minimum size of the particle that will be removed with 100% efficiency from a settling chamber of size $8\text{m} \times 4\text{m} \times 1.5\text{m}$, designed for a flow rate of $6 \text{ m}^3/\text{sec}$ at 75°C .

Solution :

Settling velocity, $V_s = \frac{g(\rho_p - \rho_a)d_p^2}{18\mu}$ (from Stoke's law)

$$\therefore d_p = \frac{\sqrt{18\mu V_s H}}{\sqrt{g\rho_p L}} \quad \text{since } \frac{L}{V_h} = \frac{H}{V_s}$$

\therefore For the above data,

$$\text{Horizontal velocity, } V_h = Q/bh = 6/4 \times 1.5 = 1.0 \text{ m/sec}$$

Minimum size of particle for 100% efficiency, is given by

$$(d_p \text{ min})^2 = \frac{18 \times 2.1 \times 10^{-5} \text{ kg/m.sec} \times 1 \text{ m/sec} \times 1.5 \text{ m}}{9.81 \text{ m/sec}^2 \times 8 \text{ m} \times 2650 \text{ kg/m}^3}$$

(taking μ gas at $75^\circ\text{C} = 2.1 \times 10^{-5} \text{ kg/m.sec}$ and ρ particle = 2.650)

$$\begin{aligned} dp \text{ min} &= 5.22 \times 10^{-5} \text{ m} \\ &= 52.2 \mu\text{m} \end{aligned}$$

Problem 7.3

Find the length of a simple gravity collector required to remove 90% of $50\mu\text{m}$ diameter particles of density 2.0 g/cc. The bulk gas velocity is 0.5m/s and the chamber is 3m in height. Calculate the length if two trays are used for same efficiency.

Solution :

We know that,

$$\text{efficiency } \eta = \frac{LV_s}{HV} \text{ where}$$

$$\eta = 0.9; L = \text{Length of chamber}$$

$$H = \text{height of chamber} = 3\text{m}$$

$$V = \text{Bulk gas velocity} = 0.5\text{m/sec}$$

$$V_s = \text{Settling velocity} = \frac{g(\rho_p - \rho_a)dp^2}{18\mu}$$

For $50\mu\text{m}$ diameter particle,

$$V_s = \frac{9.81 \frac{\text{m}}{\text{sec}} \times (2000) \frac{\text{kg}}{\text{m}^3} \times (50 \times 10^{-6})^2 \text{m}^2}{18 \times 1.85 \times 10^{-5} \text{ kg/m.sec}} = 0.15\text{m/sec}$$

$$\therefore \text{Length of the chamber, } L = \frac{0.90 \times 3 \times 0.50}{0.15} = 9\text{m}$$

b) If two trays are installed and considering bottom floor as one tray,

$$\Delta H = 3/3 = 1\text{m, is the new effective height of settling chamber}$$

Thus length of chamber with 2 trays = $9/3 = 3\text{m}$.

Problem 7.4

A multi-tray settling chamber handles $6\text{m}^3/\text{s}$ of air at 20°C . There are 8 trays including the bottom surface spaced 0.25m apart. The chamber is 4m long and 1m wide. For particles of density 2000kg/m^3 and sizes a) 70 and b) $25\mu\text{m}$, calculate the residence time, the distance settled and the efficiency of collection. Is the tray-spacing sufficient to collect all the particles of each size? Assume laminar flow. What will be the efficiency if the flow regime is turbulent in each case.

Solution :

Given data is,

$$Q = 6\text{m}^3/\text{sec}; n = 8 \text{ trays}; \Delta H = 0.25\text{m}$$

$$L = 4\text{m}; W = 1\text{m and } \rho_p = 2000\text{kg/m}^3$$

a) For $70\mu\text{m}$

$$\text{Velocity inside the chamber } V_h = \frac{Q}{n W \Delta h} = \frac{6.0}{8 \times 0.25} = 3 \text{ m/sec}$$

$$\text{Residence time } 'T' = \frac{\text{distance (length)}}{\text{velocity}} = \frac{4}{3} = 1.33 \text{ sec}$$

For laminar flow condition, the particles settle by

$y/V_s = L/V$ where V_s = settling velocity in m/sec, given by,

$$V_s = \frac{g(\rho_p - \rho_a)d^2}{18\mu} = \frac{9.81 \frac{\text{m}}{\text{sec}^2} \times (2000) \frac{\text{kg}}{\text{m}^3} \times (70 \times 10^{-6})^2 \text{m}^2}{18 \times 1.80 \times 10^{-5} \text{ kg/m.sec}} = 0.295$$

Distance settled 'y',

$$y = \frac{L}{V} V_s = \frac{4}{3} \times 0.295 = 0.393 \text{ m}$$

$$\text{Efficiency of collection } \eta = \frac{LV_s}{V_h \Delta H} = \frac{4 \times 0.295}{3 \times 0.25} = 157 \cong 100\%$$

NOTE : When $y \geq \Delta H$ ($0.393 > 0.25$)

all particles of that size (or larger) will be collected in the settling chamber.

b) for $25\mu\text{m}$ particle

(i) residence time will be same, as all the dimensions are same as before.

(ii) settling distance, $y = \frac{LV_s}{V}$

$$\text{but } V_s = \frac{g(\rho_p - \rho_a)d^2}{18\mu} = \frac{9.81 \text{ m/sec}^2 \times (2000) \text{ kg/m}^3 \times (25 \times 10^{-6})^2 \text{ m}^2}{18 \times 1.80 \times 10^{-5} \text{ kg/m.sec}} = 0.037 \text{ m/sec.}$$

$$\therefore y = \frac{4 \times 0.037}{3} = 0.05 \text{ m}$$

$$\text{(iii) collection efficiency, } \eta = \frac{LV_s}{V_h \Delta H} = \frac{4 \times 0.037}{3 \times 0.25} = 20\%$$

c) If the flow regime is turbulent

(i) Collection efficiency for $70\mu\text{m}$ particle, $\eta = 1 - \exp\left(-\frac{nWL}{Q} V_s\right)$

where $n = 8$, $W = 1\text{m}$, $L = 4\text{m}$, $V_s = 0.295 \text{ m/sec}$ (calculated), $Q = 6\text{m}^3/\text{sec}$

$$\eta = 1 - \exp\left(-\frac{8 \times 1 \times 4 \times 0.295}{6}\right) = 79.2\%$$

(ii) for $25\mu\text{m}$ particle

$$\text{collection efficiency } \eta = 1 - \exp\left(-\frac{nWL}{Q} V_s\right)$$

$$\eta = 1 - \exp\left(-\frac{8 \times 1 \times 4 \times 0.037}{6}\right) = 18\%$$

NOTE: V_s can also be calculated by the empirical formula $V_s = 30000 \rho_p d^2$
 eg : $V_s(25\mu\text{m}) = 30000 \times 2000 \times (25 \times 10^{-6})^2 = 0.0375 \text{ m/sec}$ (checked).

Problem 7.5

In the above example, is the laminar flow assumption justified? If not what is the collection efficiency for 60 μm and 50 μm particles.

Solution

Reynolds number is calculated as, $\text{Re} = \frac{2Q}{v(nW+H)}$ where

$$v = \mu_g/\rho = \text{kinematic viscosity} = 1.51 \times 10^{-5} \text{ m}^2/\text{sec at } 20^\circ\text{C}$$

$$H = n \cdot \Delta H = 8 \times 0.25 = 2 \text{ m}$$

$$\therefore \text{Re} = \frac{2 \times 6}{1.51 \times 10^{-5} (8 \times 1 + 2)} = 79,470$$

This shows that the flow is turbulent and the laminar flow assumption in the above problem was not justified.

\therefore Collection efficiency for 60 μm

$$\eta(60\mu\text{m}) = 1 - \exp\left(-\frac{8 \times 1 \times 4 \times 0.216}{6}\right) \quad (\text{since } V_s = 30000 \rho_p d^2 = 0.216 \text{ m/sec}) \\ = 68.4\%$$

$$\eta(50\mu\text{m}) = 1 - \exp\left(-\frac{8 \times 1 \times 4 \times 0.150}{6}\right) \quad (V_s = 0.15 \text{ m/s}) \\ = 55\%$$

Problem 7.6

A monodispersed aerosol 1.99 μm in diameter is passed through a gravity settler 20cm wide and 50cm long with 18 plates and channel thickness of 0.124 cm. The gas flow rate is 8.6 LPM, and it is observed that it operates at an efficiency of 64.9%. How many plates would be required to have the unit operate at 80% efficiency.

Solution

$$\text{Air flow rate} = 8.6 \text{ LPM} = 143.33 \text{ cm}^3/\text{sec}$$

$$\therefore \text{Air flow rate per channel} = 143.33/19 = 7.54 \text{ cm}^3/\text{sec}$$

Settling velocity V_s , calculated from

$$\eta = \frac{V_s}{V} = \frac{V_s}{Q/BL} = \frac{V_s BL}{Q}$$

$$\therefore V_s = \frac{Q\eta}{BL} \\ = \frac{(7.54 \text{ cm}^3/\text{sec})(0.649)}{20\text{cm} \times 50\text{cm}} = 4.896 \times 10^{-3} \text{ cm/sec.}$$

At $\eta = 80\%$, the new volumetric flow is

$$Q_2 = \frac{V_s BL}{\eta_2}$$

$$= \frac{4.896 \times 10^{-3} \text{ cm/sec} \times 20\text{cm} \times 50\text{cm}}{0.8} = 6.12 \text{ cm}^3/\text{channel. sec}$$

The number of channels required is $\frac{Q_{\text{total}}}{Q_2} = \frac{143.33}{6.12} = 23.42 \approx 24$

Problem 7.7

Design a gravity settler to remove all the iron particulates from a dust-laden gas stream with the data given as :

$d_p = 35\mu\text{m}$: uniform i.e. no distribution

gas = air at ambient conditions

$Q = 3.6\text{ m}^3/\text{sec}$

$\rho_p = 7.62\text{ g/cc}$

Solution

Collection area required can be obtained from

$$dp^2 = \frac{18\mu Q}{g\rho_p BL}$$

$$\therefore BL = \frac{18\mu Q}{g\rho_p dp^2}$$

Substituting the data,

$$BL = \frac{18 \times 1.81 \times 10^{-5} \times 3.6}{9.8 \times 7620 (35 \times 10^{-6})^2} = 12.8\text{ m}^2 \quad \dots \dots \dots (1)$$

Assuming an inlet velocity of 3m/sec, the cross-sectional area is

$$B \times H = \frac{Q}{V_h} = \frac{3.6 \text{ m}^3/\text{sec}}{3\text{ m/sec}} = 1.2\text{ m}^2$$

Based on the minimum height required for cleaning purposes, H is usually 1meter , then

$$B \times 1 \text{ m} = 1.2\text{ m}^2 \quad \therefore B = 1.2\text{ m}$$

from the value (1)

$$L = \frac{12.8\text{ m}^2}{1.2\text{ m}} = 10.6\text{ m}$$

Total volume of the settler is

$$V = (BL)H = (12.8\text{ m}^2) (1\text{ m}) = 12.8 \text{ m}^3$$

But, for economic considerations, we can take $L=B$;

$$BL = L^2 = 12.8\text{ m}^2$$

$$B = L = 3.5\text{ m}$$

$$H = 1\text{ m}$$

and in this case, the velocity of the gas would be

$$V = \frac{Q}{BH} = \frac{3.6}{3.5 \times 1\text{ m}} = 1\text{ m/sec}$$

Problem 7.8

Calculate the collection efficiency for a gas flow rate of $7 \text{ m}^3/\text{sec}$, particle density of 1500 kg/m^3 and diameter of $10\mu\text{m}$, if a multiple cyclone (64 cyclones each of diameter 24cm) is used instead of a single large unit.

Solution

The standard dimensions of the conventional cyclone are

$$b = \frac{D}{4} = \frac{0.24}{4} = 0.06\text{m}$$

$$h = \frac{D}{2} = \frac{0.24}{2} = 0.12\text{m}$$

$$\therefore \text{Area of inlet} = 0.06 \times 0.12 = 7.2 \times 10^{-3}\text{m}^2$$

$$\text{Area of all inlets} = 64 \times 7.2 \times 10^{-3} \text{ m}^2 = 0.45\text{m}^2$$

$$\therefore \text{Inlet velocity} = \frac{7\text{m}^3/\text{sec}}{0.45\text{m}^2} = 15\text{m/sec}$$

particle cut size ' d_{pc} ' taking $N_e = 5$ and $\mu_s @ 20^\circ\text{C} = 1.81 \times 10^{-5}\text{kg/m.sec}$

$$(d_{pc})^2 = \frac{9\mu_s b}{2\pi N_e V_i (\rho_p - \rho_g)}$$

$$= \frac{9 \times 1.81 \times 10^{-5}\text{kg/m.sec} \times 0.06\text{m}}{2\pi \times 5 \times 15\text{m/sec} \times 1500\text{kg/m}^3}$$

$$d_{pc} = 3.72 \mu\text{m}$$

$$\frac{d}{d_{pc}} = \frac{10}{3.72} = 2.68$$

\therefore Efficiency for $10\mu\text{m}$ particle = 90% (obtained from $\eta-d_{pc}$ curve)

Problem 7.9

Calculate the number of cyclones required to treat a flow of $60\text{m}^3/\text{sec}$ with an inlet velocity of 15m/sec . The diameter of cyclone is 1.8m .

Solution:

Total volumetric flow $Q = V \times A_{total} = n V_i B e H e$

$$\therefore \text{Number of cyclones, } n = \frac{Q}{V_i B e H e}$$

From the design considerations

$$B e = \frac{D}{4} = \frac{1.8}{4} = 0.45\text{m}$$

$$H e = \frac{D}{2} = \frac{1.8}{2} = 0.9\text{m}$$

$$\therefore \text{No. of cyclones } n = \frac{60}{15 \times 0.45 \times 0.9}$$

$$= 9.876 \approx 10$$

Problem 7.10

A fabric filter is to be constructed using bags of 0.3m in diameter and 6m long. The bag house is to receive $800\text{m}^3/\text{min}$ of air. Determine the number of bags required for a continuously cleaned operation.

Solution

Total gas flow, $Q = 800 \text{ m}^3/\text{min}$

Let the filtering velocity be 2 m/min (i.e. $2 \text{ m}^3/\text{m}^2/\text{min}$)

$$\therefore \text{Cloth area for filtering} = \frac{800 \text{ m}^3/\text{min}}{2 \text{ m/min}} = 400 \text{ m}^2$$

Area of each bag, $A = \pi DH$

$$= \pi \times 0.3 \times 6$$

$$= 5.65 \text{ m}^2$$

$$\therefore \text{Total number of bags} = \frac{400 \text{ m}^2}{5.65 \text{ m}^2} = 70.79 \approx 72$$

Problem 7.11

Design a parallel type electrostatic precipitator with 10 channels to handle $10000 \text{ m}^3/\text{hr}$ of gas for efficiency of (a) 90% (b) 99% (c) 99.9%.

Solution

Gas flow rate, $Q = 10000 \text{ m}^3/\text{hr} = 2.78 \text{ m}^3/\text{sec}$

Number of channels, $n = 10$, No. of Plates = 11

$$\therefore \text{Gas flow rate/channel} = 0.278 \text{ m}^3/\text{sec}$$

Let V_p , velocity of particle towards plate be 0.1 m/sec

Let size of each plate be $L \text{ m long} \times 2 \text{ m height}$.

$$\therefore \text{Area of collecting electrode / channel} = 2 \times 2 \times L = 4L \text{ m}^2$$

Let spacing 'S' be 0.15 m

$$\therefore V_g = \frac{Q}{nHS} = \frac{0.278}{2 \times 0.15} = 0.927 \text{ m/sec}$$

$$\therefore \text{Efficiency } \eta = 1 - \exp \left(-\frac{V_p A_c}{Q} \right)$$

$$= 1 - \exp \left(-\frac{V_p \times 2HL}{V_g \times HS} \right)$$

$$= 1 - \exp \left(\frac{-0.1 \text{ m/sec}}{0.927 \text{ m/sec}} \times \frac{2L}{0.15} \right)$$

$$= 1 - \exp (-1.4383 L)$$

a) For 90% efficiency, $0.90 = 1 - \exp -1.4383L$

$$L = 1.601 \text{ m}$$

Similarly, for 99% η , $L = 3.202 \text{ m}$

for 99.9% η , $L = 4.803 \text{ m}$

Problem 7.12

Design a parallel plate ESP with an efficiency of a) 90% b) 99% c) 99.9% of removal of $0.75 \mu\text{m}$ sized fly ash from a cement industry with a gas flow rate of $10 \text{ m}^3/\text{sec}$. Pilot - plant studies showed that drift velocity,

$$V_p = 2.5 \times 10^5 \text{ dp m/sec.}$$

Solution

$$V_p = 2.5 \times 10^5 \times 0.75 \times 10^{-6} = 0.1875 \text{ m/sec.}$$

From the efficiency equation,

$$\begin{aligned}\eta &= 1 - \exp\left(\frac{-V_p A_c}{Q}\right) \\ \therefore \frac{-V_p A_c}{Q} &= \ln(1-\eta) \\ \therefore A_c &= \frac{-Q}{V_p} \ln(1-\eta)\end{aligned}$$

a) for 90% efficiency, $A_c = \frac{-10}{0.1875} \times \ln(1-0.90) = 122.8 \text{ m}^2$

b) for 99% efficiency, $A_c = \frac{-10}{0.1875} \times \ln(1-0.99) = 245.6 \text{ m}^2$

c) for 99.9% efficiency, $A_c = \frac{-10}{0.1875} \times \ln(1-0.999) = 368.4 \text{ m}^2$

Let length, height and spacing of plates be 10m, 2m and 0.15m.

$$\therefore \text{Area of each channel} = 2 \times 10 \text{ m} \times 2 \text{ m} = 40 \text{ m}^2$$

\therefore Number of channels

a) for 90% efficiency $= \frac{122.8}{40} = 3.07$ say 3

b) for 99% efficiency $= \frac{245.6}{40} = 6.14$ say 6

c) for 99.9% efficiency $= \frac{368.4}{40} = 9.2$ say 9

\therefore Number of plates required for 90%, 99% and 99.9% efficiency are 4, 7 and 10 respectively.

The volume of a parallel plate ESP can be obtained by :

Volume of channel = Area of each plate \times spacing

$$V = \frac{A_c}{2} \times S = HLS$$

For the above problem,

$$\text{volume of ESP for 90% efficiency} = 3 \times 2 \text{ m} \times 10 \text{ m} \times 0.15 \text{ m} = 9 \text{ m}^3$$

Similarly, the volume of ESP with 99% and 99.9% efficiency will be 18 m^3 and 27 m^3 respectively.

(ii) for a cylindrical ESP: $A_c = \frac{-Q}{V_p} \ln(1-\eta)$

Let diameter and length of cylinder be 30 cms and 4m, so that the area of each electrode $= \pi D L = \pi \times 0.3 \times 4 = 3.77 \text{ m}^2$

\therefore Number of cylinders required,

$$\text{for 90% efficiency} = 122.8 / 3.77 = 38.74 \text{ say 40}$$

for 99% efficiency = $245.6/3.77 = 64.8$ say 80

for 99.9% efficiency = $368.4/3.77 = 96.22$ say 120

Problem 7.13

Design a tubular ESP to treat $10,000\text{m}^3/\text{hr}$ of a gaseous stream from a paper mill for an efficiency of a) 90% b) 99% and c) 99.9%. Assume an effective migration velocity of 0.075 m/sec .

Solution

Let, diameter of each cylinder be 30 cm

let inlet gas velocity V_g be 1 m/sec , and

let length of the tubular electrode be L_m .

$$\text{Efficiency} = 1 - \exp\left(-\frac{V_p(\pi DL)}{Q}\right)$$

Number of cylinders of 30cm dia required to maintain an inlet gas velocity

$$\text{of } 1\text{m/sec} = \frac{2.78\text{m}^3/\text{sec}}{\pi/4 \times (0.3)^2 \text{m}^2 \times 1\text{m/sec}} = 39.3 \text{ say 40}$$

Gas flow rate for each tube = Total flow / number of tubes

$$\therefore Q \text{ for each tube} = 2.78 / 40 = 0.0695 \text{ m}^3/\text{sec}$$

$$\therefore \text{For 90% efficiency } L = \frac{-0.0695 \text{ m}^3/\text{sec}}{\pi \times 0.3 \times 0.075 \text{ m/sec}} \ln(1-0.90) = 2.26 \text{m.}$$

Similarly, for 99% and 99.9% efficiency, values of lengths will be 4.52 and 6.78m respectively.

Problem 7.14

A cylindrical electrostatic precipitator of diameter 0.3m is used for separating pulverised coal flyash particles from a furnace gas stream. If the volumetric flow rate of the gas is $0.05\text{m}^3/\text{sec}$, what will be the length of the precipitator for obtaining a collection efficiency of 99.9%? What percent change in electrode collection area is required to increase the collection efficiency from 99.90 to 99.95 percent.

Solution

Data given is, $Q = 0.05\text{m}^3/\text{sec}$; $D = 0.3\text{m}$

For pulverised coal flyash, $V_p = 0.1 \text{ m/sec}$ (from table 7.3)

Area of collecting electrode $A_c = \pi D L = \pi \times 0.3 \times L$

a) For efficiency of 99.9%

$$\eta = 1 - \exp\left(-\frac{V_p A_c}{Q}\right)$$

$$A_c = \frac{-0.05}{0.1} \ln (1-0.999) = 3.45 \text{ m}^2$$

Area of the collecting electrode = 3.45 m^2

b) For efficiency of 99.95%

$$A_c = \frac{-Q}{V_p} \ln (1-\eta)$$

$$A_c = \frac{-0.05}{0.1} \ln (1-0.9995) = 3.80 \text{ m}^2$$

\therefore Percentage increase in collection area

$$= \frac{3.80 - 3.45}{3.45} = 10\%$$

Problem 7.15

A horizontal parallel plate ESP consists of a single duct 4.8m high x 6m long, with a 30cm plate to plate spacing. A collection efficiency of 94.4% is obtained with a flow rate of $95 \text{ m}^3/\text{min}$. The inlet loading is 144 grains/m^3 . Calculate the following.

- a) The bulk velocity of the gas (assume uniform distribution)
- b) The outlet loading
- c) The drift velocity for the stream.
- d) A revised collection efficiency, if the flow rate is increased to $150 \text{ m}^3/\text{min}$
- e) A revised collection efficiency, if the plate spacing is decreased to 25 cm.

Solution

a) Bulk velocity of the gas :

$$\begin{aligned} \text{Velocity } V' &= \frac{\text{Volumetric flow}}{\text{X-section area of passage}} \\ &= \frac{95/60 \text{ m}^3/\text{sec}}{4.8 \text{ m} \times 0.30 \text{ m}} = 1.1 \text{ m/sec} \end{aligned}$$

b) Outlet loading = inlet loading $(1 - \eta)$

$$= 144 (1-0.944) = 8.0 \text{ grains/m}^3$$

c) Migration (drift) velocity, V_p is given by

$$\begin{aligned} \eta &= 1 - \exp \left(\frac{-V_p A_c}{Q} \right) = 0.944 \\ \frac{-V_p A_c}{Q} &= \ln (1-\eta) = \ln(1-0.944) = 2.88 \\ \therefore V_p &= \frac{2.88 \times 95 \text{ m}^3/\text{min}}{2 \times 6 \times 4.8 \text{ m}} = 4.75 \text{ m/min} = 0.08 \text{ m/sec} \end{aligned}$$

d) Revised collection efficiency $\eta = 1 - \exp \left(\frac{-V_p A_c}{Q} \right)$

$$= 1 - \exp \left(\frac{-4.75 \times 2 \times 4.8 \times 6}{150} \right) = 0.8386$$

i.e. 83.86%

- e) Efficiency will remain same even if the spacing decreases.

Problem 7.16

A horizontal parallel plate electrostatic precipitator consisting of three gas passages 4.8m high x 4.8m deep with 30cm plate spacing is to treat 540m³/min of air. Due to a rapid expansion before inlet to the precipitator, the velocity profile is not fully developed. As a result, the volume rate of flow in the middle duct is twice that of the outer duct. Calculate the collection efficiency. (Use migration velocity of 0.08 m/sec).

Solution

Let the flow rates through the three passages be Q_1 , Q_2 and Q_3

$$\therefore Q_1 = Q_3 = Q_2/2$$

Since the total flow rate is 540 m³/min, the individual flow rates are

$$Q_1 + Q_2 + Q_3 = Q_1 + 2Q_1 + Q_1 = 540 \text{ m}^3/\text{min}$$

$$\therefore Q_1 = Q_3 = 135 \text{ m}^3/\text{min} = 2.25 \text{ m}^3/\text{sec}$$

$$\therefore Q_2 = 270 \text{ m}^3/\text{min} = 4.5 \text{ m}^3/\text{sec}$$

$$\begin{aligned} \text{Area for the outer passage 'Ao'} &= \frac{2}{3} A \\ &= \frac{2}{3} (6 \times 4.8 \times 4.8) = 92.16 \text{ m}^2 \end{aligned}$$

Area for the inner passage 'Ai'

$$Ai = A - Ao = 46 \text{ m}^2$$

\therefore The efficiency may be calculated by

$$\begin{aligned} \eta &= [1 - (\exp \frac{-0.08 \times Ao}{2Q_1} + \exp \frac{-0.08 \times Ai}{Q_2})] \\ &= [1 - (\exp \frac{-0.08 \times 92.16}{4.5} + \exp \frac{-0.08 \times 46}{4.5})] = 36.5\% \end{aligned}$$

Probllem 7. 17

An industrial installation has two ESPs, each designed to handle 48 m³/sec. The collecting surface per precipitator is 1440 m². For a migration velocity of 0.13 m/sec, calculate the efficiency of each precipitator. If one of the precipitators is shut down and it is decided to treat the total gas volume in the other precipitator, calculate the new efficiency.

Solution

Volumetric flow in each precipitator, $Q = 48 \text{ m}^3/\text{sec}$.

Collecting surface area of precipitator, $A = 1440 \text{ m}^2$

Migration velocity, $V_p = 0.13 \text{ m/sec}$

$$\eta = 1 - \exp \frac{-V_p \times A_c}{Q}$$
$$= 1 - \exp \frac{-0.13 \times 1440}{48} = 97.9\%$$

If one precipitator is shut down and the total gas volume is treated in the other precipitator,

$$\text{Efficiency} = 1 - \exp \frac{-0.13 \times 1440}{2 \times 48} = 85.77\%$$

* * *

CHAPTER - 8

CONTROL OF GASEOUS POLLUTANTS

This chapter deals with the removal of gaseous pollutants from the carrier gas which is usually air. The principal gases of concern in air pollution control are the sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon oxides (CO, CO_2), organic and inorganic acidic gases and hydrocarbons (HC). For the control of above mentioned gases, the mechanisms are chemical engineering unit operations which include adsorption, absorption, condensation and combustion. In addition to these unit operations, a general concept such as mass transfer is used in the unit operations.

Gaseous pollutant streams are like chemical process streams. The major exception is that the gaseous pollutant concentrations are usually lower than the chemical process stream concentrations. These lower concentrations make it possible to consider gaseous pollutants as ideal gases. Also, the carrier gas (air), may be treated as an ideal gas in the operating range for most of the air pollution control equipments.

Gaseous pollutants can be controlled by a wide variety of devices and choosing the most cost-effective, most efficient units requires careful attention to the particular case for which the control devices are intended. The different gaseous control devices are explained as follows.

8.1 ADSORPTION

The forces which hold atoms, molecules or ions together in the solid state exist throughout the body of a solid and at its surface. The forces at the surface may be considered to be "residual" in that they are available for binding other molecules which come in contact or in very close proximity to it. Any gas, vapour or liquid will therefore, adhere to some degree to any solid surface. This phenomenon is called adsorption or sorption. The adsorbing solid is called the adsorbent or sorbent and the adsorbed material is the adsorbate or sorbate. Adsorption is useful in air pollution control because it is a means of concentrating gaseous pollutants, thus facilitating their disposal, recovery or conversion to innocuous or valuable products.

The actual adsorption process is classified as either physical adsorption or chemi-sorption. In physical adsorption, the gas molecules adhere to the surface of the solid adsorbent as a result of inter-molecular attractive forces (Vander waals forces) between them. The adsorption process is exothermic and liberates heat depending upon the magnitude of the attractive force. The advantage of physical adsorption is that the process is reversible. The adsorbed material can be easily removed or desorbed by reducing the pressure or by increasing the temperature without any change in the chemical composition. The amount of gas physically adsorbed decreases rapidly with increasing temperature and is quite small when the temperature is above the critical temperature of the adsorbed component. Physical adsorption is usually directly proportional to the amount of solid surface available. However this build up is not restricted to a mono molecular layer; a number of layers of molecules can build up on the surface. Another desirable characteristic of physical adsorption is that the rate generally is quite rapid.

Chemi-sorption, results from chemical interaction between the adsorbate and the adsorbing medium. The bonding force associated is much stronger and the heat liberated during the process is much larger than that in physical adsorption. The energy required for the chemisorbed molecules to react with other molecular species may be considerably less than the energy required when the two species react directly in the gas phase. This lower energy requirement is one basis of explanation of the catalytic effect of solid surfaces in enhancing the rate of some chemical reactions. Chemisorption is an irreversible process. On desorption the chemical nature undergoes a chemical change. Chemisorption process which is responsible for the catalytic effect is extremely important in number of air pollution control systems.

The quantity of material that can be adsorbed by a given weight of adsorbent depends on the following factors. (1) The concentration of the material in the space around the adsorbent (2) The total surface area of the adsorbent

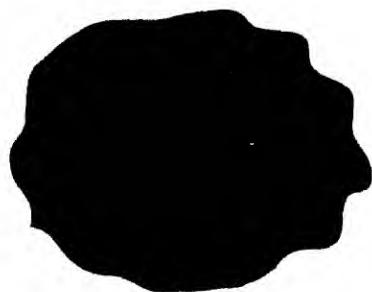
(3) The temperature (4) The presence of other molecules in the environment which may compete for a place on the adsorbent (5) The characteristic of the molecules to be adsorbed i.e. weight, electrical polarity, chemical activity, size and shape (6) The micro-structure of the adsorbing surface i.e. sizes and shapes of pores and (7) The chemical nature of the adsorbent surface including electrical polarity and chemical activity.

Some of the adsorbents commonly used in air pollution control are activated carbon, activated alumina, silica gel and molecular sieves etc. Adsorption techniques are widely used in the field of odour control for removing small quantities of pollutants present in a large volume of air. Adsorption techniques are also used for collecting valuable organic substances that cannot be picked up by scrubbing methods.

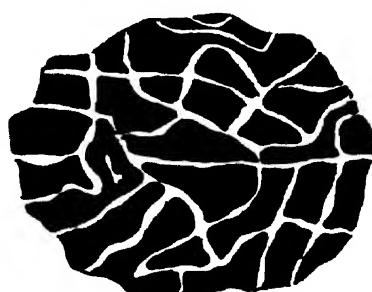
Adsorbents

Activated Carbon: Activated carbon (or activated charcoal) consists of particles of moderately to highly pure carbon with a large surface area per unit weight or volume of solid (of about $1500 \text{ m}^2/\text{gram}$ of adsorbent). It is made by the carbonization of coal, wood, fruit pits, petroleum residues and coconut or other nut shells. The extent and micropore structure of the carbon surface are of prime importance. The distribution of pore diameters is also determined both by the nature of the raw material and by the activating process. A typical activated carbon has pore diameters of about 250 micron.

Activated carbon consisting largely of neutral atoms of a single species, presents a surface with a relatively homogeneous distribution of electrical charge. Therefore, activated carbon is effective in adsorbing molecules of organic substances with less selectivity than is exhibited by other more polar-sorbents. Activated carbon is effective in adsorbing organic molecules even



Before Activation
Surface area
 $< 0.001 \text{ m}^2/\text{g}$



After Activation
Surface area
 $> 1000 \text{ m}^2/\text{g}$

Fig. 8.1 Activated Carbon

from a humid gas stream. The activity is a measure of the maximum amount of a vapour that can be adsorbed by a given weight of carbon under specified conditions of temperature, concentration of the vapour and concentration of other vapours (usually water).

Molecular Sieves : Molecular sieves have recently been developed for the control of SO₂, NO_x and Hg emissions. These materials can be tailor-set to adsorb a particular size and type of gas molecules. They can be natural crystalline zeolites or synthetic metal hydrates. The synthetic metal alumina silicates have pore diameters ranging from 3 to 10 Angstrom (10^{-10} m). The usually used metal ions are calcium, sodium, magnesium, potassium or any combination of these.

Molecular sieve pores are custom sized to adsorb only desired molecules. The effect of pore size on separation selectivity is illustrated by some data on molecular sieves compiled by the union carbide corporation. When the nominal diameter is 0.003 micron the molecules adsorbed typically might be H₂O and NH₃. By increasing the size to 0.004μm, larger molecules such as CO₂, SO₂, H₂O, C₂H₄, C₂H₆ and C₂H₅OH are also adsorbed. A further increase to 0.005μm allows the additional adsorption of natural paraffins to the exclusion of branched and cyclic hydrocarbons. Thus a fairly strong specificity can be built into molecular sieves, which enhances the engineer's control over the adsorption phenomena.

Molecular sieves contain metallic positive ions. Polar gas molecules are attracted and retained better in sieves. A partial listing of molecular sieves is given in table 8.3 and a listing of gas molecular sizes is given in table 8.2

A new molecular sieve material called silicate has been developed from a polymorph of silica. This sieve will adsorb small non polar organic molecules of the size of benzene and smaller, but will not adsorb the polar water molecules.

Molecular sieve regeneration consists of heating (eg. by steam), decreasing pressure or stripping with a non adsorbent phase gas. The adsorbed material in molecular sieves can also be displaced with a purge of adsorbable liquid, frequently water, then dried and rinsed.

Other Adsorbents : All important sorbents other than carbon are simple or complex oxides. These sorbents show considerably greater selectivity than activated carbon and over-whelmingly greater performance for polar than for non polar molecules. Due to this, they are more useful than carbon when separations are to be made among different types of pollutants, but much less useful when overall decontamination of an air stream is to be accomplished. They are essentially ineffective for direct decontamination of moist air or gas stream.

TABLE 8.1 TYPES OF ADSORBENTS

Adsorbent	Major uses
Activated carbon	Eliminating odors, purifying gases, recovering solvents
Alumina	Drying air, gases and liquids
Bauxite	Treating petroleum fractions, drying gases and liquids
Bone char	Decolorizing sugar solutions
Decolorizing carbons	Decolorizing fats, oils and waxes; decolourizing domestic water
Fuller's earth	Refining animal oils, lube oils, vegetable oils, fats and waxes
Magnesia	Treating gasoline and solvents, removing metallic impurities from caustic solution
Molecular sieves	Controling and recovering Hg, SO ₂ and NO _x emissions
Silica gel	Drying and purifying gases
Strontium sulfate	Removing iron from caustic solutions

TABLE 8.2 MOLECULAR DIAMETERS

Gas Molecule	Diameter (°A)
Hydrogen	2.4
Oxygen	2.8
Carbon monoxide	2.8
Carbon dioxide	2.8
Nitrogen	3.0
Water	3.15
Ammonia	3.8
Methane	4.0
Ethane	4.2
Ethylene	4.25
Methanol	4.4
Propane	4.9
Toluene	6.7
Benzene	6.8
Carbon tetrachloride	6.9
Chloroform	6.9

TABLE 8.3 MOLECULAR SIEVES

Sieve Type	Nominal Pore Diameter(Å)	Cation	Molecules Adsorbed	Remarks
3A	3	Potassium	<3 °A effective diameter (eg. H ₂ O & NH ₃)	Used for drying and dehydration
4A	4	Sodium	≤4 °A diameter (eg. C ₂ H ₄ & C ₂ H ₆)	Scavenge water from solvents and saturated hydrocarbons
13x	10	Sodium	< 10 °A diameter	Drying, H ₂ S and mercaptan removal

TABLE 8.4 TYPICAL PROPERTIES OF ADSORBENTS

Adsorbent	Form	Pore Volume (cm ³ /g)	Reactivation Temperature (°C)	Max. Gas Flow (cm ³ /sec/g)	Specific Heat, Cp (Cal/g °K)	Typical Adsorbates
Activated carbon	Pellets	0.60 - .80	100 - 500	-	0.25	HC larger than C ₄ H ₁₀ , organic compounds, iodine
	Granules	0.45	100 - 500	-	0.25	
	Granules	0.45	120 - 230	1.25	0.22	
	Spheroids	0.45	150 - 230	1.25	0.25	
Silica gel	Granules	0.37	175 - 300	0.82	0.22	CH ₄ through C ₄ H ₁₀ , C ₂ H ₄ through C ₄ H ₈ , H ₂ O, SO ₂ , H ₂ S, H ₂ O, H ₂ S, oil vapors
	Spheroids	-	175 - 300	0.82	0.25	
	Pellets	-	150 - 300	0.82	0.23	
	Granules	-	150 - 300	0.82	0.23	
Molecular sieves	Spheroids	-	150 - 300	0.82	0.23	See Table 8.3

Siliceous adsorbents comprise of silica gels, fuller's and other siliceous earths etc. These materials are available naturally in a wide range of adsorbent capacities per unit weight or volume of solid and their capacities are of the same order of magnitude as that of the most highly activated carbons. Silica gels are produced commercially by the reaction of sodium silicate and sulphuric acid. These adsorbents have pore sizes ranging from 20 to 10,000^{°A} and normally break down at temperatures of 250°C and above. Some metallic oxide adsorbents act as desiccants, catalyst carriers or catalysts; they are never used directly for source control of air-borne pollutants by physical adsorption because they are not electrophilic. Activated alumina (i.e. aluminium oxide) is an example of this type of adsorbent and is popularly used for the adsorption of moisture from gases. It can withstand high temperatures also. The suitability of different adsorbents is presented in table 8.1

Modified Adsorbents : For certain gases, it has been observed that the adsorptive affinity has been increased by the use of impregnated activated carbon. The addition of other chemicals to an adsorbent can promote a chemical reaction that can tie up the adsorbent with the additive. This includes chemical adsorption, can greatly increase the rate of adsorption as well as increase the capacity of the system. If the chemicals are not properly chosen, it can lead to degradation of the adsorbent causing it to be structurally weaker and to wear quicker due to attrition from the gas flow. The additive may react chemically with the adsorbent, especially at higher temperature, which could weaken and ultimately destroy the effectiveness of the adsorbent.

The rate of chemical reaction between the various pollutants adsorbed can be increased by impregnating the adsorbent with a catalyst. The modified adsorbents are often not capable of being regenerated. For example, lead acetate impregnated carbon causes chemical adsorption of hydrogen sulfide from a gas stream. The resulting lead sulfide deposit cannot be recovered without destroying the carbon, so the carbon adsorbent must be discarded when saturated.

Adsorption Equipment

Adsorbers are the devices that physically contain the adsorbent solid through which the effluent gas passes. Some of these adsorption reactors are :

Fixed Bed Unit : In this type the containers are of vertical or horizontal cylindrical shell. Activated carbon, often used as the adsorbent, is arranged as beds or trays in thin layers of 1.5 cm thickness. This saves power because of less resistance to the flow of air. These thin bed adsorbents are most oftenly used in purification of air containing very low concentration of pollutants. The adsorption is rapid and the contaminants cannot build up on the surface

rapidly enough to reduce the collection efficiency of the thin bed adsorber layer. In deep-bed adsorbers, the layers are deeper than 1.5cm. They occupy the least amount of space and are simpler to fabricate than thin bed adsorbers. Deep-bed adsorbers will be used where the savings on power costs are over ridden by other determining factors.

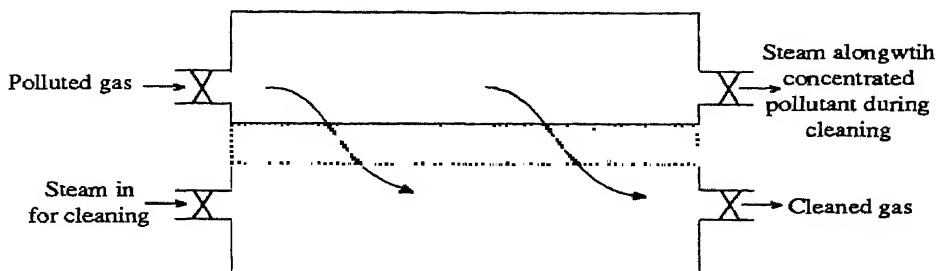


Fig. 8.2 Single-bed Adsorber

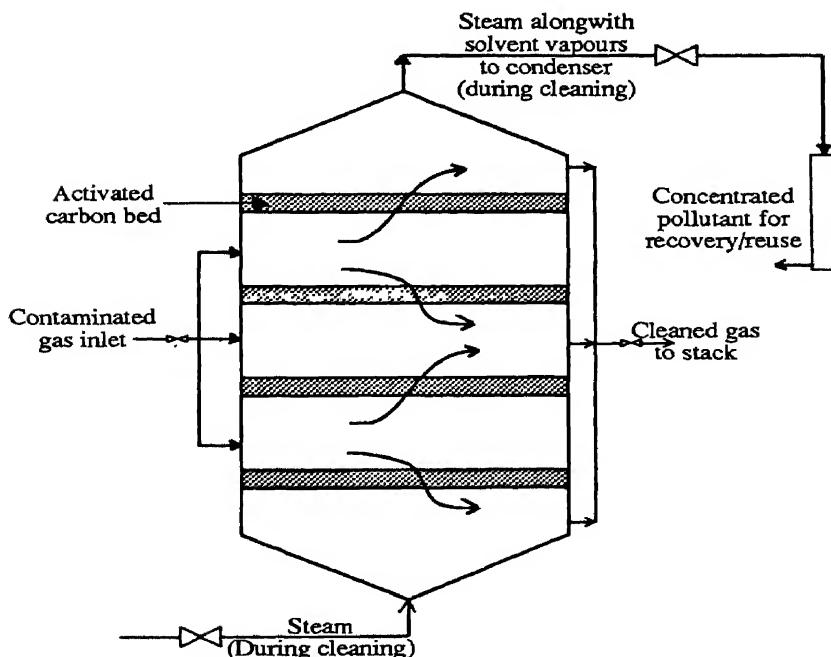


Fig. 8.3 Multiple Fixed-bed Adsorber

Moving Bed Adsorbers

In this unit, activated carbon contained in a rotating drum acts as the adsorption bed. The effluent gas contaminant is moved into the rotating drum. The vapour-laden air enters the ports above the carbon bed, passes through the cylindrical activated carbon bed, enters the space inside of this drum and then finally leaves through the ports at the ends of the drum.

Fluidized Adsorber: It contains a shallow floating bed of adsorbent and when gas passes upward through the bed, it expands and fluidizes the adsorbent. The expanding and fluidizing of the adsorbent provides intimate contact between the contaminated gas and the adsorbent and prevents channeling problems often associated with fixed beds.

Most of the adsorption units are highly efficient until a break point occurs when the adsorbent becomes saturated with adsorbate. At this point, the concentration of pollutants in the exit gas stream begins to rise rapidly and the adsorber must be regenerated or renewed. Depending upon the collected gas-desorption, adsorbers can be classified as regenerative or non regenerative. The non regenerative process is more costly because the adsorbent must be disposed after exhaustion and replaced with new material. But, non regenerative systems are economically applicable for control of pollutant sources whose vapours are odorous but present either in low concentrations (i.e. under about 2ppm) or only at intermittent intervals (eg. laboratory exhaust systems) or both.

The regenerative systems provide for the on-site periodic recovery of the adsorbent or adsorbate. Such systems may advantageously be used for the removal of vapours from polluting sources in which concentrations are about 1000ppm(0.1%). In systems which rely on physical adsorption, regeneration of an adsorbent can be accomplished by use of super heated steam or circulating hot air. The bed must be cooled before reuse. The system that allows for regeneration usually has more than one adsorption unit in operation so that the flow can be switched on to an unsaturated bed while the saturated bed undergoes regeneration.

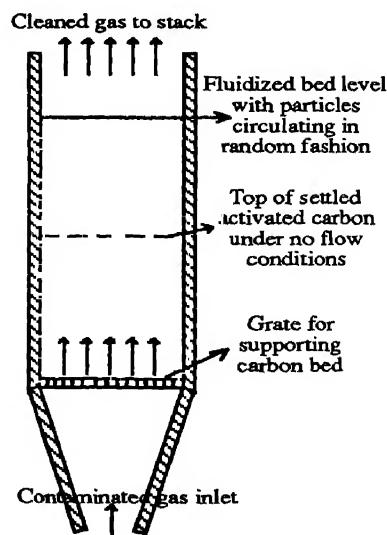


Fig. 8.4 Fluidized-bed Adsorber

Applications of Adsorption Equipment : Recovery of valuable materials from the process industries is economically desirable and adsorption allows for economically feasible recovery when concentrations of organic vapour are sufficiently high. The application of equipment include recovery of iso propyl alcohol from a citrus-fruit processing plant, recovery of methyl chloroform from a movie-film processing plant, recovery of ethyl alcohol vapours from a whiskey ware house and removal of contaminants from air prior to use in an operating room or an electronics control room. Organic vapours that can be controlled by various adsorption processes include those discharged by the following industrial processes: dry cleaning, degreasing, paint spraying, tank dipping, solvent extracting and metal foil coating. Emissions from plastics, chemical, pharmaceutical, rubber, linoleum, transparent wrap manufacturing processes and fabric impregnation processes may also be controlled by adsorption.

8.2 ABSORPTION

The principle of gas absorption is a gas-liquid contacting process for gas separation that utilizes the preferential solubility or chemical reactivity of the pollutant gas in the liquid phase. In the gas absorption technique, effluent gases are passed through absorbers (scrubbers) containing liquid absorbents that remove, treat or modify one or more of the offending constituents in the gas stream. Liquid absorbents may utilise either chemical (reactive) or physical (non reactive) changes to remove pollutants.

Efficiency of absorption depends upon the amount of surface contact between the gas and the liquid (greater the surface, the greater will be the absorption), the time gas is allowed to remain in contact with the liquid, the concentration of the absorbing media and the speed of reaction between the absorbent and the gas. Absorption (or scrubbing) has been used in the control of gases such as SO_x, NO_x, H₂S, HCl, Cl₂, NH₃ and HCs. Removal of HCs by absorption is employed in many industries, notably, asphalt batch plants, coffee roasters, petroleum coker units and varnish and resin cookers. Absorption is also used for recovery of valuable by-products like acetic acid, formic acid, chloroform, amines and ketones etc.

Liquid Absorbents

Liquid absorbents may be classified as reactive if the absorbent utilizes chemical change to remove pollutants. As an example, SO₂ may be removed from the gases by injecting water and limestone, which reacts to form calcium hydroxide. Calcium hydroxide then reacts with sulfur dioxide to form calcium sulfate salt, which can be scrubbed from the gas stream by moving water.

If gases are removed by simply dissolving the gas without chemical change, the absorbent is termed as non reactive absorbent. Water or heavy carbon oil are examples of nonreactive absorbents.

Gas solubility differs from absorbent to absorbent. For example, the solubility of nitrogen, oxygen or carbondioxide is two to ten times greater in ethanol, acetone or benzene than in water. The absorbents that are chemically similar to the absorbate (solute) generally provide good solubility. Other than this, absorbates should have a low freezing point and low toxicity and should be non volatile, non flammable and chemically stable. Economical operation demands that it should be relatively inexpensive, readily available and non corrosive, to reduce equipment repair and maintenance costs.

The main absorbents used in the various SO_2 absorption processes are aqueous solutions of alkalies (sodium and ammonia) and the alkaline earths (calcium and magnesium). The leading alkali absorbent, sodium has the advantages over ammonia solutions as it is not volatile. Ammonia solution also is widely used as a scrubber especially in fertilizer industry, as ammonium sulphate, the by-product obtained is more desirable than sodium sulfate. Alkaline earths i.e. magnesium oxide (MgO), calcium oxide (CaO) and calcium carbonate (CaCO_3) are also used in many industries.

An absorbent that cannot be regenerated for reuse but instead must be discarded is referred to as a non-regenerative absorbent. Eg. water. Absorbent that can be forced to release the gaseous pollutant that it has captured reversibly by application of heat or steam or by pressure change is referred to as a regenerative absorbent. A regenerative absorbent may allow reuse of expensive chemicals or catalysts may be necessary to chemically neutralize the pollutant for disposal as a solid or liquid, or may aid in concentration of pollutant for further processing. Eg: carbon tetrachloride, which under pressure combines with chlorine gas and removes it from the effluent gas stream.

Absorption Units (Absorbers)

Absorbers are the devices that physically contact the pollutant and the fluid in which the effluent gas is passed to provide optimum diffusion of the gas into the solution. Several types of absorbers that are currently used, include spray towers, plate or tray towers, packed towers and venturi scrubbers. Different types of scrubbers are described in detail in chapter 7

8.3. COMBUSTION

In the combustion process, organic compounds released from different manufacturing operations are converted to innocuous carbon dioxide and

water. The combustion equipment used to control air pollution emissions are designed to push oxidation reactions as close as possible to completion, leaving a minimum of unburned compounds. To obtain complete combustion, a proper proportion of oxygen, temperature, turbulence and time must be provided. The normal range for the 3Ts are : temperature : 375-825°C ; residence time: 0.2-0.6 sec ; gas velocity : 4-8 m/sec. The importance of the above are discussed already in chapter 6. The lower heating values in kJ/kg. mole of some common gaseous fuels are : methane, CH₄: 802,000; ethane, C₂H₆: 1428,000; propane, C₃H₈ : 2044,000 : carbon monoxide, CO: 283,000.

The type of combustion process to be used depends upon the type of fuel to be burned and its concentration. The combustion limits for some gasses are given in table 8.5. Most of the fuels - solid, liquid or gaseous, contain C, H, O and S which produce CO₂, CO, SO₂, H₂O and unburned HCs. The three methods of combustion commonly used in air pollution control are (1) Direct combustion (2) Thermal combustion and (3) Catalytic combustion.

Direct-flame Combustion

Direct-flame combustion, as the name implies, is a method by which the waste gases are burned directly in a combustor with or without the aid of additional fuel such as natural gas. In some cases the waste gas itself may be a combustible mixture without the addition of air. In other cases, introducing air and or adding a small amount of supplemental fuel will bring the gaseous mixture to its combustion point. In a well designed combustor, the combustion can be carried out when the combined mixture has a heating value of 900 kcal / m³ or more. If the heating value is low the gases should be preheated for the combustion process. Heats of combustion of some common fuels are given in table 8.6

Flares: Flares are usually open ended combustion units maintained at the end of a stack or chimney discharging the waste gas stream. They are equipped with pilots to ensure continuous burning of gases. The combustion process should be designed in such a way that the flame burns at any wind speed, any gas flow rate and fuel compositions. Most flares are elevated 5-100m above ground level. However, some flares, particularly emergency flares are located at ground level itself but in very well protected area. The height of flares required above the surrounding objects, H is given by

$$H = \sqrt{Q/E} - 20 D \text{ where}$$

D is the diameter of flare and Q is energy release rate in watts. E is a constant with dimensions of $\sqrt{W/m}$. E = 550 if flares are continuously exposed to equipment or structures and E = 320 if flares are continuously exposed to personnel. Direct flame combustion in the form of flares, commonly about

80m high, is mostly used in refineries and petrochemical plants to dispose off combustibles present with inert gases, such as nitrogen and CO₂. All process plants that handle hydrocarbons, hydrogen, ammonia, hydrogen cyanide and other toxic or dangerous gases are subject to emergency conditions which occasionally require immediate release of large volumes of such gases for protection of plant and personnel.

Direct flame combustion is a relatively safe method of disposal of the large quantities of highly combustible waste gases. Direct flame combustion processes are economical only if the waste gas itself contributes more than 50% of the total heating value required for incineration.

Advantages and Disadvantages of Flares

1. The main advantage is simplicity and low cost.
2. There is an inherent danger of explosion when an enclosed chamber is used to contain flammable fuel mixture. No such danger exists with the flare since it is not enclosed.
3. Suitable for both intermittent and continuous flow of low quality fuel mixture.
4. The main disadvantage is that often large amounts of heat energy and other valuable products instead of being recovered are wasted.
5. Combustion in open air is difficult to control and complete combustion of pollutants especially of hydrocarbons may not be achieved. As a result flares are often smoky and sooty and create nuisance with reference to public acceptance.

The method of injecting steam into the flame zone

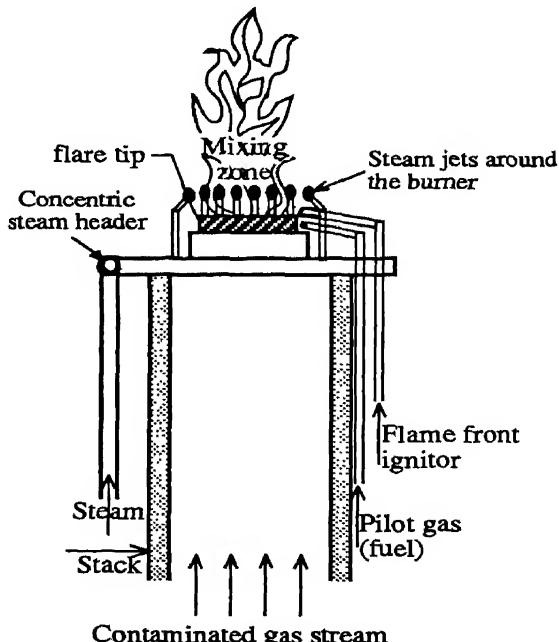


Fig. 8.5 Direct-flame Combustion

TABLE 8.5 COMBUSTION LIMITS FOR GASES AND VAPOURS IN AIR MIXTURES IN % BY VOLUME

Substance	Lower Flammability Limit	Upper Flammability Limit
Ammonia	15.0	28.0
Hydrogen	4.0	75.0
Hydrogen sulfide	4.3	45.0
Carbon monoxide	12.5	74.0
Methane	5.3	14.0
Ethane	3.0	12.5
Ethyl mercaptan	2.8	18.0
Butane	1.9	8.5
Ethylene	3.1	32.0
Benzene	1.4	7.1
Naphthalene	0.9	5.9
Water gas	7.0	72.0
Natural gas	4.0	14.0
Gasoline	1.4	7.6
Naphtha	0.8	5.0
Coal gas	5.3	32.0
Kerosene	0.7	5.0
Blast furnace gas	35	74
Producer gas	17	70
Oil gas	4.7	33
Methyl alcohol	7.3	36
Ethyl alcohol	4.3	19
Methyl ether	3.4	18
Methyl chloride	10.7	17.4
Vinyl chloride	4.0	22.0
Dimethyl sulfide	2.2	19.7

TABLE 8.6 HEATS OF COMBUSTION OF SOME FUELS IN MJ/kg

Hydrogen	120.9
Carbon	32.8
Sulphur	9.3
Carbon monoxide	10.1
Methane	50.2
Ethane	47.6
Propane	46.5
Butane	45.9
Methyl alcohol (liquid)	20.0
Benzene (liquid)	40.2

at the rate of 0.05-0.3 kg/kg gas, effectively increases turbulence in the burning zone and helps in the thorough mixing of air and fuel and hence eliminates smoke. Steam injection also reduces the length of the flame and helps in stabilizing the flame even in a brisk wind. Steam injection, however, has the disadvantage that it may retard the formation of long-chain hydrocarbons and inhibit polymerisation of hydrocarbons. Smoke can also be reduced by maintaining proper hydrogen carbon ratios. For example, a methane flare burns smokeless at a H/C ratio of 1:3.

Thermal Combustion

When the concentration of combustible pollutants is below the lower explosive limit, thermal incinerator or afterburner is one of the choice for combustion. The method is often used when the heating value of the waste gas is in the range of 50-750 kJ/m³. The waste gas stream is preheated in a heat exchanger and then passed through the combustion zone of a burner supplied with supplemental fuel. As a result, the combustibles in the waste gas stream are brought above their ignition temperatures and burn with the oxygen present in the contaminated stream. The temperatures of operation depend upon the nature of the pollutants in the waste gas, as given below

Pollutant to be oxidized	Average Temp. range, °C
Hydrocarbons	500-750
Carbonmonoxide	680-800
Odours	680-700

A properly designed and operated incinerator can completely destroy the organic vapour from the exit gases from the coffee roaster and smoke houses. A typical thermal incinerator assembly incorporating a recuperator is shown in figure 8.7. The use of a recuperator is to reduce the fuel requirements for thermal incinerator. In fact, the initial cost of the incinerator may be doubled by the addition of recuperation but the clear gas stream leaving recuperator may still have a high temperature, and hence may be used further as a preheat source for other operations.

Catalytic Combustion

A catalyst accelerates the rate of a chemical reaction without undergoing a chemical change itself. As a consequence, the residence times required for catalytic units are much less than those required for thermal units. Thermal units require 20 to 50 times as much residence time as a catalytic unit. In catalytic units, the waste gas stream need not be heated to high temperatures as in thermal incineration, because, ignition temperature is lower in catalytic processes. The catalytic temperature range for some pollutants are;

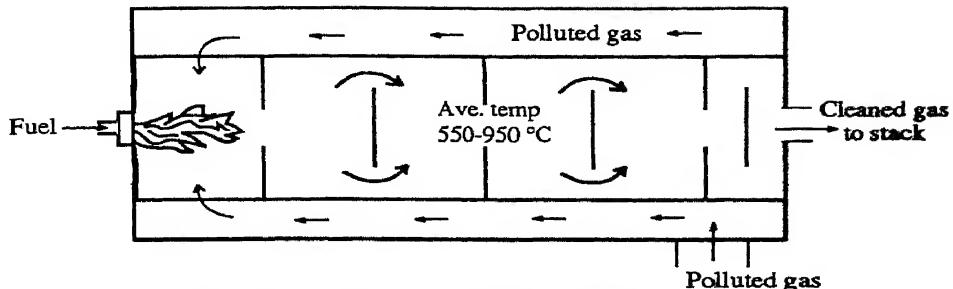


Fig. 8.6 Thermal Incinerator (After-burner)

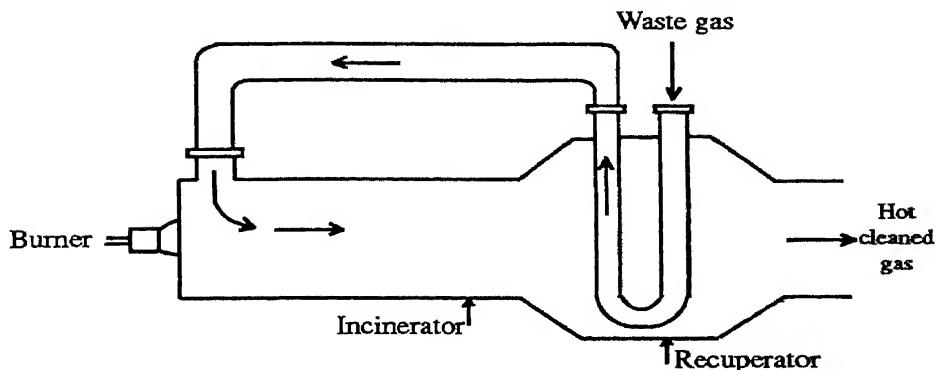


Fig. 8.7 Thermal Incinerator with Recuperator

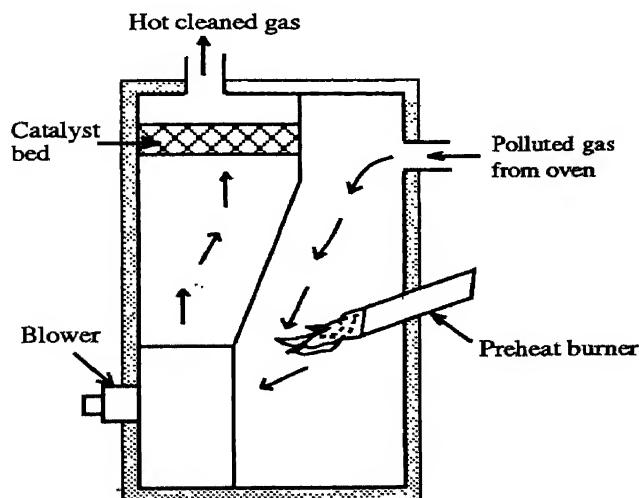


Fig. 8.8 Catalytic Combustion Unit

Solvents	250-450°C
Vegetable and animal fats	250-360°C
Chemical process exhausts	200-400°C

The catalytic oxidation of combustibles proceeds through (1) adsorption of the gas on the active surface (2) chemical reaction of combustible with the oxygen and (3) desorption of the reaction products from the surface. Hence the catalytic process is a surface reaction and suitable methods of exposing the maximum surface area are prime design criteria.

Most of the waste gases containing combustible pollutants from industrial processes are at a fairly low temperature. Therefore, preheating burner is used to bring the waste gas upto that temperature at which the catalyst will be effective. As the efficiency of catalytic combustion is on the order of 95 to 98 percent, the combustion is almost complete and the effluent gases from the catalytic conversion are CO_2 , water vapour and nitrogen only.

Many substances have catalytic properties but only a few are used for waste gas treatment. In order to be useful in air pollution control the substance must be relatively inexpensive, long lasting, able to function at the required temperature, and capable of being used in a variety of shapes. Successful catalytic beds have been formed into ribbons, rods, beads, pellets and other shapes. The catalysts used for effective pollution control are the precious metals, primarily platinum and palladium or their alloys.

Catalytic units are widely used for processes involving paint and enamel bake ovens, varnish kettles etc. The pressure drop through catalytic units is very low. Thus the operating costs are also low with the exception of the cost of maintaining the catalyst. The maintenance cost of the catalyst depends upon the nature of the fume. The waste gas must be cleaned of particulates before it enters the incinerator. Deposition of particulates on the surface of the catalyst bed decreases the available surface area for catalytic action. This lowers the effectiveness of the bed as well as its life time. The normal operating life of a catalyst without particulate deposition problem may be from 3 to 5 years. A typical catalytic combustion unit is shown in figure 8.8.

8.4 CONDENSATION

Condensation of vapour from the effluent gases as a method of recovery is applicable only if the vapour gas mixture is rich in vapour or saturated with it. In fact, it is most desirable that as much of the material as possible is recovered by condensation by cooling the gases to a temperature which is economically viable. Condensation of organic material using water at room temperature serves as an effective preliminary removal method prior to

treatment by methods such as adsorption or combustion. However, the efficiency of condensation can be increased by employing a refrigerated fluid such as chilled water.

Surface and contact condensers are the two basic types of condensation equipment. In surface condensers, the coolant such as water, refrigerant, chilled water or brine passes through the tubes whereas the vapour is on the shell side. In this condensation, physical adsorption plays a key role, since contaminants are adsorbed onto a surface as gaseous component condenses. In the shell and tube condenser, as the cooling medium flows through the tubes, the vapour condenses on the surface of the tubes. The condensed vapour collects as a film of liquid and the liquid drains off to storage.

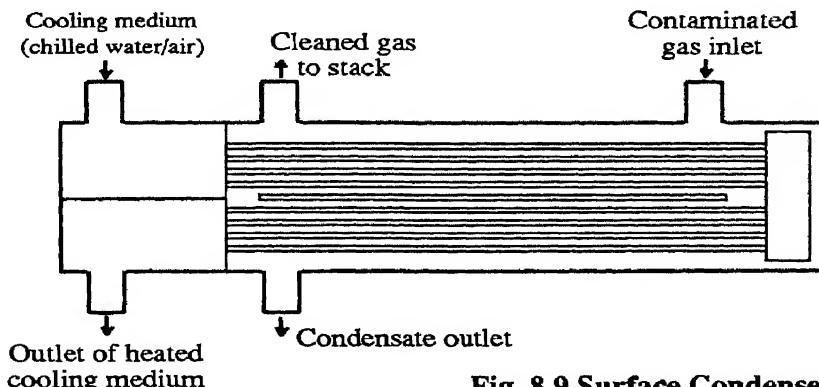


Fig. 8.9 Surface Condenser

In a contact condenser, the vapour and cooling medium are brought into direct contact. The cooled vapour condenses and the water and condensate mixtures are removed, treated and disposed off. The chief advantages of contact condensers are that they are less expensive and more flexible than surface condenser and they are more efficient in removing organic vapour. The different absorption processes like spray towers, packed towers, venturi and cyclone scrubbers also belong to the family of contact condensers. These are already described with figures in chapter 7.

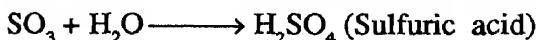
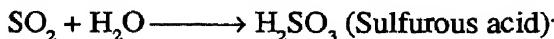
The specific application of the process of condensation depends upon the amount and type of coolant used, the liquid waste disposal problems and the amount of compound to be recovered. The method of condensation is widely used as an air pollution control device in petroleum refining, petrochemical manufacturing, manufacturing of ammonia and chlorine solutions and miscellaneous processes involving dry cleaning, degreasing and tar dipping.



CHAPTER - 9

SO_x CONTROL TECHNOLOGY

SO_x includes six different gaseous compounds of sulphur namely, sulphur monoxide, SO; sulphur dioxide, SO₂; sulphur trioxide, SO₃; sulphur tetroxide SO₄; sulphur sesquioxide, S₂O₃ and sulphur heptoxide, S₂O, out of which SO₂ and SO₃ are the most significant in air pollution. SO₂ is a colourless nonflammable and nonexplosive gas with a suffocating odour. It has an odour threshold of 0.5 ppm and taste threshold of 0.3 ppm. It is highly soluble in water at about 113 grams per litre at 20°C. It has a molecular weight of 64.06 and is about twice as heavy as air. It has a residence time of 2-4 days during which it can be transported to as far as 1000km . It is relatively stable in the atmosphere. It reacts photochemically to form SO₃, H₂SO₄ or salts of sulfuric acid. It reacts with water vapour in air to form a weak acid, the sulphurous acid.



SO₂ may be considered as the most significant air pollutant due to its ability to interfere with man and nature on both micro and macro scales. About 70% of acid rains are due to SO_x emissions and SO_x is the main culprit in affecting human health, destroying vegetation and damaging materials and art-treasures. SO_x control technology has assumed a great significance in the recent past as a means of preserving and protecting the environment.

Every day about one million tonne of SO₂ is released into the atmosphere from anthropogenic sources. It is primarily generated from the combustion of all fossil fuels-coal, petroleum and natural gas in industries and thermal power plants and small domestic units. Due to high population escalation these domestic units compete with any big industry as they can never have a pollution control system and many times may even exceed the levels of the former. Many cities all over the world are experiencing undesirable concentrations of SO_x (Ref. Table given below) and the situation demands immediate measures to mitigate SO_x emissions by proper control technology.

Mean annual concentrations of sulphur dioxide between 1976 and 1980 for cities in the GEMS network are presented below . The USEPA standard is included for comparision.

City	Country	Annual Mean(pphm)
USEPA standard		2.0
Milan	Italy	7.2
Saopaulo	Brazil	3.7
London	United Kingdom	2.8
Teheran	Iran	2.3
Madrid	Spain	2.3
Tokyo	Japan	1.9
Montreal	Canada	1.4
Sydney	Australia	1.3
Calcutta	India	1.2

Source : Bennett et al, (1985) and GEMS(1983)

9.1 CONTROL / REMOVAL TECHNOLOGY

There are six procedures for controlling the emissions of SO_x. They are either in-plant control measures or effluent treatment methods.

- (i) Natural dispersion by dilution.
- (ii) Using alternate fuels
- (iii) Removal of sulphur from fuels (Desulfurization)
- (iv) Process modifications
- (v) Control of SO_x in the combustion process
- (vi) Treatment of flue gas emissions.

The different control methods are described as follows:

9.2 NATURAL DISPERSION BY DILUTION USING TALL STACKS

A control method involving dispersion of a pollutant from tall stacks seem archaic. Nevertheless, there is considerable controversy over this technique as opposed to flue-gas desulfurization. The control method is based on natural dispersion at high elevation so that the ground level concentrations are acceptable at all times. In India, minimum stack heights of 30 m are recommended. Similarly, the height of chimney, H required for effective dispersion of Q kg/ hour of SO_x emissions is given by, $H = 14 Q^{0.3}$. This condition may demand stack heights of 400- 450m also. For example, the TVA Cumberland Power Station in Tennessee has twin 300m concrete chimneys while International Nickel Company has built one that is 380 m high, only to reduce concentrations by dilution in atmosphere. It is also a common practice to stop discharging the effluents into the atmosphere during adverse meteorological conditions. However, this technique is not possible in large scale power plants etc.

9.3 USING ALTERNATE FUELS

A switch to natural gas from the conventional high-sulphur fuels like coal and petroleum to lessen SO_x emissions is an available alternative. Liquefied Natural Gas, LNG also is an effective alternative. However, for utility use, cost will be much higher than that of other alternatives. Low sulphur coal is another alternative, but obtaining low sulphur coal from the ground is neither quick nor cheap. Table 9.1 gives different fuels and their sulphur content.

Table 9.1 Sulfur Content in Fuels

Substance	% Sulfur	Calorific value
Anthracite	1.0	34.0
Bitumen	1.6	25.3
Coal tar	0.5	38.0
Coke	0.5	29.0
Crude oil	0.5-3.0	varies
Fuel oil	2-4	43.5
Lignite	1.5	23.0
Natural gas	traces	34.0
Peat	1.0	18
Wood	0	18

9.4 REMOVAL OF SULPHUR FROM FUELS

The process of removing sulphur prior to combustion is theoretically attractive but practically ineffective. Coal consists of sulphur in both organic and

inorganic forms. The inorganic form of sulphur is iron disulfide (FeS_2) mostly available in the forms of pyrites and marcasites. Apparently, washing seems to be an effective process with more than 30% of sulphur being removed. But this results in a loss of combustible material and may increase the requirement of coal and thus the cost. Organic sulphur is present in the form of cystine, thiols, sulfides and some other cyclic compounds, which can only be removed by chemical processing.

Hydro-desulfurization of coal using a solvent extraction process can remove both organic sulphur as well as inorganic sulphur. In this process finely ground coal is mixed with anthracene oil to form slurry and this slurry is heated at a very high temperature of 450°C. The ash residue consisting of both organic and inorganic forms of sulphur is eliminated by pressure filtration. To avoid repolymerisation a small amount of hydrogen is also added. The coal solution filtrate is sent into a chamber to remove lighter fractions. The hot liquid residue is cooled to a brittle solid fuel which can be pulverized. The product will be liquefied at about 450°C. It has a higher heating value than raw coal, and contains less than 1% of sulphur.

Coal gasification is another process widely used for the Indian coal reserves. There are several processes to convert coal into gaseous form. The earlier processes like water-gas and producer-gas processes produced gas of lower quality. The new processes are more effective which give a better quality besides removing both organic and inorganic types of sulphur. Catalytic hydrogenation of coal suspended in tar at 100–250 bars at 450°C can achieve 75 percent desulfurization with the consumption of 20 kg hydrogen per tonne of feed coal. About 5 percent of this hydrogen is transformed to hydrogen sulfide, an unwanted by-product. Similarly, impure natural gas can be freed of hydrogen sulfide by scrubbing with monoethanolamine or other amines. The sulphur can be recovered by dry catalytic conversion when molten sulphur is obtained. Usually 0.5 to 5 percent of sulphur is present in heavy fuel oils. The hydro-desulfurization process is used for desulfurization of fuel oil. In this process high temperatures are maintained between 400°C to 550°C. The fuel oil is treated with hydrogen in the presence of a catalyst. The residue is eliminated by pressure filtration with pressures ranging from 35 to 70 atmospheres. The sulphur is recovered by sending it into a flash evaporator where lighter fractions are removed. Almost all coals dissolve in solvent oils at high temperatures (550°C) and pressures (75 bars) in the presence of hydrogen which prevents polymerisation and helps in the removal of organic sulphur. Coal gasification appears to be a promising method for the abundant coal reserves in India. Oil gas can be scrubbed free of sulphur and can be used in gas-burning devices.

9.5 PROCESS CHANGES

Process changes involve new or modified techniques lowering atmospheric pollutant emissions. On similar lines, DCDA (Double Catalysis Double Absorption) process was developed and was found to reduce SO_2 emissions from 2000-5000 ppm to less than 500 ppm in the stack gases.

Most of the conventional sulfuric acid plants till 1970, were designed for about 95% conversion of SO_2 in four stages and proved to be an effective process as this was the optimum level of oxidation. However, this led to concentration of SO_2 in stack gases in the region of 2000ppm and more. The present desirable concentration of 500 ppm can easily be achieved with a double stage contact conversion. This technique is known as Double Catalysis, Double Absorption (DCDA) process.

Earlier, in the conventional contact processes SO_2 produced by the burning of sulphur with preheated air was converted to SO_3 by passing over vanadium pentoxide catalyst in four stages. The gas was cooled and absorbed with high efficiency in a circulating stream of 98 to 99 % sulfuric acid. This results in the effluent gas with high SO_2 concentrations which is usually above the permitted standards. Hence tail gas scrubbing was further necessary for bringing the SO_2 concentration to acceptable limits.

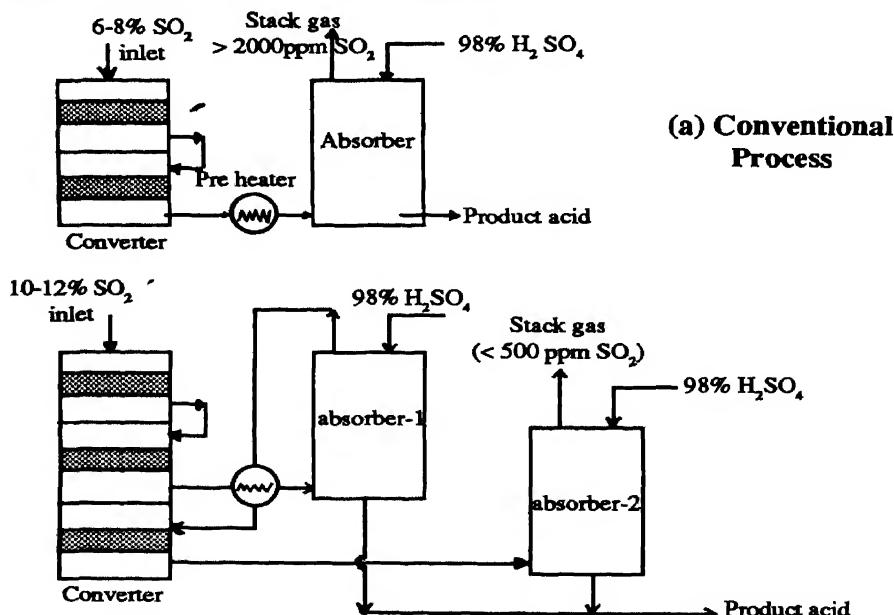
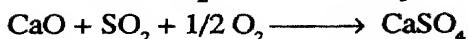
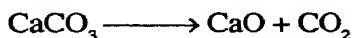


Fig. 9.1 (b) Manufacturing of H_2SO_4 by DCDA Process

This problem led to a modern modification of contact plant which is called the DCDA process. In this process sulphur is burnt with air in a horizontal spray - type combustion chamber. The emitted SO₂ gas from the sulphur burner has a very high temperature. It is cooled in the waste heat boiler, which recovers surplus heat as the by product, steam. From the waste heat boiler, the gas flows to the converter system in different stages. The gases from the converter, after 90% of SO₂ has been converted to SO₃, are interrupted and passed at an intermediate stage to an absorber to remove SO₃. The gases are then reheated and returned to the converter for further conversion. They then pass through the additional catalyst , are cooled, pass through a second absorber and then to the atmosphere. The unconverted gases, after being heated by the gases entering the absorber, are returned to the next stage of converter. As a result, the overall SO₂ conversion efficiency increases. It is also possible to use, higher inlet concentrations of SO₂ (10-12%) as against the usually employed 8% concentration. The thermal efficiency of the system can further be improved with suitable waste heat recovery methods like utilizing heat from sulfur burners or heat from oxidation of SO₂ to SO₃. At high pressures of about 22 atm. and 9% SO₂, conversion efficiencies of upto 99.7% with SO₂ concentration as low as 40 ppm can be achieved. The use of oxygen instead of air further decreases the plant size and volume of gases. Thus the DCDA process requires just one extra absorption tower than the conventional plant. It has been established that any plant of capacity 50 tonne of acid per day and above can be converted into a double absorption system economically. Another advantage of DCDA process is that it can be adopted to a wide range of SO₂ concentrations. This process is proved to be economical and may be strongly recommended for almost all the H₂SO₄ manufacturing units.

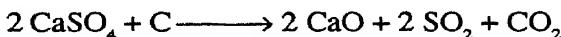
9.6 CONTROL OF SO_x IN THE COMBUSTION PROCESS

Here, finely powdered limestone is injected directly into the conventional combustion chamber. The limestone is calcinated to CaO by the heat of combustion and it reacts with SO₂ contained in the flue gas to form sulfites and sulfates. The unreacted materials and flyash are removed by dry collectors.



The formation of CaSO₄ is most favoured at temperatures above 1000°C. Due to the smaller residence time in combustion zone limestone does not completely react with SO₂ to produce a stoichiometric yield of CaSO₄. At

temperatures above 1200°C, CaSO_3 is unstable and SO_2 removal by sulfite formation is inhibited. As a result, the process removes less than half of the sulphur oxides. Due to this, the dry limestone injection process, although relatively simple and easy to operate is not very attractive from the point of view of control technology. Research is going on to increase the efficiency of this process and other widely used processes like the fluidized bed combustion process. In this process limestone and crushed coal together form the fluidized bed and oil is used as the fluidizing medium. The operating temperatures are of the order of 700 - 1000°C since the fluidized beds are capable of transferring high heat. This process proves to be quite effective as it removes more than 90% of sulphur. In addition to high SO_2 removal efficiencies, the fluidized bed combustion process, prevents the onset of ash fusion and as a result, the fouling and corrosion of boiler tubes associated with the molten slag are considerably reduced. Also, the formation of nitrogen oxides by the nitrogen fixation reaction are reduced. The method also has some drawbacks. It requires design modification for boilers and also additional installations for the preparation of limestone. If the limestone is ground to the same size as coal then a practically inseparable mixture of ash and lime is produced. The fine ash can be elutriated and partially sulfated lime is regenerated.



This regeneration, which requires temperatures in excess of 1000°C, would substantially suppress the consumption of limestone.

9.7 TREATMENT OF SULPHUR FROM FLUE GAS EMISSIONS

Progress in developing satisfactory desulfurization processes for flue gases has been extremely slow because of the complexity and magnitude of the problem. The technical and economic feasibility of most desulfurization processes are closely related to plant size and location. It seems unlikely that a single desulfurization method will be developed that is capable of controlling effluents from all types of sources. The control techniques to be employed depend upon such factors as boiler size, configuration, load pattern, geographical location and the like. Nearly fifty flue gas desulfurization processes have been proposed, but as such no ideal process exists. The general classification of these processes may be wet and dry.

9.8 DRY METHODS

The dry methods can be divided, broadly, into two types.

- 1) Oxidation / reduction methods
- 2) Metal oxides usage

Oxidation / Reduction

CATOX Process : This method of oxidation is popularly known as the "Cat-Ox" process and produces sulfuric acid. In this process fly ash is first removed from the flue gas by a high temperature electrostatic precipitator. SO₂ is then catalytically oxidized to SO₃ and recovered as sulfuric acid. If the exit gases are at a lower temperature, they may be heated. V₂O₅ at 400-500°C is used as a catalyst for good conversion efficiency. In a modified oxidation process, SO₂ and oxygen present in the stack gas are absorbed on the surface of an active carbon catalyst which catalyzes the oxidation of SO₂ to SO₃. SO₃ reacts with the moisture present to form H₂SO₄ in the pores of active carbon. The combined effect of absorption and catalysis by the active carbon leads to a complete conversion of SO₂.

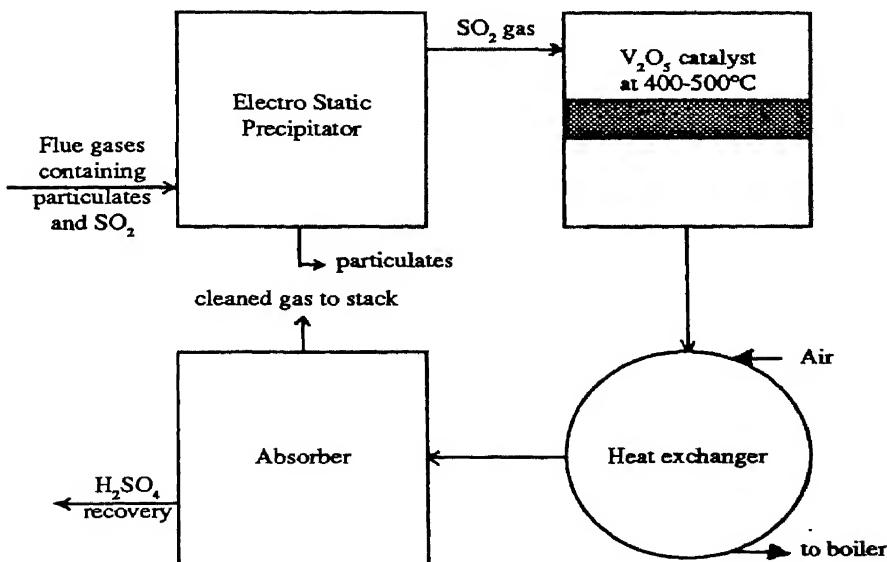
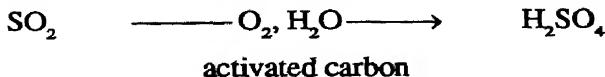


Fig. 9.2 CatOx Process of Removal of SOx

Westvaco Process : This process also involves oxidation/reduction. This process is unique in that it utilizes fluidized beds of high efficiency activated carbon and converts H₂SO₄ to sulphur. Flue gas is contacted with activated carbon in the absorber unit and SO₂ is oxidized to SO₃.



The carbon which is used as a catalyst is fed to a sulphur generator where it is contacted with H_2S to form sulphur.



A fraction of the sulphur is recovered by vaporization and is recondensed as a molten product. The remaining fraction of sulphur reacts with hydrogen in a hydrogen sulfide generator to form H_2S .

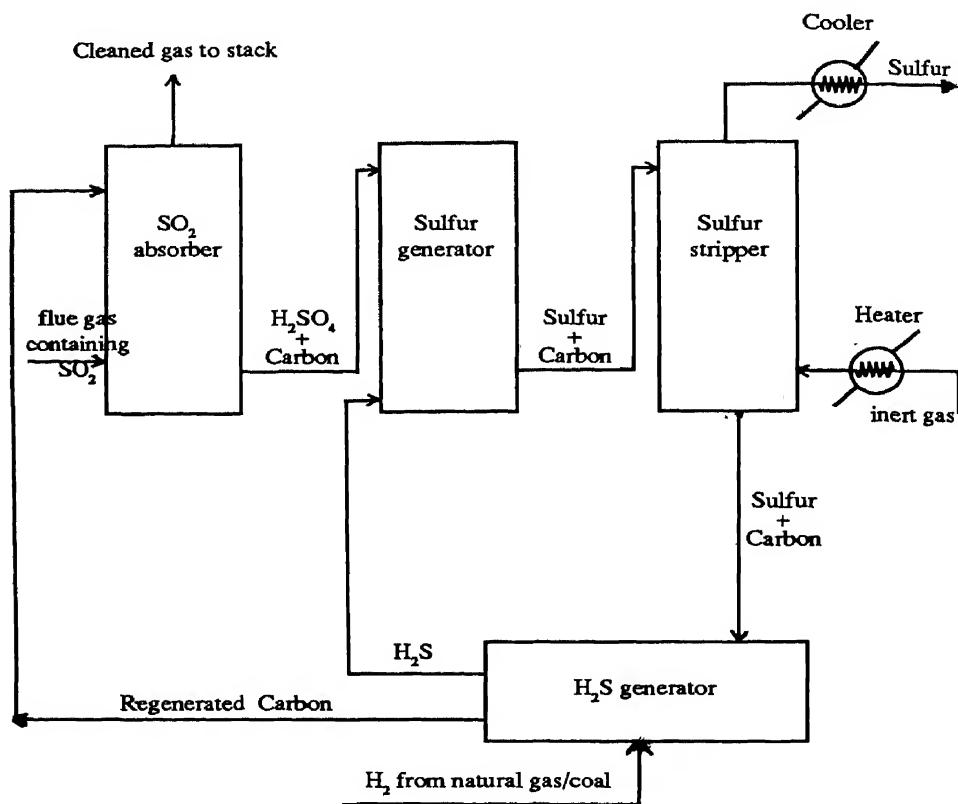
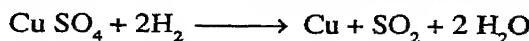


Fig. 9.3 Westvaco Process

SCOT Process : In the 'SCOT' (Shell Clauss Off-gas Treatment) process, developed in the Netherlands, almost complete removal of sulphur or its compounds is possible. The gases are reduced while sulphur and its compounds are converted to H_2S . In this process SO_2 reacts with copper oxide at a temperature of about 400°C to form copper sulfate.



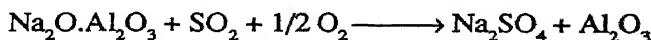
Copper sulfate is then reduced at the same temperature in a hydrogen rich gas



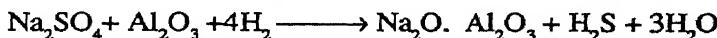
The concentrated SO₂ is then sent to a Clauss sulphur recovery plant. The Clauss off gas is heated with the addition of a reducing gas (H₂,CO) and passed through a reactor containing a cobalt-molybdenum catalyst. The absorber used for removal of H₂S is often a diisopropanolamine (DIPA) solution SO₂ concentrations of less than 250 ppm can be obtained with this process.

Use of Metal Oxides

In this process sodium aluminate (Na₂O. Al₂O₃) is used to remove SO₂ in a fluidized bed. In this process, developed by U.S. Bureau of mines, the dust-free flue gas is fed to a reactor wherein the absorbent, a porous form of sodium aluminate (Na₂O. Al₂O₃), adsorbs SO₂ at a temperature of 300°C.



The product from the above reaction is contacted with a reducing gas such as hydrogen in a regenerator at about 680°C to form hydrogen sulfide.



From this the sodium aluminate is recycled and hence the process is called a cyclic adsorption process. Sulphur can also be produced as a by-product from the H₂S gas by sending it into a Clauss unit.



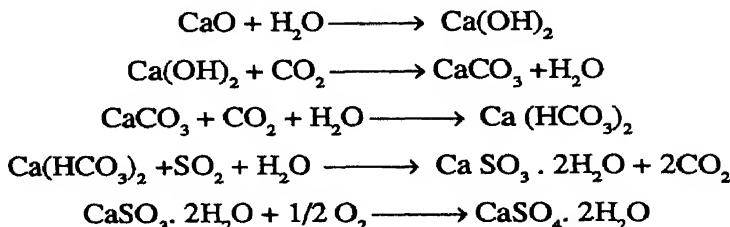
However, maintenance of the granular strength of sorbent is the main problem relating to this process. The rigorous temperature and chemical cycling to which the sorbent is subjected, deteriorate the sorbent by causing crystalline growth and loss of surface area.

9.9 WET PROCESSES

The main unit responsible in a wet process is the scrubber-a spray tower, a cyclone scrubber, a venturi scrubber or a packed tower. Most of the currently available wet flue gas desulfurization methods use slurries of compounds of calcium, magnesium and sodium. In the wet process the treated gases are kept at low temperatures in the range of 25 - 50°C. This creates a problem in the dispersion of the flue gas. Hence reheating is required which consumes heat in the range of 3% of the heat of fuel used in the combustion chamber. Some of the wet processes are described as follows:

Calsox Process (Lime and Limestone Scrubbing) : Here the flue gas is scrubbed with a 5 to 15 percent slurry of calcium sulfite / sulfate salts which

also contains amounts of lime (CaO) and limestone (CaCO_3). The SO_2 reacts with the slurry to form additional sulfite and sulfate salts. The solids are continuously separated from the slurry and discharged into a settling pond. The remaining liquor, at a pH of 6 to 8, is recycled to the scrubbing tower after fresh lime or limestone has been added. A schematic representation of the process is shown in figure. Although overall mechanism for the process is complicated, the following reactions are likely to occur :



The problems in this process include scaling, corrosion, erosion and solid waste disposal. A sizeable disposal area adjacent to plant is required. Another drawback of the process is the necessity for reheating the cleaned flue gas. Reheating is accomplished by installing a gas cooler before the scrubber and a gas stack heater after the scrubber. Thus two additional units must be provided to the gas flow system.

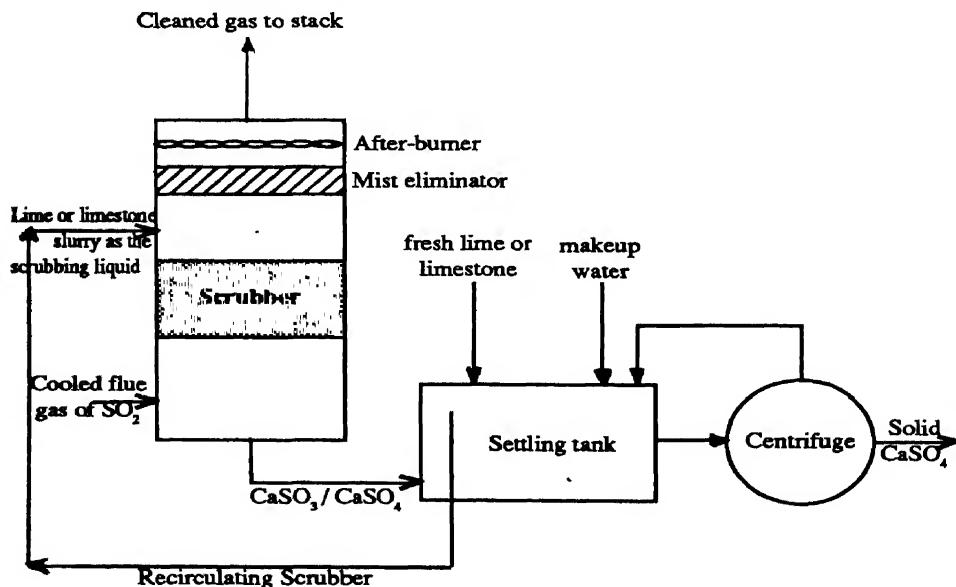
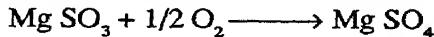
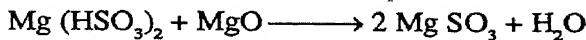
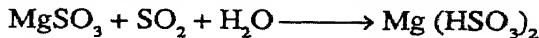
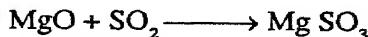


Fig. 9.4 SO_x Control by Lime / Limestone Scrubbing

Chemico Process (Magnesium Oxide Scrubbing) : In this process, known as the "Chemico Process", magnesium oxide acts as a venturi scrubber by absorbing SO₂ and generating magnesium sulfite and sulfate



The mixed sulfite / sulfate slurry alongwith unreacted MgO is separated from liquid phase in a centrifuge.



This process is a regenerative process as the mother liquor is regenerated. Concentrated SO₂ (10 to 15%) evolved from the flue gas is used in making elemental sulphur or reprocessed to manufacture H₂SO₄.

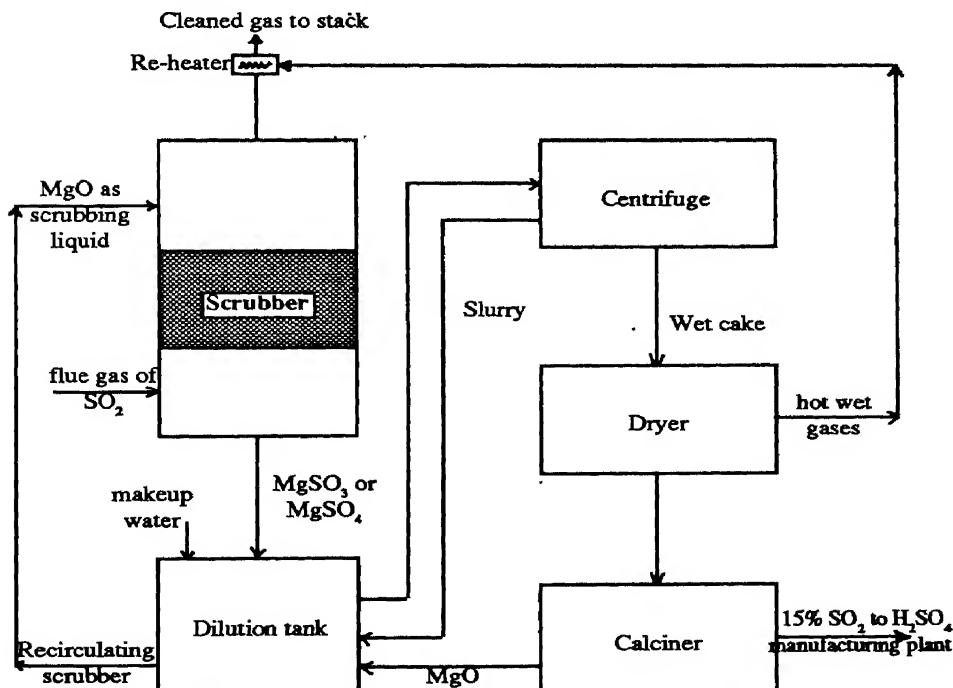
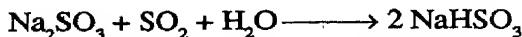


Fig. 9.5 SO_x Control by Chemico Process using MgO

Wellman Lord (Single Alkali) Process: This process removes sulphur dioxide by washing fuel gases with an aqueous solution of sodium sulfite. It is quite a common practice in chemical industries, in which 90% of desulfurization is possible. In this process sulfite is converted to bisulphite as the SO_2 from flue gases is absorbed by a saturated solution of sodium sulfite.



The sodium bisulphite formed is led to a double effect evaporator cum crystallizer where it decomposes into sodium sulfite at a temperature of around 100°C . This results in the ejection of SO_2 and steam.



Fly ash is removed before the SO_2 scrubbing to keep the rate of its accumulation in the scrubbing liquid low. SO_2 and water vapour released from the evaporators are passed into a condenser and the product goes to the dissolving tank for dissolution of Na_2SO_3 crystals and the rich SO_2 gas is processed. Sodium sulfate is produced in this reaction which is removed and substituted by an equivalent amount of NaOH .

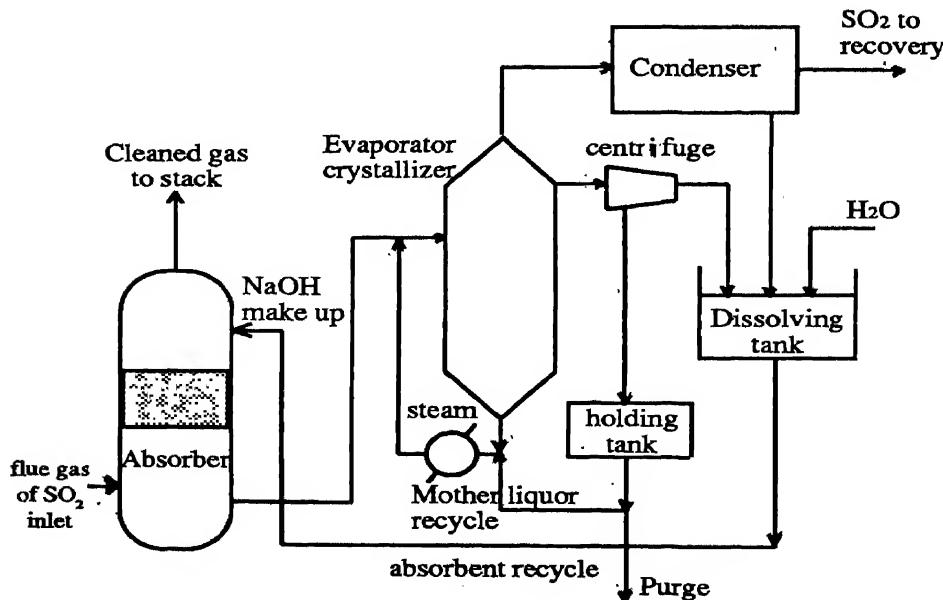
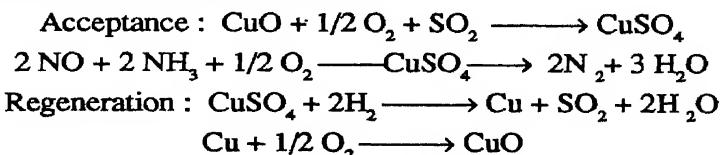


Fig. 9.6 Wellman-Lord (Single Alkali) Process

Clear solutions of either sodium or ammonia are excellent absorbers of SO₂. The regeneration step can be carried out at a relatively low temperature in a liquid system. The one advantage that sodium scrubbing has over ammonia is that the cation is nonvolatile. Fume development is another problem in almost all ammonia scrubbers. Both processes produce an unavoidable side product, sodium sulfate in one case and ammonium sulfate in the other.

CuO/CuSO₄ Process: This process removes NO_x and SO_x simultaneously by using copper oxide (CuO) supported on stabilized alumina placed in two or more parallel passage reactors. The reactions, which characterize process operation can be expressed as



Flue gas is introduced at about 400°C into one of the reactors where SO₂ reacts with CuO to form copper sulfate (CuSO₄). The CuSO₄ and to a lesser extent, the CuO act as catalysts in the reduction of NO_x with NH₃. When the reactor is saturated with CuSO₄, flue gas is switched to a fresh reactor for acceptance of the flue gases and the spent reactor is regenerated. In the regeneration cycle hydrogen (H₂) is used to reduce CuSO₄ to copper (Cu), yielding an SO₂ stream of sufficient concentration for conversion to sulfur or sulfuric acid.

'ASARCO' Process: The American Smelting and Refining Company has developed a process to control the emissions of SO_x by absorption of flue gases in dimethylaniline. In this process, called the ASARCO process, the desulphurized gas is further sent through sodium carbonate solution, and then to diluted H₂SO₄, where the gas is scrubbed for traces of sulphur and dimethylaniline if any. The SO₂ absorbed dimethylaniline solution is passed through a steam distillation column where dimethylaniline is treated and recycled. The tail gas left into the stack after this scrubbing process consists of SO₂ of about 500 ppm. This process can be used for SO₂ gas concentrations of more than 3%.

'COMINCO' Process: The U.S. based COnsolidated MINing and smelting COmpany has developed a process to remove SO₂ by using aqueous ammonia solution in zinc plants. This process, named as COMINCO process, can be used for gas concentrations of 5% to as low as 0.3%. In this process a 30% aqueous ammonia solution absorbs SO₂ producing ammonia bisulphite (NH₄HSO₃). Then in a stripping column the NH₄HSO₃ solution is added to 95% H₂SO₄ which strips the solution and ammonium sulfite is produced. This process has a removal efficiency of about 95% in zinc roasters.

Citric Acid Scrubbing: This process was developed by United States Bureau of mines as early as in 1960s for specific application to non ferrous smelting industry, power and refining industries. From economic view point it is claimed that the citrate process using aqueous solution of sodium citrate, is applicable to flue gases containing 500 ppm to 5 percent by volume of SO_2 . The removal efficiency achieved is 80 to 90%. One of the major advantages of this process is that elemental sulphur is the primary product, which is easily stored and directly marketable. No significant sludge disposal is required and the organic acid reagent is non toxic and biodegradable.

The different SO_x removal processes are summarized in table 9.2. The different absorption units are already described in chapter 7 in detail.

TABLE 9.2 SO_2 REMOVAL PROCESSES

Pocess Details (Material used)	Active Material	Final Product
Dry Processes		
1. Carbon adsorption at 125°C reaction with H_2S to S and H_2 to H_2S	Activated carbon/ H_2	Sulfur
2. Spray dryer, absorption by sodium carbonate of slaked lime solution	$\text{Na}_2\text{CO}_3/\text{Ca}(\text{OH})_2$	$\text{Na}_2\text{SO}_3/\text{Na}_2\text{SO}_4$ $\text{Na}_2\text{SO}_3/\text{CaSO}_4$
Throwaway Scrubbing Processes		
3. Limestone or lime slurry	CaO/CaCO_3	$\text{CaSO}_3/\text{CaSO}_4$
4. Na_2SO_3 solution	Na_2CO_3	Na_2SO_4
5. Double alkali : Na_2SO_3 solution regenerated by CaO or CaCO_3	$\text{CaCO}_3/\text{Na}_2\text{SO}_3$ CaO/NaOH	$\text{CaSO}_3/\text{CaSO}_4$
6. MgSO_4 solution regenerated by lime/limestone	MgO/MgSO_4	$\text{CaSO}_3/\text{CaSO}_4$
Regenerative Scrubbing Processes		
7. $\text{Mg}(\text{OH})_2$ slurry	MgO	15% SO_2
8. Na_2SO_3 solution	Na_2SO_3	90% SO_2
9. Sodium citrate solution	H_2S	Sulfur
10. Ammonia solution	NH_4OH	Sulfur



CHAPTER - 10

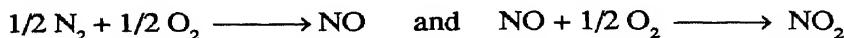
NO_x CONTROL TECHNOLOGY

NO_x is one of the four major air pollutants and is the element primarily responsible for the formation of photochemical smog. About 30% of acid rains also are due to NO_x. There are two sources of nitrogen which contribute to the formation of nitrogen oxides during combustion - one is the atmospheric nitrogen and the other is the nitrogen present in the fuel itself. Nitrogen without the presence of any known catalyst, combines with oxygen during combustion to form oxides of nitrogen.

The various reasons for the increase of oxides of nitrogen in the ambient atmosphere may be the increased emissions of NO_x from industries and automobiles and various other sources. Well over 90% of all the man-made nitrogen oxides that enter our atmosphere are produced by the combustion of various fuels.

The real danger posed by NO_x at the concentrations found in metropolitan areas lies in its role in photochemical reactions leading to smog formation. These atmospheric reactions lead to the formation of chemical compounds that do have a direct adverse effect on human beings and plants. In some situations, NO_x may be present in a high enough concentration, yet not react to form smog because other necessary conditions for the reaction are absent. However, nearly every major city in India at times experiences the effects induced by the presence of NO_x.

The actual quantities of NOx produced by any given industry can be quite large. For example, a 750-MW gas or coal fired power plant produces around 75 to 100 tonnes of NOx per day. The type of fuel used can change the amount of NOx released significantly. About 60% of NOx is contributed by fuel combustion in the stationary sources and about 40% by transportation. The stable gaseous oxides of nitrogen include N₂O (nitrous oxide), NO (nitric oxide), N₂O₃ (nitrogen trioxide), NO₂ (nitrogendioxide) and N₂O₅ (nitrogen pentoxide). An unstable form, NO₃ also exists. Of all these oxides of nitrogen the only ones present in the atmosphere in any significant amount are N₂O, NO and NO₂. These three are the potential contributors to air pollution. The main chemical reactions in the formation of nitrogen oxides are



Nitric oxide (NO) is a colourless gas and its ambient concentration is usually far less than 0.5 ppm. At this concentration its biological toxicity in terms of human health is insignificant. N₂O is an inert gas with an aesthetic characteristic. Its ambient air concentration is 5 ppm. It has a balanced environmental cycle which is independent of other oxides of nitrogen.

However, nitric oxide is a precursor to the formation of nitrogen dioxide and is an active compound in photochemical reaction in air pollution. NO₂ (nitrogen dioxide) is a reddish brown gas and is quite visible in sufficient amounts. NO₂ directly affects human health only if it is present in extremely high concentrations. Exposure to 15 ppm of NO₂ causes eye and nose irritation and pulmonary discomfort is noted at 25ppm for exposure of less than 1 hour. NO₂ concentration of 1 ppm can be detected by the eye. The threshold limit in ambient air is considered to be 5 ppm for daily exposure. In general the concentration of oxides of nitrogen are expressed under the formula NO_x (or on an "equivalent NO₂" basis).

TABLE 10.1 NOx EMISSION FACTOR

SOURCE	AVERAGE EMISSION FACTOR
COAL	
Household and commercial	3.2 kg/ton of coal burned
Industry and utilities	8.0 kg/ton of coal burned
FUEL OIL	
Household and commercial	5-7 kg/m ³ of oil burned
Industry	7.0 kg/m ³ of oil burned
Utility	10.5 kg/m ³ of oil burned

NATURAL GAS

Household and commercial	1.50 mg/m ³ of gas burned
Industry	2.75 mg/m ³ of gas burned
Utility	5.02 mg/m ³ of gas burned
Gas turbines	2.60 mg/m ³ of gas burned

WASTE DISPOSAL

Conical incinerator	0.3 kg/ton of waste burned
Municipal incinerator	0.9 kg/ton of waste burned

MOBILE SOURCE COMBUSTION

Gasoline - powered vehicle	11.4 kg/m ³ of gasoline burned
Diesel - powered vehicle	22.4 kg/m ³ of oil burned
Air craft - conventional	9.20 kg/flight per engine
- fan-type jet	4.20 kg/flight per engine

NITRIC ACID MANUFACTURING 26 kg/ton of acid produced**10.1 THERMODYNAMICS OF NO AND NO₂ FORMATIONS**

In order to interpret data correctly and analyse the amount of pollution caused by various oxides of nitrogen one must have a basic understanding of the thermodynamics and kinetics of nitrogen-oxygen relations, especially at high temperatures. The equilibrium reactions for the formation of NO and NO₂ are

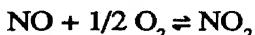
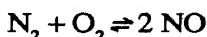


Table : 10.2 : Equilibrium constants for the formation of nitric oxide from molecular oxygen and nitrogen : N₂ + O₂ ⇌ 2NO

T (°K)	K _p = (pNO) ² / (pN ₂) (pO ₂)
300	10 ⁻³⁰
1000	7.5 × 10 ⁻⁹
1200	2.8 × 10 ⁻⁷
1500	1.1 × 10 ⁻⁵
2000	4.0 × 10 ⁻⁴
2500	3.5 × 10 ⁻³

TABLE : 10.3 : Typical NO composition at various temperatures for the equilibrium reaction $N_2 + O_2 \rightleftharpoons 2NO$, as a function of N:O ratio

T (°K)	NO Concentration in ppm	
	N : O = 4	N : O = 40
1200	210	80
1500	1300	500
1800	4400	1650
2000	8000	2950
2200	13100	4800
2400	19800	7000

TABLE : 10.4 : Equilibrium constants for the nitric oxide oxidation reaction to nitrogen dioxide: $NO + 1/2 O_2 \rightleftharpoons NO_2$

T (°K)	$K_p = (pNO_2) / (pNO)(pO_2)^{1/2}$
300	10^6
500	1.2×10^2
1000	1.1×10^{-1}
1500	1.1×10^{-2}
2000	3.5×10^{-3}

TABLE: 10.5 : Predicted equilibrium compositions of NO and NO_2 at various temperatures for the simultaneous reactions $N_2 + O_2 \rightarrow 2NO$ and $NO + 1/2 O_2 \rightarrow NO_2$ for an initial composition of 3.3% O_2 and 76% N_2

T (°K)	NO (ppm)	NO_2 (ppm)
300	1.1×10^{-10}	3.3×10^{-5}
800	0.77	0.11
1400	250	0.87
1875	2000	1.8

10.2 NO_x CONTROL TECHNOLOGY

NOx emissions from flue gases can be reduced by (i) dilution in atmosphere by increasing stack height or by discharging effluents into the atmosphere

only during favourable meteorological conditions (ii) modification of operating and design conditions and (iii) treatment of flue gases. The method of control of NO_x by dilution is similar to that of SO_x, particulates and other pollutants.

10.3 NO_x CONTROL BY MODIFICATION OF OPERATING AND DESIGN CONDITIONS

On the basis of the thermodynamics and kinetics involved in the formation of NO_x, the following in-plant measures can be adopted to reduce the emissions of NO_x. These are based on the principles that NO_x emissions can be reduced by (i) reducing the peak temperature (ii) reducing the residence time at the peak temperature and (iii) reducing the availability of oxygen i.e. by maintaining higher N/O ratios. The in-plant control measures are:

1. Low Excess Air Combustion: The presence of excess air affects both the temperature and oxygen concentration of gases in the post combustion zone. Normal boiler units operate in the presence of 10-20% excess air to ensure complete combustion of the fuel but this excess air provides enough oxygen for reacting with nitrogen. The results for pulverized coal firing in an experimental unit are shown in figure.

In this specific case, NO_x decreased from 600 ppm at 25% excess air to as low as 175 ppm at 1.4% excess air. But this results in lowering of carbon combustion efficiency. It was observed that combustion efficiency falls from 99.5% at 25% excess air to around 92% at 2% excess air. This occurs inspite of the fact that the flame temperature increases as the inlet air concentration approaches the stoichiometric value. The rapid drop - off in oxygen concentration in this case dominates over the temperature effect.

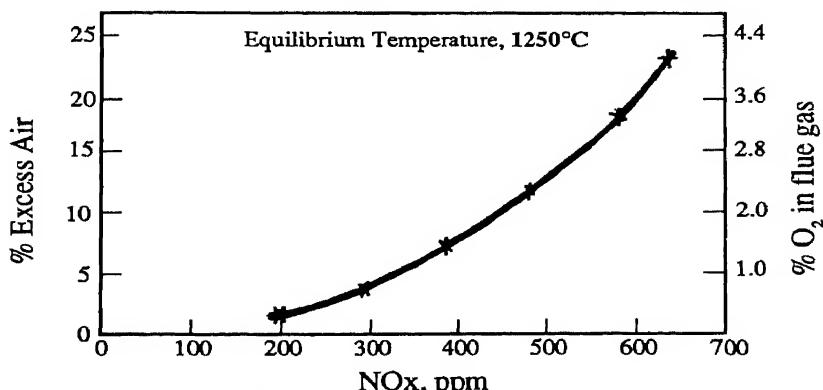


Fig. 10.1 Effect of Excess Air on NO_x Formation

2. Decreasing Combustion Air Temperature: In many industries waste heat is available to help preheat the air entering a combustion process. Although this process leads to appreciable energy savings, the added energy increases the flame temperature. Thus NOx emissions increase. Data from full sized boiler tests indicate a three fold increase in NOx emissions when combustion air is preheated from 25° to 300°C. Since temperature has a major influence on nitric oxide formation, an effective method of control is cooling of primary flame zone by heat transfer to surrounding surfaces.

3. Two Stage Combustion: This is one of the most effective control methods for the suppression of the formation of nitrogen oxides. In the first stage the fuel and air are burned at near - stoichiometric conditions. All the fuel is fired with only 85-95% of total air requirements at the bottom of the furnace followed by secondary air injection higher up in the furnace to complete the combustion. Thus in the primary zone incomplete combustion of the fuel takes place resulting in reduced concentrations of NOx in furnace gases. Heat removal and gas dilution between zones cause the temperature of the gases after the primary zone to decrease so that the final stage of combustion process occurs at a lower temperature. Reduction in the emission of NOx by 38% for coal and oil firing and by 50% for natural gas combustion has been observed under these conditions.

4. Flue Gas Recirculation: The recirculation of coal flue gas into the combustion chamber is found to be quite effective in reducing NOx formation from stationary sources. A portion of the cooled flue -gas is injected back into the combustion zone. This additional gas acts as a thermal sink and reduces the overall combustion temperature. In addition, the oxygen concentration is lowered as the flue gases going out have a higher N/O ratio i.e. lower oxygen availability. Both these effects favour a reduction in NOx emissions. One disadvantage is the increased cost of duct

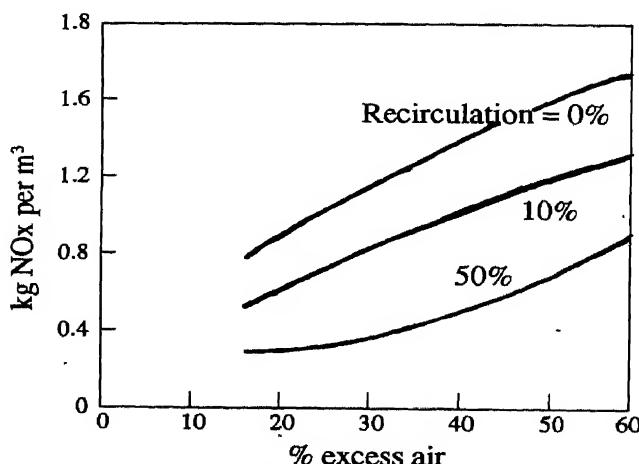
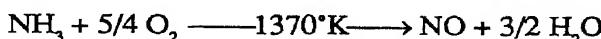
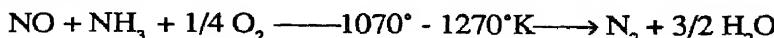


Fig. 10.2 Effect of Recirculation on NOx

work, since large volumes of gas are mixed with the primary air prior to combustion. Effect of recirculation in oil-fired furnaces is shown in figure.

5. NH₃ Injection:



Maximum NOx reduction occurs with the ammonia injection process. However, this is highly sensitive to temperature. A very narrow temperature range of $1240 \pm 50^\circ \text{K}$ is to be maintained. The addition of hydrogen can extend the effective temperature range. With a H₂ - NH₃ ratio of about 2:1, NOx reduction is possible even at 970°K. About 40-60% NOx reductions are possible in both gas and oil fired boilers and process heaters. A NH₃ - NOx ratio of 1.5 is commonly used for initial NOx levels of 200 ppm or less at residence times of 0.2 to 0.3 seconds. If NOx concentration is more the ratio may be reduced to 1.0. Minimizing excess air further increases the efficiency of the system. Since the temperature in a boiler changes with load and / or fuel fired, NOx control with NH₃ may dictate load restrictions. Inspite of this disadvantage, it is a commercially offered system potentially applicable to a broad spectrum of stationary combustion systems including industrial boilers and process furnaces.

6. Injection of Water and Steam: Injection of water or steam into the combustion zone is also effective in reducing emissions of nitrogen oxides. At present, there are still no reliable quantitative data on the effect of this method in boilers. This method is similar to that occurring in flue gas circulation. Injecting water to the extent of 10-15% of the total combustion air can reduce the temperature level in the furnace to some extent.

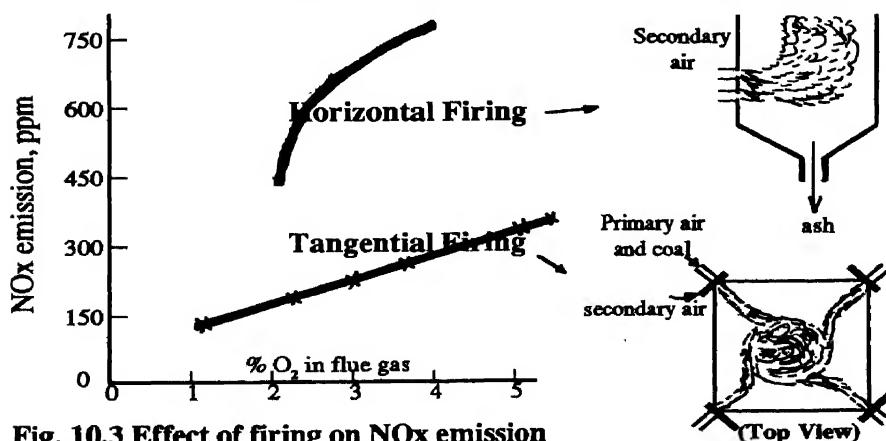


Fig. 10.3 Effect of firing on NOx emission

7. Modification of Furnace Burner Configuration: The two basic furnace designs are the tangential and the horizontal methods of firing. In the tangential method of firing, the flame and the combustion products rotate in an upward spiral around the walls of the furnace, and the furnace itself is used as the burner. This results in low peak flame temperature and consequently reduction in NO_x emissions. In the horizontal firing, the flame is at right angles to the walls of the fire box. This tends to concentrate the hot gases thereby leading to higher flame temperatures and more NO_x emissions.

A combination of a number of methods described above can be a best approach of the control of nitrogen oxides by combustion. For example, two stage combustion used in conjunction with low excess air firing in natural gas fired boilers results in as high as 90% reduction in NO_x emission. The methods mentioned for control of NO_x may favour high concentrations of carbonmonoxide. Hence any modification of systems, which is proposed to control oxides of nitrogen must be examined carefully for its simultaneous effect on carbonmonoxide emissions.

10.4 NO_x CONTROL BY TREATMENT

The modification of design and combustion techniques, in general, is to prevent or to suppress the emission of nitrogen oxides in the combustion chambers. However if the measures are not enough or too costly, stack gas treatment is necessary. Stack gas treatment is an efficient method for the control of NO_x. The methods are (A) absorption by liquids (B) adsorption by solids. (C) catalytic reduction - selective and non-selective and (D) electron beam irradiation.

A. Absorption by Liquids

The oxides of nitrogen can be absorbed by water, hydroxide and carbonate solutions, sulfuric acid, organic solutions and molten alkali carbonates and hydroxides. Several scrubbing techniques were developed which initially used solutions of sodium and calcium hydroxide. Some of the mostly adopted methods are:

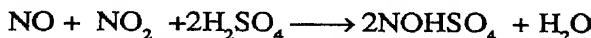
(i) Absorption by Alkaline Solutions: NO_x absorption by using aqueous alkaline solutions like NaOH and MgOH also yields good results. The removal efficiency is high if one half of the 'NO' is oxidized to NO₂ or if NO₂ is added to the gaseous stream so that the optimum NO / NO₂ molar ratio of 1:1 is maintained. This is a prominent method adopted during desulfurization of power plant emissions by such alkaline solutions. In the desulfurization process about 10% of NO is oxidised to NO₂ before the flue gas reached the scrubber. The scrubber then removes about 20% of the total NO_x in equal parts of NO and NO₂.

(ii) Absorption by Lime: Aqueous suspension of calcium hydroxide can be used as the scrubber to reduce NO_x levels to 200 ppm. The calcium nitrite in the solution can further be converted to more valuable calcium nitrate by treating with sulfuric acid.



The NO evolved may be recycled to the nitric acid plant and calcium nitrate can be used as a fertilizer. Thus the process reduces NO_x, recovers NO and gives a valuable fertilizer simultaneously.

(iii) NO_x Absorption by H₂SO₄: H₂SO₄ reacts with NO_x to form violet acid, H₂SO₄NO and nitrocyl sulfurous acid, NOHSO₄



The NOHSO₄ formed is very stable in concentrated acid. Any moisture in the flue gas is picked up by the acid and hence drives the equation to the left. To avoid this problem high temperatures (120°C) are maintained, so that vapour pressure of water in the solution is equal to the partial pressure of water in the flue gas. The use of sulfuric acid to remove SO₂ and NO_x simultaneously as well as separately is currently under active investigation.

(iv) NO_x Absorption by Magnesium Hydroxide: In this process the oxides of nitrogen are absorbed by hydroxide liquor in an absorption tower. The magnesium nitrite solution leaving the absorber is taken to a pressure reactor where the nitrite is converted to nitrate. The by product NO is oxidized to NO₂. The liquid leaving the pressure reactor, consisting

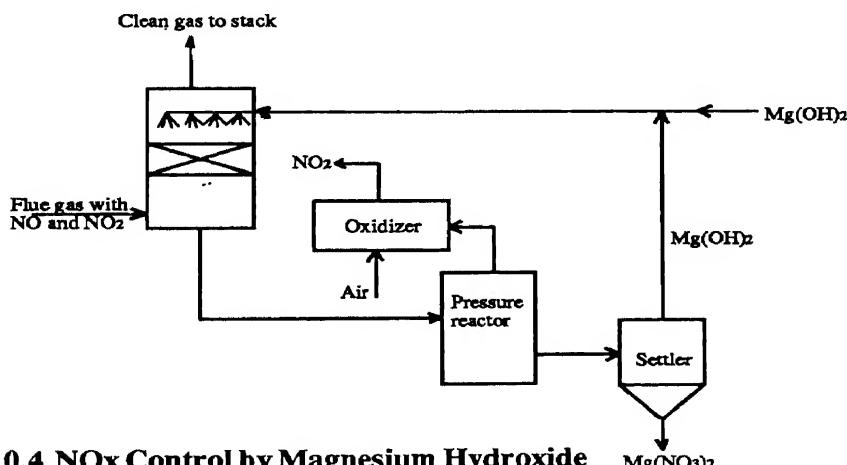


Fig. 10.4 NO_x Control by Magnesium Hydroxide

of $Mg(NO_3)_2 / Mg(OH)_2$ is sent to a settling chamber where nitrate is separated from the hydroxide. Part of the NO_2 from the oxidizer is sent to the absorber to maintain equimolar concentrations of NO and NO_2 while the rest of NO_2 is used for nitric acid production.

A continuous catalytic absorption process using stripped nitric acid as the absorbing medium has been reported. The advantage of this is that it not only reduces NO_x in the tail gas to a tolerable level but also recovers NO as nitric acid. Some of the scrubbing techniques, correctly used are:

1. Two stage absorption, first in water and then in sodium hydroxide yielding nitrite and nitrate salts.
2. Absorption in various types of ammoniacal solutions such as waste caustic ammonia liquor, ammonium bicarbonate and ammonium bisulfate.
3. Absorption with an aqueous suspension of lime, where calcium nitrite and nitrate can be recovered for use as fertilizers.

B. Adsorption by Solids

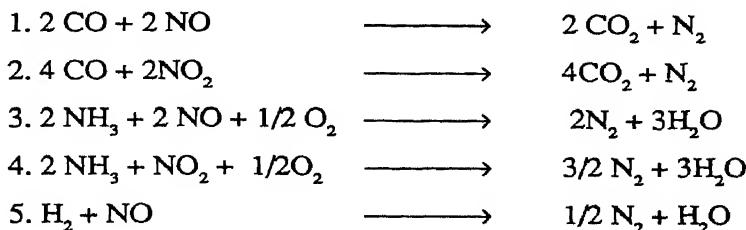
The adsorbents that show some capacity for oxidizing NO to NO_2 , and for adsorbing nitrogen dioxide are activated carbon, silica gel, molecular sieves, ion-exchange resins, and certain metal oxides, particularly manganese and alkali-ferric oxides. The use of activated carbon (char) to adsorb oxides of nitrogen has been studied extensively. Activated carbon has a high adsorption rate and capacity compared to other materials. However, regeneration may be a problem.

A potential fire and explosion hazard may be another difficulty with this material since O_2 is usually present in most stack gases. Thus the efficiency of char decreases with quantity of O_2 present in flue gas. Manganese oxides and alkali-ferric oxides show technical potential. However, sorbent attrition is a major technical stumbling block. The most suitable adsorbent for NO_x is the one which can be regenerated and at the same time which does not preferentially react with water vapour or with CO_2 in the flue gas. The most promising adsorbent is ferrous salt. Molecular sieves also can be used for NO_x control, particularly for NO_x from nitric acid plants. In this process two beds operate batch wise- one adsorbs NO_x from the tail gas while the other bed is regenerated.

C. Catalytic Reduction

Selective Catalytic Reduction (SCR): Selective catalytic reduction refers to a process that chemically reduces NO_x with NH_3 over a heterogeneous catalyst in the presence of O_2 . The process is termed selective because the reducing agent NH_3 preferentially attacks NO_x rather than O_2 . However the

O₂ enhances the reaction, and is indeed a necessary part of the reaction scheme. Thus SCR is potentially applicable to flue gas from fuel-lean firing combustion systems, that is, the flue gas is under oxidizing conditions (e.g. greater than 1% O₂). Non-selective catalytic reduction (NSR) processes are applicable to flue rich firing combustion conditions (i.e. reducing conditions in the flue gas). The overall SCR reactions can be expressed as



Equation (3) represents the predominate reaction since approximately 95% of the NOx in combustion flue gas is in the form of nitric oxide (NO). An NH₃: NO molar ratio of about 1:1 has typically reduced NOx emissions by 80-90% with a residual NH₃ concentration of less than 20 ppm.

The SCR processes require a reactor, a catalyst, and an ammonia storage and injection system. Due to increased pressure drop across the SCR reactor, some increase in boiler fan capacity, or possibly an additional fan, may be necessary. The optimum temperature for the catalytic reaction is in the temperature range 570-720° K. To obtain flue gas temperatures in this range, the reactor is usually located between the boiler economizer and the air preheater. A typical flow diagram is shown in figure.

Vanadium compounds have been found to promote the reduction of NOx and to be unaffected by the presence of SOx. Titanium dioxide (TiO₂) has been found to be an acceptable carrier since it is resistant to attack from SO₃. Thus,

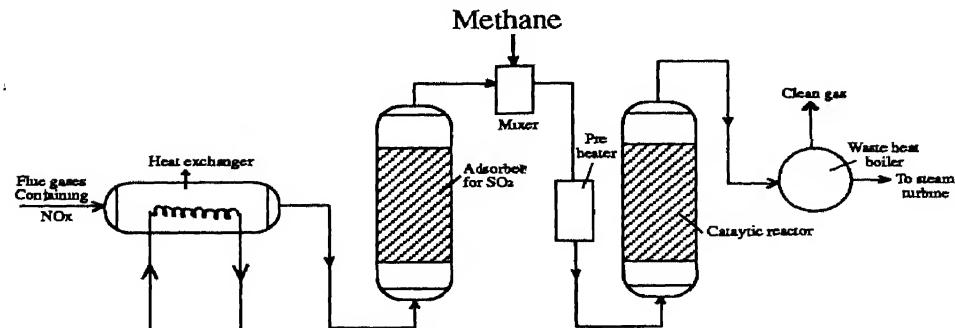


Fig. 10.5 Seletive Catalytic Reduction of NOx using Methane

many SO_x resistant catalysts are based on TiO₂ and V₂O₅; however, constituents and concentrations of most catalysts are proprietary.

Reactor and catalyst configurations also vary with the application, primarily to accommodate the different particulate concentrations. Natural gas-fired boilers employ SCR catalyst as spherical pellets, cylinders, O-rings and reactor vessels as fixed packed beds. However designs for use with oil-and coal-fired boilers have to be capable of tolerating particulates (fly ash) in the flue gas stream. For these applications, a parallel-flow catalyst is preferred. Parallel flow means that the gas flows straight in channels parallel to the catalyst surface. The particulates in the gas remain entrained while NO_x reaches the catalyst surface by turbulent convection and diffusion.

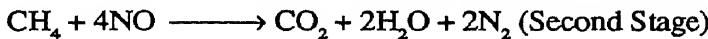
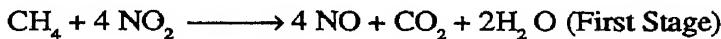
Even though much progress has been made in catalyst and reactor design, some problems still remain. The catalysts may not be resistant to all contaminants in flue gas or be able to tolerate high particulate loadings. In addition, fine particulates, smaller than about 1 μm , may blind the catalyst surface. Long-term operation without catalyst plugging or catalyst erosion needs to be demonstrated for coal-fired applications. Catalyst life also needs to be extended from the current guarantees of 1 to 2 yr of applications with SO_x and particulates in the gas stream.

The NH₃ : NO_x molar ratio and the flue gas space velocity are the major operating variables affecting the level of NO_x control achieved for a given boiler condition and SCR system. An NH₃ : NO molar ratio of 1:1 can achieve about 90% NO_x reduction, with higher NH₃ rates resulting in higher undesirable NH₃ emissions.

One of the major concerns with SCR processes is the formation of solid ammonium sulfate $\{(\text{NH}_4)_2\text{SO}_4\}$ and liquid ammonium bisulfate $(\text{NH}_4\text{HSO}_4)$. It is difficult to completely avoid them since some unreacted NH₃ from an SCR system and some SO₃ from combustion of sulfur-containing fuels are always present. The biggest problem seems to be the deposition of $(\text{NH}_4)_2\text{SO}_4$ and NH_4HSO_4 on the air preheater. These compounds are corrosive and can form deposits that plug the air preheater. Other concerns and potential problems include: emission of NH₃ and NH₄ compounds causing or increasing the emission of undesirable compounds such as SO₃; lack of proven NH₃ analytical control systems; sensitivity of the process to temperature changes due to boiler load swings and disposal or reclamation of spent catalyst in an environmentally acceptable manner.

Despite these potential problem areas and uncertainties, the processes have been successfully installed and operated in Japan on gas, oil and coal fired boilers. If 80% or more NO_x reduction is required SCR is the only option.

Non Selective Catalytic Reduction: Reducing agents other than NH₃, such as CO, H₂ or CH₄, completely reduce NO at temperatures of 300 - 400°C and space velocities in excess of 50,000 m³ per hour per m³ (space velocity is the volume rate of gas flow per volume catalyst). Non noble metal catalysts such as supported copper oxides may also be used for NOx control. These reductants act non-selectively, reacting with O₂ and SOx present in the flue gas, in addition to NOx and thus huge amounts of reductants must be added. For non-selective catalytic reduction of NOx in stationary combustion sources stoichiometric or sub-stoichiometric air must be used in the primary combustion zone. This reduces the cost of the reducing agent. NOx removal by CH₄ is as follows: when hydrocarbons like methane are used for removing NOx higher oxides of nitrogen are converted to NO in the first stage. In the second stage NO is reduced to nitrogen. Oxygen in the tail gases reacts simultaneously with the hydrocarbons to produce water vapour and carbon-dioxide as below:



In this process sulphur compounds must be removed first as they poison the catalyst. The tail gases are first heated to about 400°C and then mixed thoroughly with methane. The mixture is then sent to the reactor. The activity of the catalyst falls off with time. Its activity can be prolonged by maintaining higher inlet gas temperatures.

D. Electron Beam Irradiation

This process simultaneously removes 90% of NOx and SOx with NH₃ activated by electron beam irradiation, without the need for catalysts. The process first requires removal of fly ash from the flue gas. Then ammonia is added and then the gas enters the electron beam reactors. There, ammonia in the presence of electrons converts NOx and SOx into a dry powder of ammonium sulfate [(NH₄)₂SO₄] and ammonium nitrate sulfate [(NH₄)₂SO₄ · 2 NH₄NO₃]. After the dry powder is removed by a second particulate collection device, the treated flue gas leaves the system hot enough to be exhausted through the stack without reheat. The waste generated also is a potential fertilizer feedstock.



CHAPTER - 11

NOISE POLLUTION

Unwanted sound is called noise. The noises of modern society are profoundly annoying to the individual human being. One noisy motorcyclist or scooterist crossing a city can disturb the sleep of many people. The most important change which is evident in most places in this century, is the explosion of human population. This has exerted pressure on all available resources. One of them is significant rise of noise level. Not only raised human voices but also sound from various sources like construction sites, loudspeakers, radio, microphone, automobiles, aeroplanes, railway engines, irrigation pumps etc. break the silence of the environment. Noise has gained such an intensity that it grates on everyone's nerves. Surveys of complaints and physical measurements, all show noise pollution to be one of the major hazards of modern life, especially in urban areas - areas which are the most industrialized, urbanized and motorized.

Surveys show that noise is now perceived in many countries to be the major negative factor affecting the quality of life. In the United States, for example, noise is ranked second only to crime. In West Germany, a 1979 poll indicated that 45 percent of the population believed that the protection against noise is more important than building new roads. In Japan, there are currently more complaints about noise than about any other form of pollution. It is high time to realise the importance of protection against noise pollution on global basis. It will not be untrue to admit that Indians are noisy people. In India, every occasion or sentiment is manifested in a noisy manner-be it a religious

occasion, an election or a family celebration.

A decibel (dB) is the standard unit for the measurement of noise. The zero on a decibel scale is at the threshold of hearing, the lowest sound pressure that can be heard. On this scale, 20 dB is a whisper, 40 dB the noise in a quiet office, 60 dB normal conversation, 80 dB in a bus, 100 dB in a train, 120 dB in a loud thunder and 140 dB the level at which a sound becomes physically painful. As it is measured on a logarithmic scale, a noise of 10 decibels is 10 times more powerful than 1 dB and 20 dB are 100 times more powerful, 40 dB 10000 times more powerful and so on.

There are variety of noises such as domestic noise, traffic noise, aircraft noise, construction noise and industrial noise, all leading to discomfort to human beings. Traffic noise makes our lives most uncomfortable. To a great extent domestic noise can be easily controlled by rational use of radio and TV through use of earphones. Noise in house-hold can be minimised by using carpets, drapery and upholstered furniture. The noise of sirens can also be modulated. An attempt was made to create silent zones around educational institutes, hospitals etc. in India but it did not work although it was most successful in Britain. Traffic noise is due to cars, motorcycles, trucks and buses. For instance a car gives 60 dB, a bus gives 80 dB, whereas a truck gives 85 dB and motorcycles, scooters, mopeds produce noise of level 85-90 dB. These noises are bounced on the hard surfaces of buildings and are reflected back to the ears. Usually noise is produced by air turbulence around the body of moving cars and tyres especially on cement roads. In cold countries snow tyres make more noise. In India, motor cycles are the worst culprits, wherein the noise originates from exhaust and engine. It can give 110-120 dB noise. Mufflers are designed in motorbikes to reduce noise. Trees and bushes are planted on highways to reduce noise by dispersing it on leaves and branches. Usually in good town planning, the bedrooms in buildings are located away from roads to give peace and tranquility.

11.1 SOURCES OF NOISE

Sources of noise are mainly either industrial or non-industrial. Non-industrial sources of noise are mainly loud speakers, automobiles, aeroplanes, trains, construction works, radios, microphones, house-hold appliances etc. The noise levels in decibels from various sources are detailed in table 11.1. Sources may also be classified as indoor and outdoor noises.

Indoor Noises : The sources of indoor noises are moving people, crying of babies, playing of radios, banging of doors, traffic on staircase, movement of furniture, conversation of the occupants, operation of cisterns and water closets, noise of type writers, working of nearby machines etc.

Outdoor Noises : These noises are created from nearby streets and the largest source of outdoor noise is generally the automobile traffic on the road. The other sources of outdoor noises are railways, aeroplanes, loudspeakers, machines in nearby factories etc.

11.2 EFFECTS OF NOISE POLLUTION

After considerable research it was shown that the greatest amount of threat to human body comes from noise vibrations which are high pitched, loud, poor in tone and are long lasting. Another type of noise which can cause harm to human body is the sound due to explosion, which has a high amplitude but lasts for a very small duration. Various body systems affected by noise are auditory system, circulatory system and nervous system. The basic hearing mechanism is Cochlea, that is containing about 20,000 small hair cells. The temporarily damaged cells due to noise may be born again if ear is given rest. But prolonged exposure to noise may permanently damage them.

Auditory System: Medical research has confirmed that a certain type of noise is capable of affecting human auditory system and can result in loss of hearing. The effects on hearing mechanism can be in three forms:

- Temporary threshold shift
- Permanent threshold shift and
- Acoustic trauma.

Noise Induced Temporary Threshold Shift (NITTS) : It is a measure of efficiency of hearing the auditory threshold, that is the sound pressure level at which one can just begin to detect a sound. Temporary threshold shift or auditory fatigue is a short term effect which follows exposure to a high noise level and from which the subject recovers after a few hours. The loss of hearing cannot be recovered completely.

TABLE 11.1 Noise Levels of Some Noisy Sources

S.No.	Noisy Sources / Areas	Noise Level dB(A)
1.	Threshold of audibility (inaudible)	0
2.	Breathing	10
3.	Rustling of leaves due to wind	20
4.	Quiet conversation	20-30
5.	Quiet garden	30
6.	Ticking clock	30
7.	House in quiet street	35
8.	Conversation at 1m	40

9.	Inside small shops	55
10.	Radio music	55-60
11.	Computer rooms	55-60
12.	Loud conversation	60
13.	Type institute	60
14.	Office noise	65
15.	Class room teaching	55-60
16.	Children playing	60-80
17.	Home appliances	65-75
18.	House hold generators	70-80
19.	Medium road traffic (main street)	70-80
20.	Freight train at (25-40 kmph) at 150 m	77
21.	Printing press	80
22.	Morning bhajans	75-90
23.	Inside concert halls during performance	85
24.	Vacuum cleaner	80
25.	High volume air sampler	80-85
26.	Heavy road traffic (highways)	80-90
27.	Inside jet aircraft	85
28.	Sports car	80-95
29.	Inside cinema theatre	85-95
30.	Buses and trucks (gross wt 3.5 tonne)	85-95
31.	Freight trains (at 65 kmph) at 7.5m	96
32.	Trucks (gross weight 3.5 - 12 tonne)	90-100
33.	Propeller type jet plane at 300 m	90-100
34.	Marriages	80-100
35.	Namaaz	90-105
36.	Laboratory machines (turbines)	90-100
37.	Concrete mixtures	90-105
38.	Motor cycles and cars (horns)	90-105
39.	Weaving springs	105
40.	Rail engine at 15 m	97-105
41.	Train whistle at 15 m	110
42.	Pneumatic drill	110
43.	Thunder storm	110
44.	Jet take off at 300 m	100-110
45.	Riveting steel plates	110-130

46.	Loud speakers	100-120
47.	Steel rolling	95-105
48.	Pile driving	110-130
49.	Threshold of pain	120
50.	Jet take off at 100 m	120
51.	Jet engine at 25 m	140
52.	Diwali crackers	125-160
53.	Firing hand gun	140-170
54.	Space vehicle launch - short distance	140-170
55.	Naval gun shooting	160-180
56.	Exploding bomb (major permanent damage in a short time)	190

TABLE 11.2 Acceptable Noise Levels, IS : 4954 - 1968

Acceptable Outdoor Noise in Residential Areas			Acceptable Indoor Noise Levels for Various Types of Buildings		
SI No	Location	Noise Level dB (A)	SI No	Location	Noise Level dB (A)
i	Rural	25-35	i	Radio & TV studio	25-30
ii	Suburban	30-40	ii	Music room	30-35
iii	Residential (urban)	40-50	iii	Hospitals, class room, auditorium	35-40
iv	Urban (residential & business)	40-50	iv	Apartments, hotels, homes, conference rooms, small offices	35-40
v	City	45-55	v	Court rooms, private offices, libraries	40-45
vi	Industrial area	50-60	vi	Large public offices, banks, stores etc.	45-50
			vii	Restaurants	50-55

TABLE 11.3 Ambient Air Quality Standards in Respect of Noise
 [Amendment of Environment (protection) act, 1986 (29 of 1986)]

Area Code	Category of Area	Limits in dB (A)	
		Day Time 6 am - 9 pm	Night Time 9 pm - 6 am
A	Industrial area	75	70
B	Commercial area	65	55
C	Residential area	55	45
D	Silence zone	50	40

NOTE: Silence zone is defined as area upto 100 meters around such premises as hospitals, educational institutions and courts. The silence zones are to be declared by the competent authority. Use of vehicular horns, loud speakers and bursting of crackers shall be banned in these zones. Mixed categories of areas should be declared as one of the four above mentioned categories by the competent authorities and the corresponding standards shall apply. These rules may be called the Environment (protection) act third amendment rules, 1989 (Dated 26-12-89). This shift has been observed in many factory workers by measuring the threshold on Monday morning and at the end of the day. This type of temporary damage is not immediately discernible to the individual.

Noise Induced Permanent Threshold Shift (NIPTS): This occurs gradually, over perhaps, a few years and is not obvious to the individual until it has reached an advanced stage. This is an irreversible damage to the nerves and the inner ear and results in loss of sensitivity at high frequencies most markedly at about 4000 Hz. Due to this shift sibilants are not clearly heard making the understanding of conversation very difficult. Thus it remains throughout the life time of the affected person.

The adverse effects of noise may be broadly classified as follows:

- Annoyance, fatigue and boredom
- Loss of hearing
- Physiological effects
- Masking
- Effects on human performance

Annoyance: A noise is said to be annoying if an exposed individual or a group of individuals would reduce the noise, avoid or leave the noisy area if

possible. Both loudness and annoyance increase with increasing sound level. In general, noise whose sound level fluctuates is more annoying than the same average steady noise whose sound level is constant. An individual's activity during noise exposure may affect his reaction to noise, such as sleep interference. Noises which occur at random and unpredictable intervals are significantly more disturbing than noises which occur at predictable, periodic intervals. An individual annoyance due to noise is generally influenced by his experience or exposure to noise.

Physiological Effects: These are divided into short term and long term effects. Short term effects include changes in breathing amplitude, rate of saliva and gastric secretion, blood pressure, heart-beat rate and pulse rate, dilation of the eye pupil and varying gastro-intestinal problems. Long term effects include increased cardiac oxygen demand, plasma cortisol, blood cholesterol etc.

Masking: Masking is the process by which the threshold of audibility for one sound is raised by the presence of another (masking) sound. A particular noise is considered unwanted or annoying based on the degree to which it masks the hearing of certain wanted sounds such as speech and music. In mining environment, masking is certainly a critical safety issue, where noise may mask the sounds of shaft and haulage signals, warnings before blasting or the sound of approaching tugs.

Effects on Human Performance: The less variation in a strange noise, the less it will affect the performance adversely. For similar sounds and tasks, regular intermittent sounds are less likely to impair average performance than continuous ones are. In contrast, unpredictable intermittent sounds may be more harmful. Effects of noise on performance are more likely to be detrimental above sound pressure levels of 95 dB. High frequency sounds are likely to affect performance more seriously than low frequencies. Noise is relatively unimportant if the average rate of work is considered but it increases the accidents or errors caused by momentary inefficiency, which are of serious concern in any industrial environment. In general there is a risk of hostile behaviour during and after exposure to noise. Deliberate and intentional memory may be normal or even improved by noise, but the recollection of incidental features of the situation deteriorates. However there is a general depression or apathy which continues to persist for a time outside the situation in which noise has been experienced.

Acoustic Trauma: It is a condition of sudden permanent aural damage resulting from an intense-short-term exposure, which may be single exposure. This sound is capable of rupturing the eardrum that results in some degree of permanent hearing loss. However, when only the ear drum is

damaged without any damage to inner and middle ear the ear drum hears with time and full hearing is usually restored.

Effect on Circulatory System: Exposure to noise makes the blood vessels shrink. Also, blood supply to many parts of the body decreases on exposure to sound. The cause of headaches which result due to exposure to noise is also due to the decrease of blood supply to the brain. Some effect of vibrations on heart has also been reported when small blood vessels are subjected to the noise vibrations. They contract in spasm and this is accompanied by thickening and clotting of blood, which may very well cause heart attack. At 160 dB major permanent damage may be caused if sound is produced.

Effect on Nervous System: The various effects of noise pollution are :

- (i) Trucks, buses and cars on the roads, the trains on their tracks, the jet aeroplanes in sky-they all are producing more and more of noise as their number is increasing. Haphazard growth of the cities, inspite of the efforts of the city planners, is bringing small and large industries beside or inside the residential areas. The transistors, the radios and the loudspeakers make their own contribution. Much noise came from people, a vast majority of whom are not aware that by speaking loudly they are being a nuisance. The presence of noise takes away the essence of music and speech.
- (ii) Exposure to noise tells upon the health. Very loud noise of 150 decibels can cause a rash under the collar, in between the fingers and the thighs. Ear drums may get ruptured. It can cause giddiness and nausea. 130 - 135 dB sound produces dizziness and vomiting.
- (iii) Exposure to over 100 decibel for a few hours lessens efficiency and makes one more prone to accidents. It makes one aggressive and quarrelsome. Even in those who are sleeping, exposure to loud noise causes a disturbance in their brain waves.
- (iv) It can lead to irregular or faster pulse beats, enlarged hearts and increase in blood cholesterol. It causes mental fatigue, irritability and precipitates or aggravates mental tension and neurosis. Prolonged exposure to noise results in temporary deafness or nervous breakdowns.
- (v) Most disturbing observation is that loud noise increases heart rate of the foetus inside the abdomen of a pregnant mother. This may cause irreparable damage to the unborn baby. Also, as ear is the first organ that develops fully after conception even the unborn may be badly affected by noise pollution.

- (vi) Infrasonic waves cause motions and may be used to disperse mobs. Buildings may be demolished by them. Ultrasonic waves, which are often used as disinfectants, are harmful to life.

11.3 MEASUREMENT OF NOISE POLLUTION

The sounds vary in pitch, which is defined as the relative highness or lowness of a sound. Pitch is determined by the frequency of sound wave i.e. the rapidity with which it vibrates. A high pitched sound with its fast vibration is more penetrating than one with low pitch. The intensity of sound is measured in decibels (dB). This scale was devised to measure the smallest difference in sound which is detectable by the human ears. Its gradations move up not in simple arithmetic progression but in multiple progression based on logarithmic scale.

The subject of noise control is not an easy one to master. Part of the difficulty lies in interdisciplinary action it borrows generously from the fields of mathematics, dynamics, vibrations, fluid mechanics, thermodynamics, electronics, psychoacoustics, material science and engineering acoustics. Nomenclature and jargon are other obstacles to be overcome and noise control engineering, perhaps more than any other field, has an abundance of new terms which must be mastered while learning the subject. Also seemingly insidious nature of the way sound is generated and propagated often defies intuitional noise reduction solution which in other areas of engineering are based upon experience.

An understanding of the fundamentals of sound generation and propagation is essential to the engineer responsible for initiating and carrying out noise control programmes. Sound in the physiological sense is the result of pressure vibration in the air which acts on the surface of eardrum. The ear converts this pressure variation into electrical signals which are then interpreted by brain as sound.

Sound is a form of energy which is emitted by a vibrating body and on reaching the ear causes the sensation of hearing through nerves. Sounds produced by all vibrating bodies are not audible. In order to produce an audible effect, the frequency (i.e. number of vibrations per second) of the vibrating body should be greater than 20 Hz and less than 20,000 Hz. These are known as frequency limits of audibility. Sounds of frequencies less than 20 Hz are called infrasonic and greater than 20,000 Hz are called ultrasonic

Propagation of Sound : Due to vibrations of a body compressions and rarefactions are produced. These travel in air to the ear and produce sound. The particles of air vibrate about their mean positions and transmit momentum and energy through air to the receiver (ear).

Characteristics of Sound : Sound consists of wave motion in an elastic medium. These waves travel through the medium from the source of sound to the listener. Sound waves consist of vibrations in pressure or oscillations of the medium in which they travel. The rate of oscillation is called the frequency or pitch of the sound and is measured in cycles per second or Hertz. High pitched sounds have high frequencies and are more disturbing. Loudness may be described as 'Listeners' auditory impression of the strength of a sound' and is therefore a subjective judgement. It is expressed in units called 'Sones'. Sound is not electromagnetic radiation. It cannot be propagated through vacuum.

Sound Pressure N/m ²	Intensity watt/m ²	dB
2×10^{-5}	10^{-12}	0
2×10^{-4}	10^{-10}	20
2×10^{-3}	10^{-8}	40
2×10^{-2}	10^{-4}	80

In general 80 dB (10 sones, depending upon frequency) may be considered as the critical level for ear damage. The ear is able to analyse the sound into frequency component and the range of a young person with perfect hearing is from 20 - 20,000 Hz. Normally hearing is most acute in the frequency range of 2000 - 5000 Hz but is reduced rapidly below 200 Hz and above 10,000 Hz. The ear is potentially liable to damage if it receives high intensity noise. The human ear responds to a change in sound pressure in the range of 0.00002 Pa.

Effect of Distance from the Source: In a homogeneous and undisturbed environment a spherical point source emits sound equally in all directions. The sound pressure level decreases in inverse proportion to the distance from the source. If the sound pressure level L_1 in dB is measured at a distance of r_1 m then the level L_2 at a distance of r_2 m can be calculated by using the relationship.

$$L_2 = L_1 - 20 \log_{10} (r_2 / r_1)$$

Thus, the sound pressure level decreases 6 dB for each doubling of distance from the source and 20 dB for each increase in distance from the source by a factor of 10.

Sones: Loudness is also expressed in Sones. One sone is equal to the loudness of 40 dB sound pressure at 1000 Hz. The same 40 dB at 5000 Hz means twice as loud and it therefore is 2 sones. The receptivity of ears of

human beings are not same. Many animals (dogs) can hear sounds inaudible to human ear. So in psycho-acoustic terms, we have to consider both sound intensity and frequency which is called "Phone" or decibel at 1000 Hz. The relation between sones and phones is given by

$$\text{Log}_{10} S = 0.03 (P-40)$$

Description of Decibel Scales: The decibel is a mathematical scale similar in use to a logarithmic scale. It is used to describe the intensity or energy level of a physical quantity compressing the quantity into numbers that are convenient for data presentation. Fundamentally it is ten times the base ten logarithm of the ratio of a power or energy quantity with respect to a reference base of the same physical quantity.

$$L_E = 10 \text{ Log}_{10} E / E_{ref} \text{ dB where}$$

L_E = Energy or power level in decibels

E = Energy or power quantity of interest in watts

E_{ref} = Reference energy or power quantity of interest in watts

Sound Pressure Level: A normal human ear is capable of functioning over a pressure range of about one million. Secondly, experiments have shown that the ear responds in a logarithmic manner to the perceived loudness of sound. The sound pressure level, L_p , is given by

$$L_p = 10 \log_{10} [P / P_{ref}]^2 \text{ dB}$$

Addition of Sound Levels: Ambient noise in any industrial environment is due to several sources and thus, it is necessary to find the combined resultant sound level when there are more than one source. The combined sound level is not the sum of the individual levels, but is calculated as follows.

Addition of unequal sound levels L_1 and L_2 ($L_1 > L_2$)

Difference between dBs	Correction to be applied to L_1
0	3
1	2.5
2	2
3	2
4	1.5
5	1
6	1
7	1
8	0.5
9	0.5
≥ 10	0

To combine the sound levels of several sources (more than two) first combine the levels of first and second source which results in 'L' dB. Based on the difference between this combined level L and the level of third source, again calculate the new combined level L. Any number of sound levels may be combined in this manner.

Weighing Networks: The human ear is not equally sensitive to all frequencies and hence, though the sound pressure level of two different sounds may be the same the first may be judged to be louder than the second if the sound power of the first is concentrated in a frequency region where the ear is more sensitive. Thus, sound pressure level is not a measure of the loudness of a sound. To obtain levels which bear a closer relationship to loudness judgements than sound pressure level, "frequency weighing networks" are incorporated in the sound measuring instruments. These weighing networks (or filters) alter the sensitivity of the instruments with respect to frequency, so that the instrument is less sensitive at frequencies where the ear is less sensitive. Thus, all standard sound measuring instruments make allowance for frequency dependent response of the ear by using filters which attenuate the levels in the different frequencies and thereby give direct readings which reflect the sensitivity of the ear. Since the amount of attenuation is dependent upon the sound level, the three weighing networks (A, B and C) usually employed, have frequency characteristic response simulating 40, 70 and 100 dB equal loudness contours. Taking into account the fact that human ear is more responsible for high frequency sounds (1000 to 5000 Hz) than low frequency sounds, dB (A) is the unit of measurement used in regulations of noise measurements in industrial, commercial and residential environments. It is the universally used sound level.

11.4 CONTROL OF NOISE POLLUTION

It may not be possible to have a total elimination of annoying sounds but attempts should be directed to reduction at source, reduction of the duration of exposure etc.

The sounds generated and transmitted in air directly to human ears are known as air borne sounds. The air - borne noise possesses less power, continues for a long duration and is confined to places near its origin. It is transmitted to the receiving room in two ways: (1) by air path between two rooms such as doors, windows, ventilators, key holes, ducts, pipes etc. and (2) by forced vibration set up by the transmitting room to the walls, floors and ceiling of the receiving room.

The sounds which originate and progress on the building structure are known as structure borne sounds or impact sounds. The structure borne noise is powerful, propagates over long distances and persists for a very short

duration. It is developed in solid structures and is then transmitted as air-borne noise. The closing of doors, vibration of machines etc. set up vibrations in solid materials of the structure which result in transmission of noise to the receiving room.

Noise Reduction at Source: Reducing noise at the source itself is the most promising method, which is accomplished as follows :

- (i) **Selection of Machinery:** Noise should be reduced as near the source as possible so that acoustical treatment is less expensive and a large number of people are protected from the noise. While the operational processes in a factory may be fixed and may have no quieter alternative, careful selection of the machine tools and equipment to be used may considerably help attaining lower noise levels in the machine shop. One make of machine tool may have noisy mechanical system compared with another of similar performance.
- (ii) **Reducing Noise from Potential Sources :** Impact that is not essential to a process should be quietened. Noise from handling and dropping of materials on hard surfaces may be reduced by using soft resilient materials on containers, fixing rubber tyres on trucks, trolleys etc. Machine noise may be kept to a minimum by proper maintenance. Proper lubrication reduces noise by friction from conveyors, rollers etc.
- (iii) **Noise from Radiating Surfaces:** This can be reduced by reducing the radiating area. For example, if the area is halved, the noise intensity will be reduced by three dB and at low frequencies the reduction will be much greater. Supporting structures for vibrating machines and other equipment should be frames rather than cabinets or sheeted enclosures. If an enclosure is used, precaution should be taken to isolate it and line it on the inside with sound-absorbent material. The noise radiated by machinery guards can be minimized by making them of perforated sheet or of wire mesh.
- (iv) **Reducing Transmission of Mechanical Vibrations:** A vibrating source does not usually contain a large radiating surface but the vibration is conducted along mechanically rigid paths to surfaces that can act as effective radiator. If the rigid connecting paths are interrupted by resilient material, the transmission of vibration and consequently the noise radiated may be greatly reduced. The reduction depends on the ratio of the driving (forcing) frequency of the source to the natural frequency of the resilient system.
- (v) **Material for Isolators:** Vibration isolators are usually made of resilient materials like steel in the form of springs, rubber, cork and felt.

Because of the large range of deflections obtainable in coil springs, they may isolate vibrations over a large spectrum of low frequencies. Metal springs transmit high frequencies (from about two hundred to several thousand c/s) very readily. Transmission of these frequencies can be reduced by eliminating direct contact between the spring and the supporting structure. Rubber or felt pads may be inserted between the ends of the spring and the surfaces to which it is fastened.

Rubber pads may be used to isolate very effectively, relatively small machinery, engines, motors etc. It may be used in compression or in shear. Some rubber mountings use rubber in shear as the primary elastic elements and rubber in compression as a secondary element which furnishes snubbing action if the mounting is subjected to an overload. Felt or cork or both may be used as resilient mats or pads under machine bases.

Large press droppers which create serious impact vibration in heavy machine shops, may be mounted rigidly on massive blocks of concrete having weights many times greater than the weights of the supported machines. The inertia blocks may, in turn, be isolated from the building structure by large wooden block and with thick pads of cork.

In critical installations, attempt should be made to locate the resilient mounts in a plane which contains the centre of gravity of the mounted assembly. It is also preferable to locate the mounts laterally as far away as possible from the centre of the machine.

Rigid mechanical ties between vibrating machine and building structure short circuit or reduce the effectiveness of isolators. Loose and flexible connection should be inserted in all pipes and conduits leading from the vibrating machine. Where flexible connections are impracticable, bends should be inserted into the pipes or the pipes themselves should be supported on vibration mounts for a considerable distance from the source.

- (vi) **Noise Reduction by Enclosures and Barriers:** Air borne noise generated by a machine may be reduced by placing the machine in an enclosure or behind a barrier. Much larger noise reduction can be achieved with complete enclosures. The enclosure may be in the form of close - fitting acoustic box around the machine such that the operator performs his normal work outside the box and thus is not subjected to the high noise levels of the machine. The enclosure may also be made of sheet metal lined inside with an acoustical material.

Where size of the machine, working area and the operation do not permit close - fitting enclosures, the machine may be housed in a room

of its own. The inside of the enclosure should be lined with sound-absorbing materials to reduce the noise level of the contained sound. The walls of the enclosures shall also have adequate transmission loss to provide proper sound insulation.

A partial elimination of noise in certain directions may be obtained by barriers or partial enclosures. Two sided or three sided barrier, with acoustic absorption material may affect appreciable noise reduction. Where it is possible, the opening should face a wall covered with sound absorbing material. If the top of the enclosure is open, the reduction may be increased by placing the sound-absorbing material on the ceiling overhead.

- (vii) **Acoustical Absorption Devices:** In order to reduce the general reverberant noise level in machine shops, acoustical material may be placed on the ceiling and side walls. With this treatment three to eight dB reduction of middle and high frequency noise may be achieved. This would bring down the general reverberation noise level and as a consequence, the noise conditions may become less confusing.

For efficient noise reduction functional sound absorbers may be clustered as near the machine as possible. These units may be suspended and distributed in any pattern to obtain lower noise levels within the machine shop. Compared on the basis of equal total exposed surface areas, functional sound absorbers have slightly higher noise reduction coefficients.

Ear Protection Aids: For noisy industries, the workers should be provided with ear protection aids like earplugs, headphones or noise helmets. A unique form of operational modification is employing deaf persons to handle noisy equipment, wherever possible, subject to suitable safe guards. The noise levels must be reduced to a point where the noise hazard will be reduced to a condition of acceptability.

Design of Doors and Windows: For reducing noise, it is necessary to design carefully the doors and windows of the room. The sound travels through very thin cracks between the door and wall. Excellent sound insulation is obtained by constructing glazed windows with double or triple panes of glass. The air space at the edges of such panes is filled with sound absorbing material.

Treatment of Floors, Ceilings and Floorings: It is known that floating floors and suspended ceilings help considerably in reducing noise. Suitable sound absorbing materials like hair, felt, acoustical tiles and perforated plywood and specially made porous materials are available and can be fixed on walls, floors and ceilings to have reduction in noise. It is suggested to use

a few suspended absorbers from the ceiling for reducing deflections from the ceiling and for absorbing the machine noise. These absorbers may be suspended on the top of the machine and as close as possible to it.

Planting of Trees: A new concept gaining acceptance is the planting of trees like Neem, Tamarind, Coconut etc. near schools, hospitals, public offices and such sites. The presence of trees is likely to reduce the noise to the extent of about 8 - 10 dB. Similarly indoor plants are helpful to reduce noise in a house by 8 to 10 dB. Belts of trees or shrubs may also be used as barriers of sound. It has been found that in dense evergreen woods, the attenuation of sound is about 18 dB per 300 m at 500 c/s. This is due to absorption by the foliage on one hand and multiple scattering on the other. Obviously, denser the barrier, greater is the attenuation.

Use of Silencers or Filters: This method is applicable to the control of noise from ducts, exhausts or convey systems, the ends of which must be open to the atmosphere. For this purpose glass wool or mineral wool covered with a sheet of perforations may be used.

Vibration Damping: This arrangement is attempted to reduce vibration. A layer of damping material in the form of resilient pads made of rubber, neoprene, cork and plastic may be adopted for high frequency vibrations. It is desirable to make massive base for a vibrating machine.

Noise Control by Locations: Another practical method of reducing noise is by increasing the distance between the source and work vicinity. Machines, processes and work areas which are approximately equally noisy should be located together. Areas that are particularly noisy should be segregated from quiet areas. The office space in a factory should be as far as possible segregated from the production area and preferably be located in a separate building. If a common wall is unavoidable it should be heavy with minimum connecting doors and no permanent openings.

Noise control by Absorption of Reflected Sound

Ceiling: The absorptivity of the ceiling can be increased by introducing large absorbing area without interference with other operations. Two methods are commonly employed (1) by suspended grid system, using lay-in or concealed grid type panels or tiles and (2) by vertically suspending panels of absorbent material. If ceiling treatment does not give required attenuation, reflections from the walls should be reduced by applying absorptive treatment to them.

Screens: After the above treatments if the noise is to be reduced further, it is advisable to use screens around the noisy machines. Sound reduction of the

order of 10 dB (A) to 15 dB(A) may be achieved by using screens in an already treated area. The various other absorbing materials are acoustic plaster (a plaster of granulated insulating material and cement), compressed cane or wooden boards, perforated asbestos, teak plywood packed by wire etc.

Noise Control by Town Planning and Legislations: Vibrations from external sources such as railways, cars, traffic, factories etc. create structure borne sound. The most effective method of reducing such noise is to have a rational town planning. The city is divided into suitable zones and residential zones are placed away from railways, workshops, factories and main streets.

A vigorous pursuit of the existing legislative measures, especially during the festivals and marriage functions should be made to control noise pollution.

Good mental and physical health requires that exposure to loud noise should be minimised on the roads, inside the factories, at construction sites and inside residential buildings. Noise produced inside the factories is very harmful for the workers as they are continuously exposed to it for years together. It is detrimental to the interests of the owners as well as it lessens efficiency of the workers and makes them accident prone.

It is the duty of the town - planners to segregate industries from residential areas. If this is not done there is not only the nuisance from noise but also from air - pollution. Inside the houses one can lessen noise by using carpets or rubber on the floor. Heavy curtains also lessen the propagation of noise. Fans and other electrical equipments need care so that they make the least noise. The most important thing is to make people aware that noise is bad for physical and mental health. Many people yet do not know it!



CHAPTER - 12

INDOOR AIR POLLUTION

In order to stay alive, a person has to inhale about 25,000 breaths of air each day i.e. about 25m^3 of air per day. The air should be fresh and clean. As civilisation improved man has constrained his life to indoors and started living more and more indoors within the structures built by him. This led to the severe problem of "Indoor Pollution". Man and several thousands of household products made by him pose a serious threat to indoor air quality. These products include cleaners, detergents, paints, air fresheners, disinfectants, insecticides etc. Indoor air pollution often leads to severe health hazards like irritation to the eyes, nose, throat, headache and most importantly the respiratory problems. The indoor pollution also leads to buildup of mental tensions leading to severe decrease in productivity among factory workers. Workers in polluted atmosphere are supposed to be subjected to severe fatigue than the workers in normal environment. Indoor environments often have higher levels of air pollutants than their surroundings in rural as well as urban areas.

12.1 CAUSES OF AIR POLLUTION

There are various causes for the indoor air pollution. Improper location of vents and exhausts, air conditioning without proper ventilation, use of new materials like synthetic materials, detergents and waxes lead to the generation of many irritating and sometimes toxic fumes. Fluorescent lamps emit ultraviolet light and may provide energy for the photochemical reactions

among pollutants thus creating indoor smog. Lead and cadmium may be released from improperly formulated surfaces of ceramic foodware. Dead and poor circulation of air seems to be the problem causing indoor air pollution in many of the cases.

The many causes of indoor air pollution may be divided as follows:

Problem	% Contribution to Indoor Pollution
Ventilation	55%
Building materials	5%
Biological	5%
Outdoor pollutants	10%
Indoor pollutants	15%
Miscellaneous	10%

In all, improper ventilation seems to be the main cause in more than half the cases of indoor air pollution. Discomfort is a subjective sensation which people experience in ill-ventilated and crowded rooms. The main causes of discomfort are physical changes of temperature, humidity, air movement and heat radiation. For a long time it was believed to be due to increased carbondioxide and decreased oxygen, resulting from respiration. This theory has since been refuted. Studies have shown that the oxygen content may be reduced to 18 percent and the carbondioxide content may be raised to over 5 percent, without adverse effects, provided the temperature and humidity are kept satisfactorily. In the 'Black Hole of Calcutta', 146 prisoners were imprisoned in a small room. There were two small windows which were adequate to supply all the oxygen needs, even then only 23 survived. Similarly on March 12, 1944 the Salerno train disaster killed 512 people, in a train accident. The engine stalled while the train was in the middle of a long tunnel. The oxygen in the tunnel was used up by the passengers in a matter of minutes. Then they started to gasp for air and one by one died of suffocation. The deaths were attributed to changes in physical condition of the air, leading to heat retention. Mostly, the problems of ventilation are physical, not chemical, cutaneous not respiratory.

12.2 SOURCES AND EFFECTS OF INDOOR AIR POLLUTANTS

The effects of some of the major indoor air pollutants are as follows:

1. Dusts : Out of every 100 asthma cases about 60 are due to dust pollution. Dusts, especially those in houses contain 'mites' which cause asthma. Every one gram of dust contains about 200 mites each with an average size of 0.3mm. These are common in all types of houses - with tiled roofs, slabbed

houses or huts. These mites normally breed in the dusts of rugs, carpets, clothing, utensils, books etc. When these are cleaned, mites come out alongwith other microorganism like fungi and hairs. Normally when winter starts these old rugs etc. are taken out and used causing asthma. Mites grow rapidly in environments with high humidity and low temperature. Mites can be eliminated by providing proper ventilation to the rooms. Ventilation allows sun-rays to enter the rooms and sun-rays are good disinfectants as they contain UV rays. Unused clothes, bedsheets, rugs etc. must be thoroughly washed in boiling water or dry cleaned before using them again. As asthma creates hypertension and affects cardiovascular systems, persons exposed to dusts or asthma should relax well before participating in physical activities.

2. Electro Magnetic Pollution: Pollution by electromagnetic rays (EMR) from transformers, tubelights, radios, televisions, air conditioning units etc. is highly dangerous and has deleterious effects on the human beings. Though the study of the effects of electromagnetic pollution on man is still in its primary stage it has already been shown that rats subjected to EMR have shown an increase in temperature of rectum and ultimate death. Children must be kept as far away as possible from these sources of EMR.

3. Asbestos: Asbestos is generally used as a building material such as ceiling and floor tiles and work boards. Asbestos becomes a health hazard only when fibers are released into the air and become friable (easily crushed). Release of asbestos in large quantities occur mainly during maintenance, repair, renovation and often construction activities.

4. Pollens: Studies have revealed that pollens, fungal spores and various types of dusts, pollute indoor air and cause allergic diseases, especially asthma. Pollens from trees, shrubs, herbs, grasses and weeds cause allergy. The most beautiful garden city of India, Bangalore, is languishing with 30% of its population suffering from asthma.

5. Combustion Products: The major combustion sources that have the largest contribution to indoor air contamination are gas stoves, unvented space heaters, wood stoves and tobacco smoke. The combustion products include NO_2 , CO , SO_2 and particulates. CO_2 is relatively non-toxic. However it is a very good indicator of indoor air quality and adequacy of ventilation. CO is produced by gas stoves and this amount will be dissipated by ventilation system and a combination of a fan and hood over stove. However, cooking substantially increases the level of CO as air supply will be partially cut-off by vessels placed over the gas flame. NO_2 is another important combustion by-product with a pungent odour.

6. Formaldehyde: Commonly known in solution as formalin , it is a

highly toxic and irritant gas that precipitates and destroys protein. Formaldehyde is a major component of urea-formaldehyde foam insulation, particle boards, some paper products, fertilizers, chemicals, adhesives, glass and packing material. Incomplete combustion of hydrocarbon based fuels is estimated to produce large quantities of formaldehyde which may enter the indoor environment. Formaldehyde vapours leak into the air when temperature increases and they combine with other contaminants into a mix that can cause headaches, respiratory irritation, watery eyes, nausea and heart problems. Due to the extensive use of plywood for partition walls and cots the problem is more aggravated.

7. Indoor Pollution due to Burning of Traditional Fuels: About 50% of the world's households are using traditional fuels such as firewood, animal dung, coke etc. for cooking. The common pollutants which cause indoor air pollution problems due to the combustion of these traditional fuels are particulate matters, oxides of sulphur, oxides of nitrogen, carbonmonoxide, hydrocarbons and organic and odour causing chemicals. The emission quantity of these pollutants depends upon the type of fuel used, type of stove or furnace used, feed rate, amount of additional air and operating conditions. In our country, over 80% of the time of housewives is spent in an indoor environment of which 4-6 hours is spent in kitchen. It was found that emissions of sulphur dioxide and total suspended particulate matter from all the three fuels were much higher than the average annual ambient air quality.

12.3 CHANGES IN INDOOR AIR QUALITY

Human occupancy and activity vitiate air in occupied rooms and give a sense of discomfort to the occupants. The changes in air that take place in confined air in confined places are both chemical and physical.

a) Chemical Changes: The air becomes progressively contaminated by carbondioxide and the oxygen content decreases due to metabolic processes. An average man at rest gives off 20 litre of carbondioxide per hour. This may increase upto 65 litre during physical activity. In a mixed gathering comprising all age groups, the per capita output of CO_2 is taken as 16 litres per hour. In addition to CO_2 , unpleasant odours arise from foul breath, perspiration, bad oral hygiene, dirty clothes and other sources.

b) Physical Changes: By far the important changes that occur due to human occupancy are the physical changes. These are:

Rise in Temperature: The indoor temperature tends to rise as a result of the emanation of body heat. A man at rest gives off approximately 400 B.Th.U. per hour. B.Th.U (British Thermal Unit) is the quantity of heat

required to raise the temperature of one pound of water by 1°F. 1 B.Th.U. = 252 calorie = 1050 Joule. Under conditions of physical exertion, the heat output may go upto 4,000 B.Th.U. also.

Increase in Humidity: There is an increase in relative humidity due to moisture evaporated from the skin and lungs. The exhaled air contains about 6 percent of water vapour.

The exhaled air contains even microorganisms in suspension. Unless the vitiated air is replaced by fresh air, it may adversely affect the comfort, health and efficiency of the occupants. The effect of indoor air pollutants like temperature and humidity are dealt in detail in the chapter on the effects of air pollution on human beings.

12.4 CONTROL OF INDOOR AIR POLLUTANTS

The indoor pollution can be controlled by:

Source Removal and Elimination: Significant sources of outdoor air pollutants such as motor vehicle exhausts from streets and parking lots, loading ducts, emissions from cooling towers, roof operation emissions and exhaust of nearby buildings and industrial sources should be avoided. Smoking indoors should be strictly prohibited. Use of better house appliances also can eliminate the pollution to certain degree.

Improved Building Design: The buildings should be suitably designed to avoid transmission of combustion by-products with better placement of the kitchen which influences the overall functioning of the building and its indoor climate. Provision of a chimney alongwith general ventilation can solve the problem to certain extent.

12.5 AIR CLEANING SYSTEMS

Some indoor air contaminants, principally particulates, can be removed effectively by commercially available filtration and removal technology. There are several air cleaners like media filters, electrostatic air cleaners, adsorbers, centrifugal separators, air washers and other absorbers. Most of these devices are relatively expensive and generally suitable for air conditioned buildings only.

The indoor air pollution can be dangerous to health. Good ventilation is the easy option for this problem. Planned layout of kitchen and rooms of public congregation may prevent the pollution. A normal human being gives off 0.3 LPM of CO_2 at rest and 1 LPM during physical activity. The exhalations contain about 1 ppm of CO. Concentrations of these pollutants build up in the absence of ventilation to undesirable values. Indoor pollution can be con-

trolled by disinfection, ventilation and lighting as follows.

1. Disinfection: In recent years disinfection of air received much attention. Many of the germicides or disinfectants used can pollute air. Usually the disinfectants used contain formaldehyde which is a highly toxic and irritant gas. It precipitates and destroys protein. It is effective against vegetative bacteria, fungi and many viruses but only slowly effective against bacterial spores and acid-fast bacteria. It does not injure fabrics and metals and may also be used for disinfection of blankets, beds, books and other valuable articles. Triethylene-gluconol vapours are found to be effective air bactericides particularly against droplet nuclei and dusts. Ultraviolet radiation has also been found to be effective in special situations such as operation theatres and infectious disease wards. Since direct exposure to UV rays is dangerous to eyes and skin, the ultraviolet lamps are shaded and are located in the upper portions of the rooms near the inlet of air. UV rays have not proved effective for general use, in public assembly and school rooms. Application of oil to the floors also reduces the bacterial content of the air. Air disinfection is still in the experimental stage.

2. Ventilation: The concept of ventilation lies not only in the replacement of vitiated air by a supply of fresh out-door air, but also in the control of the quality of incoming air with regard to its temperature, humidity and purity with a view to provide a thermal environment that is comfortable and free from risk of infection. Among the different types of ventilation, natural ventilation is the simplest system of ventilating small dwellings, schools and offices. In this method the wind direction is made use of. (When wind blows through a room it is called perflation and when it is obstructed it is called aspiration.)

Mechanical Ventilation: This artificial ventilation, used to reduce vitiated air and bacterial density is of four types, namely (1) Exhaust Ventilation (2) Plenum Ventilation (3) Balanced Ventilation and (4) Air Conditioning .

(i) Exhaust Ventilation: In this system air is exhausted to the outside by exhaust fans usually driven by electricity. As air is exhausted, a vacuum is created which induces fresh air to enter the room through windows, doors and other inlets. Exhaust ventilation is generally provided in large halls and auditoria. The exhaust fans are housed in apertures of the external walls, high up near the roofs.

(ii) Plenum Ventilation: In this system fresh air is blown into the room by centrifugal fans so as to create positive pressure, and displace the vitiated air. Plenum or propulsion system is used for supplying air to air-conditioned buildings and factories.

- (iii) **Balanced Ventilation:** This is a combination of the exhaust and plenum systems of ventilation. The blowing fan must balance the exhaust fan.
- (iv) **Air Conditioning:** Air conditioning is defined as "the simultaneous control of all, or atleast the first three of those factors affecting both the physical and chemical conditions of atmosphere within any structure. These factors include temperature, humidity, air movement, distribution, dust, bacteria, most of which affect in greater or lesser degree human health and comfort". In air conditioning the air is first filtered and then saturated with water vapour. The excess of moisture is removed and the air is heated to the desired temperature before it is supplied. The difference between the outside and air-conditioned air temperatures should not be more than 20°F, otherwise it gives a sense of discomfort. Where there is air conditioning, transition rooms are sometimes provided so that people may not be suddenly exposed to high or low temperatures. The transition rooms help people in getting acclimatized, by stages, to high or low temperatures.

3. Lighting: Good lighting is essential for efficient vision. If the lighting conditions are not good eyes are put to strain which may lead to fatigue and loss of efficiency. The artificial light should have a colour similar to the day light colour. The source should be steady so that there is no flickering. There should be uniform distribution of light, so that sharp shadows and glare are absent. Ceilings and roofs should have a reflection factor of 80%; walls: 50 - 60%; furniture : 30 - 40% and floors: < 20%

By proper planning of towns and buildings the natural light can be efficiently utilised. The general principles that are considered in planning for the best utilisation of day light are orientation, removal of obstruction, location of windows and interior decoration. For example, ceiling should be white, upper portions of the wall should be light tilted and the lower portions to be darker to give comfortable contrast to the eyes.

12.6 CIGARETTE SMOKE

Cigarette Smoking is injurious to health - rather say 'Cigarette Smoke is injurious to health'. 500 ppm i.e. 500,000 $\mu\text{g}/\text{m}^3$ of carbonmonoxide for five minutes with frequent repetition may be a representative of cigarette smoking dose, 10-30 ppm of CO being an ambient air pollution problem. This may result in inactivation of upto 5% of haemoglobin. The presence of other pollutants also has a significant impact on the humans. Similarly, the exposure to oxides of nitrogen present in cigarette smoke is about 100 ppm, whereas the average exposure to heavy air pollution over periods of about an

hour will not exceed 1.5 ppm. The other pollutants in cigarettes are carcinogens, aldehydes, tar, hydrogen cyanide, lead etc. with nicotine being the main pollutant entering the body. Filter cigarettes can remove them to a greater extent, but not upto a safer limit.

Environment includes not only air, water or soil but also refers to the one created by one's cultural habits i.e. drinking, smoking and eating behaviour. Smoking has been found to be responsible for development of high incidence of lung cancer. N-nitroso compounds, hydrazine and polyaromatic hydrocarbons have been found to be cancer causing components in tobacco smoke. Chewing of tobacco also brings carcinogens in contact of skin to cause different oral cancers. Children are more susceptible to the ill-effects of cigarette smoke and must be prevented from initiating smoking habits. It should be prohibited in all public places to prevent the passive smoking effects on innocent people. As an initial measure, the development of tobacco related diseases can be reduced by using 'less harmful cigarettes' made up of less tar containing tobacco. Smoking should be prohibited in offices, universities, all educational institutions, aircraft, trains, buses, theatres, cinema halls etc. There should be a 'No Smoking Day' throughout the nation once a week to create anti-smoking awareness amongst people. The display of advertisements regarding the sale of cigarettes and other tobacco products at prominent public places like railway stations, hospitals and educational institutions should be banned. It should be noted that every day about 1500 crores of cigarettes are burnt in the world and that about 6 lakhs people die because of smoking in India alone.

The effects of cigarette smoking are more important than the effects of air pollution, as far as lung cancer or chronic pulmonary diseases are concerned. But when both factors are present it has a more detrimental effect. Thus cigarette smokers are at unusual risk, if they live in areas with substantial air pollution and the effects of air pollution on chronic pulmonary diseases are more likely to occur in cigarette smokers. It was observed that smokers in their twenties suffered a chronic disease three times as often as non-smokers. Cigarette smoke causes a delay in recovery from acute virus infections of the respiratory tract, perhaps because it reduces ciliary action required to cleanse the air ways.



CHAPTER - 13

ODOUR POLLUTION

'Odour' is undoubtedly the most complex problem of air pollution. Unfortunately, the only good measuring device for odour pollution is the human nose, which is notoriously undependable. Some individuals cannot detect odours easily whereas some have the ability to detect very minute quantities of substances in the range of 1ppb also. Moreover, people have a mixed reaction to a given odour. Perfumes, very much liked by some people, may be very much disliked by others. There is a marked disagreement with reference to the offensiveness of selected odours. In addition, there are two other problems which interfere with the detection and measurement of odour. They are (i) unfamiliar odour is more easily detected and is more likely to cause complaints than a familiar one and (ii) because of odour fatigue, given sufficient time, a person may become accustomed to almost any odour and be conscious of it only when a significant change in intensity occurs.

Food processing, oil refining, paper and rubber industries, tanneries, sugar mills, distilleries etc. are the major odour emitting industries. Odours may not cause direct damage but are as much a nuisance as noise, dust or corrosion. Until now, very little attention was given to the control of odorous air contaminants, consequently, Osmics, the science of smell, has remained unexplored to a great extent.

13.1 THEORY OF ODOUR

Exactly at the top of the juncture of the nasal passages and the top of the throat, the right and the left olfactory clefts are located. The total surface area of each chamber is about 6 sq.cm. in an adult. The long, narrow olfactory cells are located in the olfactory cleft with their length perpendicular to the plane of the nasal cavity. The olfactory nerve carries the 'smell impulse' from the olfactory cleft to the olfactory bulb of the brain. A substance gives odour if it is (i) volatile, so that it continuously loses molecules to the atmosphere for transportation to the olfactory system (ii) capable of being absorbed on the sensitive surface of the olfactory epithelium and (iii) customarily absent from the olfactory region i.e., the odorous substance must be one which is not already present on the olfactory epithelium, so that, when it arrives there alongwith the inhaled air, it brings about a sudden change like a sensation. Thus, when air is inspired through the nasal passages, the molecules of the volatile odorous substance are directed to the olfactory receptors where they are finally adsorbed. As adsorption is an exothermic process, the lodgement of odour-molecules causes an energy-change that causes electrical impulses which pass up the olfactory nerve to the brain. Brain finally makes us feel the smell. Smells often carry intense emotional value, depending on a given individual's personal experiences. A person's favourable reaction to an odour, or lack thereof can affect judgement. Odour felt depends on the chemical composition and the molecular structure of the odorous substance and the physiology of the receptors and the nervous pathway. Some substances have similar odours for similar or dissimilar chemical constitution. Odour strength may change with dilution and in the presence of strong odours, weak odours cannot be perceived. Odours, like other air pollutants, travel downwind and disperse in atmosphere.

13.2 SOURCES OF ODOUR

Generally odours are originated from a solid, a liquid or a concentrated gas. Sometimes odours escaping from sewer manholes also cause severe complaints. Sources of odour may be confined in space, like emission from ducts or they may be unconfined, like drainage ditches, lagoons, ponds etc.

Some of the malodorous pollutants are hydrogen sulfide, carbon disulfide, mercaptans, products of decomposition of proteins (especially those of animal origin), phenols and some petroleum hydrocarbons. Apart from this, odorous compounds are also generated due to various human activities, garbage dumps, sewage works and agricultural activities. Motor vehicle exhausts also are malodorous but are unfortunately liked by many especially the children!

Wastewater treatment plants release the malodorous gases of hydrogen sulfide and ammonia. Often, odour-producing substances include organic vapours such as indoles, skatoles, mercaptans and nitrogen-bearing organics. H_2S is the most commonly known and prevalent odorous gas associated with domestic wastewater collection and treatment systems. It has a characteristic rotten egg odour, is extremely toxic and is corrosive to metals such as iron, zinc, copper, lead and cadmium.

As almost every substance produces odour, the sources of odour are many and it is almost impossible to prepare a complete list of them. Table 13.1 gives some of the sources of odours (produced in industrial operations).

TABLE 13.1 SOURCES OF ODOURS

No	Industry	Odorous material
1.	Chemical	Ammonia, phenols, mercaptans, hydrogen sulfide, chlorine, organic products
2.	Tanneries	Flesh, blood, hair
3.	Fertilizer	Ammonia, nitrogen compounds
4.	Food	Cannery waste, dairy waste, meat products, packing-house wastes, fish, cooking odours, coffee roaster effluents
5.	Foundries	Quenching oils
6.	Petroleum	Sulphur compounds from crude oil, cresols
7.	Pharmaceutical	Biological extracts and wastes, spent fermentation
8.	Pulp and paper	Mercaptans
9.	Sugar mills	Molasses, mercaptans
10.	Rubber	Burning rubber, solvents, smoke
11.	Sewage treatment	H_2S , CH_4 , ammonia, indoles, mercaptans

13.3 MEASUREMENT OF ODOUR

As discussed earlier, human nose is a good measuring device of odour. The human nose assisted by selected devices or prescribed procedures is the basic system for evaluating odours. In general, odour determinations are made by a panel of 6 to 15 trained individuals subjected to given concentrations of odorous substances. The measurements of odours fall into three categories:

1) determining the threshold concentrations of odorous substances and 2) establishing the type and intensity of atmospheric odours and 3) tracing or tracking of a given odour in the atmosphere to its source. The first category involves primarily 'pure' odours, that is, the odour of a single substance. In the second category, the odour of several substances may combine in the atmosphere to give the impression of a single odour.

The four attributes of the olfactory system applicable to measurement of odour are intensity, pervasiveness, quality and acceptability.

Intensity is the magnitude of perceived sensation i.e. some numerical or verbal indication of the strength of the odour. A gradual increase in intensity is readily detected, although persons may become fatigued by odour.

Pervasiveness means a change of magnitude or acceptability on dilution and it is sometimes referred to as 'odour potential ratio' or 'threshold dilution ratio'. These essentially are measures of the ability of an odour to pervade a large volume of dilution air and continue to possess a detectable intensity. A pervasive odour of mercaptans and decomposed proteins will tend to spread in all directions over a community.

Quality describes the characteristics of odours in terms of association with a familiar odorant, such as a coffee or onions, or by associating a familiar odour with an unfamiliar odorant by analogy.

Lastly, acceptability is the degree of like or dislike of the odour sensation and depends to a large degree upon the experiences of the person during the odour evaluation. It designates the odour as pleasant or disagreeable.

For each odour there exists a concentration below which no perception is possible for most individuals. This concentration is called the threshold concentration or minimum identification level. Table 13.2 gives odour thresholds for some substances.

Vapour-dilution method is the basis for most of the odour-measuring devices. In this method, the amount of odour producing substance added to purified air is generally increased until an observer or 'sniffer' can just barely detect the odour. The measurements involve the determination of the number of dilutions of a sample of the odourous gas required to render it odourless. The odour threshold is then expressed in terms of odorant concentration, but rather in such subjective units as 'threshold odour units' or 'dilutions'. Thus the relative strength of the odour is determined, with stronger odours requiring greater number of dilutions with odour-free air to bring the odourous gas to the threshold of odour detection. The odour threshold is reported to be 100 ppm for acetone, 21.4 for carbon tetrachloride (CCl_4), 10 for HCl gas, 4.68

for benzene, 1 ppm for acetic acid, 0.47 for SO_2 , 0.047 for phenol, 0.0021 for methyl mercaptan, 0.02 for pyridine and 0.001 ppm for ethyl mercaptan.

TABLE 13.2 ODOUR THRESHOLDS IN AIR

Chemical	Odour Threshold (ppm)	Odour description
Acetic acid	1.0	Sour
Acetone	100.0	Chemically sweet
Amine monomethyl	0.021	Fishy, pungent
Amine trimethyl	0.0021	Fishy, pungent
Ammonia	46.8	Pungent
Carbon disulfide	0.21	Vegetable sulfide
Chlorine	0.314	Bleach, pungent
Diphenyl sulfide	0.0047	Burnt, rubbery
Formaldehyde	1.0	Hay or straw like
Hydrogen sulfide	0.00047	Eggy
Methanol	100	Sweet
Phenol	0.047	Medicinal

Generally, odour intensity increases with the odorant concentration. The relationship between odour intensity and concentration can be expressed as

$$P = K \log S \text{ where}$$

P = Odour intensity, K is a constant and

S = Odour concentration

The values of ' K ' have been found to vary from 0.3 to 0.6

A similar equation, known as the psycho-physical power law is given by :

$$P = K_2 S^n \text{ where}$$

K_2 and n are constants peculiar to each odorant. The value of ' n ' usually ranges from 0.15 to 0.8

Determination of the Type and Intensity of Odours

A panel of 6 to 15 persons in normal health are employed for measurement of odour intensity. At a given location and at the same time, the panel members sniff the air and report individually the nature and intensity of the odour. Some experience may be required to identify an odour. The odour intensity is usually stated according to predetermined rating system. A widely used 5-point scale for odour intensity is given in table.

The expert panel method is fairly expensive and limited to short periods of use. Also, care must be taken because mixtures of two or more different odours can be very misleading. Thus, the identification and determination of odours in the open air is even less precise than the determination of threshold values in the laboratory.

Observed odour	Odour intensity
No odour	0
Threshold level (barely perceptible)	1
Faint perception	2
Definite odour (easily noticeable)	3
Strong odour	4
Very powerful odour	5

Another method uses 'scentometer' for odour evaluation directly in the field. The instrument has the widest dilution range (upto 128) of all vapour-solution instruments designed for field use.

Odorants in the atmosphere or gas streams may also be collected by passing known volumes of air or gas through a column of activated carbon or condensation techniques. The collected odorants may then be taken to a laboratory and released by vacuum desorption and distillation.

13.4 ODOUR CONTROL METHODS

As discussed earlier, odour also is an important environmental problem. Controlling objectionable odours is an important problem of air pollution. Odours are caused by gases, mists or solids discharged into the atmosphere from industrial, commercial, municipal and domestic operations. One of the most effective means of abating odour is control at source. In many cases, this can be achieved by good sanitation practices, as the most persistent and offensive odours arise due to putrefaction.

The two general approaches to odour control are (1) to reduce concentration so that the smell is less intense and therefore less objectionable and (2) to change the quality of the odourant so that the smell becomes more pleasant and acceptable to the people. In the first approach, odour control is achieved by reducing the source of the odour; diluting the odour by greater ventilation or dispersion; removing the odour from a gas stream by adsorption, absorption, oxidation or chemically converting the odorous product to one less odorous. In the second approach, attempts are made to hide the original odour by introducing a more powerful odour having a pleasing scent or by modifying the original odour.

The following methods may be employed alone or in various combinations to eliminate or diminish odours.

1) Modification of the Process : In some cases odour control can be done by a change in the process, a change in the composition of process materials or removal of impurities etc. These methods include the substitution of low-odour solvents for highly odorous ones and adjustment of process variables like temperature, residence time etc. Such alterations make the resultant source less intense or more tolerable from the point of odour generation and are often feasible both technically and economically.

2) Ventilation / Dilution: Odour intensity being a function of the odorant concentration, properly designed ventilation is the most common method for removal of odours from enclosed spaces. Discharging the odorous air by means of a stack tall enough to let natural atmospheric dispersion take place, is the simplest method of odour discrimination. The ground level concentration is a function of stack geometry, odorant concentration in the emitted gas stream and meteorological conditions. Taller stacks can disperse odours effectively and hence the maximum ground level concentrations will be very less.

3) Adsorption : Activated carbon is widely used for odour control, because it has large surface area and has a preferential attraction and high retentivity for organic vapours. It is applied to deodorize (1) a gas stream before being discharged to the atmosphere (2) an odorous ambient atmospheric air before it is used in buildings or (3) an indoor atmosphere being recirculated. Conventional face velocities of 100 to 180 m/min. are used and bed thickness may vary from 2.5 to 7.5 cm for thin beds to 30 to 90 cm for thick beds. Care must be taken to ascertain whether or not non-odorous substances that are easily adsorbed by the charcoal are present in the odorous gas stream. These non odorous substances may saturate the activated carbon bed reducing or preventing the bed functioning as an odour control device. The retained material can be desorbed easily and the carbon can be reactivated and used again. But, if the concentration of the odorous material is very high, the method may not be economical.

4) Absorption : Absorption is applicable when the gases are soluble or emulsifiable in a liquid or react chemically in solution. Air scrubbers or washers are employed when odorant is (1) soluble in the scrubbing liquid (2) condensable at the temperature of the scrubbing liquid, such as water or (3) capable of becoming attached to particulates in the scrubber. Numerous types of scrubbers employing a wide range of liquids are available, the choice dependent upon the odour to be removed. Plain water or water added chemical reactants are widely used because of the low cost involved.

5) Oxidation /Combustion: This is achieved by direct flame incineration, catalytic incineration or chemical oxidation, as discussed below :

i) **Direct flame incineration :** In this flame oxidation process, the odorous gases are made to pass through a combustion chamber at a temperature of the order 650-820°C, in the presence of excess oxygen. In most cases, natural gas is selected as the fuel. Hence the major products of combustion are CO₂ and water vapour. The main demerit of this method is that the cost of the fuel required to produce the combustion temperature is quite high. Sometimes, heat exchangers may be employed to recover the heat from the hot incinerated gases and used for pre heating the effluent gases, steam generation etc. In addition to natural gas, propane and low sulfur oil may be used as fuels.

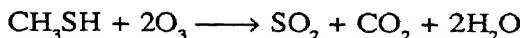
ii) **Catalytic incineration :** Catalytic incineration may be employed to remove odours by oxidation. This process is selective when the cost of heating the gas stream to 650°C is very high. In catalytic unit, oxidation takes place at a much lower temperature than necessary for direct incineration. The gases pass through specially designed units containing catalyst elements, on the surface of which oxidation occurs. During the catalytic oxidation, the constituents in the gas stream such as hydrocarbons and other organic malodours, react with oxygen to form CO₂ and water vapour. In general, complete oxidation should take place to solve the odour problem. Catalytic combustion of most of the organic constituents is initiated at about 260°C and is self-sustaining. Colder gas streams must be pre-heated before coming into contact with the catalyst.

Usually, certain metals and metal oxides are used as catalysts in oxidation reactions. Platinum and platinum-rhodium alloy distributed on a suitable support are highly effective as catalysts. The commercial catalyst units should have the properties of high specific surface, low resistance to the flow of gases and arrangement in a manner as to provide turbulent mixing of process gases.

Unfortunately, the life of the catalyst is easily reduced by 1) poisoning 2) obstruction of the catalyst surface by carbonaceous deposits and 3) loss of catalytic surface owing to abrasion by solid particles in the gas stream. Commercial catalyst units are being used for the odour control of effluent gases from chemical plants, varnish manufacture, paint and enamel-baking ovens, refuse incinerators, refineries burning waste cracking gases and coffee roasters.

iii) **Chemical oxidation :** Oxidizing agents such as ozone, chlorine, chlorine dioxide, hypochlorites and permanganates can destroy odours by

chemical conversion so that the possibility of detection of odours is greatly reduced.



As shown in the above equation, CH_3SH , having an odour threshold of 0.001 ppm is converted by ozone to SO_2 whose odour threshold is 0.5 ppm. The other two products of oxidation are CO_2 and H_2O which are odourless. Thus the oxidants convert the malodorous substances to substances of high threshold values. Ozone converts organic matter to aldehydes, ketones and acids. As it is harmful to humans and vegetation, its use must be confined to unoccupied spaces. Potassium permanganate solutions can deodorize sulphur compounds, amines, phenols and unsaturated compounds like styrene and acrolein.

6) Odour Masking and Counteraction : When two odorous substances of different concentrations are mixed, the stronger one will predominate. In other words, strong odours tend to mask weaker ones and this is known as 'odour masking'. Here, a strong odour, usually, a pleasant one is used to 'mask' or cover a weak unpleasant odour. However, care must be taken to see that the odorant used for super-imposing the pleasant odour is not flammable, corrosive or allergic. The methods used for odour masking are : 1) spraying, vaporizing or atomizing the odorant into the stack emissions and 2) adding directly to a process or mixing the odorant with the scrubbing liquor. Odour masking can also be used to control odours in outdoor places like refuse dumps or waste lagoons etc.

When odours of different concentrations are mixed together, the intensity of each odour is diminished. This effect is known as 'counteraction' or neutralization. Odour pairs like musk and bitter almond; rubber and cedar wood effectively reduce odours.

The fishy smell of amines, fecal odour of skatoles, skunk smell of mercaptans and the stinking odours of other substances such as diamines (with odour of decayed flesh) and organic sulfides (odour of rotten cabbage) produce a psychological stress in humans. Offensive odour can cause poor appetite for food, lowered water consumption, impaired respiration, nausea and vomiting and mental perturbation. They also may deteriorate personal and community pride, interfere with human relations, discourage capital investment, lower socio-economic status and deter growth, decrease market and rental property values and tax revenues and hence demand stringent odour pollution control measures.



CHAPTER - 14

AUTOMOBILE POLLUTION

Transportation is the main reason for air pollution especially in urban areas, where 60% of the air pollution is caused by automobiles only. The problem is of much concern in our country as the vehicular population is increasing at an alarming rate every year. The number of four wheelers are going up by 10 per cent every year while two and three wheelers by about 20 per cent. For example, in India, the number of two wheelers in 1970 and 1988 are 50 and 82 lakhs respectively and the number of passenger cars in 1970 and 1988 are 6.5 and 16 lakhs respectively. United States, with more than one vehicle for every one person in the country, alone burns more than 200 billion gallons of gasoline per year. The problem of automobile pollution is far more serious than one can imagine and therefore, the assessment of the impact of vehicular pollution on urban environment is essential. Vehicles travelling in major metropolitan areas are estimated to account for 80% of all carbonmonoxide, 50% of hydrocarbons, 30-40% of oxides of nitrogen and almost 100% of the lead present as air pollutant.

Mobile combustion sources include automobiles, trucks, buses, rail-road locomotives, aircraft and marine vessels. Pollutants from these sources

contain both toxic compounds and organic materials that are not in themselves objectionable but which react in the atmosphere to form smog which is highly objectionable.

14.1 VEHICULAR EMISSIONS

An average car during a day's run releases 0.5-1.5 kg of pollutants. The pollutants from the reciprocating engines as a consequence of combustion process may include the following:

1. Unburned hydrocarbons, UBHC
2. Carbonmonoxide, CO
3. Oxides of nitrogen, NOx
4. Carcinogens
5. Oxides of sulfur, SOx
6. Lead and its compounds
7. Particulate matter
8. Odours

Technically, vehicle emissions, according to their origin, can be divided into three categories. The percent contribution of these three sources are as below.

S. No.	Type of emission	% CO	% NOx	% HC
1.	Exhaust emissions	98-99	98-99	65
2.	Evaporative emissions	0	0	10
3.	Crank case blow-by	1-2	1-2	25

A. Exhaust Emissions

Complete oxidation of hydrocarbon fuel yields only carbondioxide and water as the products of chemical combination. When air is used as the source of the oxygen required for combustion, some of the oxygen and nitrogen combine to from nitric oxide. Under the conditions of combustion in an internal combustion engine, other products are also formed. These include carbonmonoxide, hydrogen and partially oxidized materials primarily in the aldehyde family. Some of the fuel is chemically rearranged by cracking or synthesizing reactions. Both absolute and relative concentrations of combustion products are influenced by numerous factors. Some of the prominent factors include air fuel ratio, ignition timing, absolute charge density, combustion chamber geometry and variable engine parameters such as speed, load and engine temperature.

Carbonmonoxide: Ideally, gasoline engines could be made to operate with CO levels near zero. Although the zero limit is not a reasonable target, less than 1/2 % CO is a reasonable goal. This low level of CO emission can be achieved only with some sacrifice in auto-driveability or engine performance. Typically, concentrations of CO in emissions are high during the engine idle mode and decrease as engine speed is increased outside of the idle range. About 2 ppm of CO being a desirable value, many cities all over the world including Bombay, Calcutta and Delhi are suffering from high CO concentrations of 20-70 ppm. CO is emitted mostly by vehicles run on petrol like most of the cars, three wheelers and two-wheelers. In Bombay alone, nearly 300 tonnes of carbonmonoxide are released from vehicular exhaust everyday.

Unburned Hydrocarbons : Concentrations of unburned hydrocarbons are influenced by air-fuel ratio in the same manner as CO is influenced i.e., lowest-emission levels are associated with an air-fuel ratio near stoichiometric. Further as with CO, higher levels of hydrocarbon-emissions are associated with idle and low-speed operation. Exceptionally high values of hydrocarbons in the exhaust, usually, are indicative of misfiring.

Oxides of Nitrogen : This pollutant is generated first as nitricoxide (NO) with conversion to nitrogen dioxide (NO_2) subsequent to the combustion event. Other nitrogen oxides are involved in much lesser amounts. The aggregate of the variable mixture, including NO and NO_2 , is commonly designated as NOx. Factors that tend to increase combustion temperature and to increase oxygen availability, also tend to increase NOx emission. Air-fuel ratio is found to be the dominant influence upon NOx emissions and the highest emissions are associated with air-fuel ratios slightly on the lean side of stoichiometric. The other factors relevant in NOx generation are engine compression ratio, spark timing and intake air temperature and humidity.

Particulate Matter: Exhaust emissions produce large numbers of extremely fine particles with approximately 70% by count in the size range of 0.02-0.06 μm . These particulate materials consist of both inorganic compounds and organic compounds of high molecular weight. The most significant fractions of automotive particulate emissions are lead compounds resulting from the use of tetraethyl lead as a fuel additive to provide the anti-knock characteristics necessary for present-day high-compression engines.

Lead and Other Heavy Metals: Combustion of gasoline containing lead additives is a primary source of lead in urban atmosphere. Tetraethyl lead is added to petrol to improve its antiknock quality and after combustion, lead is released through the exhaust. Lead is also emitted through petrol tanks and while fuelling in the petrol bunks. Lead is highly toxic even at trace levels.

Children should not be exposed to more than 100-150 µg of Pb per day. Infact many urban children ingest upto 200 µg of Pb everyday. Similarly, persons working in petrol bunks are prone to 'occupational diseases' caused by lead ingestion.

B. Evaporative Emissions

10 to 30% of the hydrocarbons in vehicular emissions belong to this category. The estimate is uncertain because techniques for measuring evaporative emissions involve large uncertainties. However, even at the lower limit of the estimate, these losses are significant. Fuel tank losses consist primarily of the more volatile fractions of gasoline displaced from the vapor space above the liquid fuel in the gas tank. Depending upon the direction of temperature changes, tank fill and tank agitation, the vapors may be discharged at any time, with vehicle either operating or stationary.

C. Crank Case Blow-by

Crankcase blow-by accounts for about one-fifth of the hydrocarbons in all vehicle emissions. Vehicles with badly worn engines may discharge blow-by in much larger quantity to account for upto one-third or more of the total. Experimental evidence fully establishes that the blow-by gases are primarily (i.e. about 85%) carburetted fuel air mixture that flows past the piston during the compression stroke and prior to the passage of flame through the mass.

14.2 MOTOR FUEL COMBUSTION

As in the combustion of other fuels, complete combustion is desired at stoichiometric amounts of air. Incomplete combustion results in the increased production of hydrocarbons in addition to carbonmonoxide. Increasing the amount of air by increasing the Air-Fuel Ratio, helps reduce the amount of incomplete combustion but it generates more nitric oxides. However, if the air-fuel ratio is very high, there will be dilution of the gases and a cooling of the combustion chamber. This cooling finally decreases NO_x concentrations as shown in figure 14.1.

Most of our transportation energy is derived from the combustion of a liquid petroleum fuel in an internal combustion engine. Thus the emission products are similar to oil and gas combustion products. Gasoline and diesel oil, the two major fuels, are obtained from the refining of crude oil. Crude oil is fractionated in a refinery to produce a number of petroleum products. The amount of each product varies with the crude and the fractionating process. For example, a crude may be processed to obtain 55% gasoline, 35% light oils such as diesel oil, kerosene, heating oils and jet fuels and 10% of lubricating, asphalt and other heavy oils. Gasoline may be represented by C₈H_{17,5}. It contains 0.01 to 0.05% of sulfur. Diesel oil contains more sulfur.

Stoichiometric combustion of gasoline and diesel fuels requires an air-fuel ratio of about 15. The stoichiometric equation is:



The fuels are combusted by mixing the finely atomized/vaporized liquid fuel with stoichiometric amounts of air in an internal combustion chamber. The mixture is pressurized and then ignited by either a sparking device or by the cylinder-compression heat. Spark Ignition (SI) engines use carburetors to pneumatically atomize / vaporize the gasoline fuel.

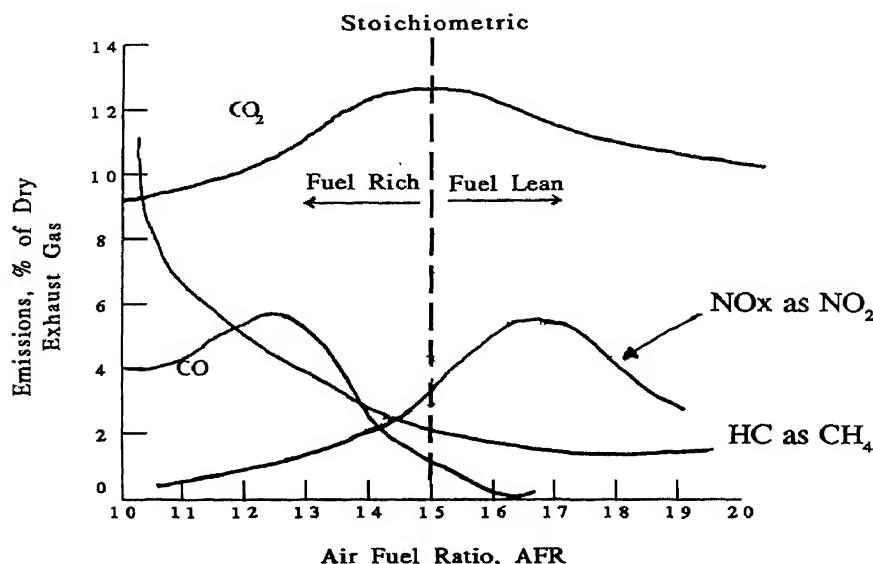


Fig. 14.1 Effect of AFR on Automobile Emissions

The products of combustion depend mainly on the type of fuel - diesel or petrol; condition of vehicle - old or new; operation mode - idle, acceleration or deceleration and the type of engine - 2 stroke or 4 stroke. The following table gives exhaust data for diesel and petrol engines.

S. No.	Pollutant	Diesel Engine	Petrol engine
1.	Particulate matter	0.5 g/m ³	0.01 g/m ³
2.	Carbonmonoxide	< 0.1% by volume	> 10% by volume
3.	Hydrocarbons	< 300 ppm	< 1000 ppm
4.	Oxides of nitrogen	1000–4000 ppm	2000–4000 ppm

The concentrations of exhaust gases also depend on the operating variables. The effects of engine operating conditions on the composition of auto exhausts are given in the following table.

Parameter	Idle	Acceleration	Cruising	Deceleration
Air fuel ratio	11-12.5	11-13	13-15	11-12.5
% CO	4-6	0-6	1-4	2-4
NOx, ppm	10-50	1000-4000	1000-3000	10-50
HC, ppm	500-1000	50-500	200-300	4000-12000
Unburnt fuel as % supplied fuel	4-6	2-4	2-4	20-60

The major pollutants emitted by diesel driven engines are oxides of nitrogen, smoke and formaldehyde, in addition to carbonmonoxide and hydrocarbons. Indian buses and trucks have been observed to emit heavy smoke. The present Indian Standard of 65 HSU under free acceleration was seen to be met only by 40 percent of the city buses and 35 percent of the inter-state ones. More than 90 percent of the trucks and mini-buses emit smoke higher than 65 HSU. It is evident that petrol driven vehicles contribute about 80 percent of atmospheric carbonmonoxide and diesel driven vehicles contribute a major portion of oxides of nitrogen, smoke and odour.

In India, two wheelers which have generally two stroke engines, are getting increasingly popular. They account for more than 50% of the country's gasoline consumption and with their rapidly growing members, they pose serious air pollution problems in many cities. The emission of hydrocarbons from two stroke engines is 10-20 times more than that from four stroke engines.

In two stroke engines, exhaust hydrocarbons and carbonmonoxide are the major pollutants and NOx emissions are less compared to four stroke engines. As far as hydrocarbon-emissions are concerned, two and three wheelers are the principal contributors. The following table gives emission data for 2 stroke and 4 stroke engines.

Pollutants	Emission rate, g/bhp-hr	
	2-stroke	4-stroke
HC	60.0	6.0
CO	100.0	150.0
NOx	1.2	2.5

14.3 AUTOMOBILE EMISSION CONTROL

Automobile emissions can be controlled as below :

1. Control of Crankcase Emissions : A control device called 'positive crankcase ventilation, PCV' prevents blow-by from the crankcase by returning gases to the cylinders to be burned inside the engine instead of being vented into the atmosphere. To function properly positive crankcase ventilation or smog value must be clean and should be inspected at every oil change and be replaced every 20,000 kms. or one year.

2. Control of Exhaust Emissions : Exhaust emissions are reduced in various ways. One approach is based on the principle of reducing HC and CO emissions by adding fresh air to the hot exhaust gas to supply necessary oxygen needed for more complete burning as the mixture moves through the exhaust system. This system also includes engine modifications to increase the effectiveness of burning within the combustion chamber itself. Modifications include an engine-driven air pump, air control and distribution equipment to deliver air to each exhaust port, carburetor modifications, distributor and vacuum advance modification and manufacturer's recommended maintenance.

Another approach is the controlled combustion system which utilizes engine design parameters to achieve emission control through combustion. This system includes an air-fuel mixture control, modified ignition timing, and recommended maintenance. Exhaust emission device systems require periodic servicing of ignition and carburetor systems, especially engine idle speeds, spark timing and air-fuel ratio adjustments.

3. Control of Evaporation Emissions: Fuel evaporation emissions can be reduced by the installation of a fuel tank with a built-in chamber to provide an assured thermal expansion volume for the fuel. The tank is vented into a vapor-liquid separator which returns liquid to the tank and passes vapor through a pressure-vacuum relief valve to an activated carbon canister. Vapor is stored in the canister until purged by a vacuum created when engine operation empties the vapor into the intake manifold and then into the combustion chamber, where it is burned. Some vapour control systems have no carbon canister, but instead use the engine crankcase as a storage container. Evaporative emissions are low for diesel engines because they use a closed injection fuel system and because diesel is less volatile than petrol.

4. Alternatives to the Gasoline Engine: Many alternatives to the gasoline engine have been suggested including the steam engine, the gas turbine engine of air that reduces HC and CO, the stratified charge-fuel injection

engine, the free-piston diesel engine, the electric car (using zinc - air battery/lithium - nickel - halide battery / sodium - sulfur battery). Of these, the one appearing to have best possibility is an electric car using a fuel cell, which uses hydrazine, ammonia or alcohol linked with an auxiliary fast - discharge battery for peak acceleration. Using improved fuels is another approach. These fuels include diesel fuel, liquid petroleum gas (LPG), compressed natural gas (CNG), liquid natural gas (LNG), solar energy, nuclear power and the fuel produced from liquid hydrogen.

5. Strict Implementation of Legislations : Immediate control measures need to be introduced to curtail the growing degradation of the urban environment by implementing the legislations strictly. The Indian Standards for vehicular emission are :

1. For every motor vehicle powered by compression ignition (diesel engine) smoke density shall not exceed 65 Hartridge Smoke Units as measured by the free acceleration method.
2. Vehicles powered by spark ignition engine (Otto engine) shall comply with the emission standards for carbonmonoxide not exceeding 3% by volume of exhaust gases during idling. Vehicles which have five years of life shall comply with emission standards of CO not exceeding 4.5% by volume of exhaust gases during idling.

Automobile emissions can be minimised by the formation of more stringent emission standards for new as well as used vehicles. Also, emission levels on new vehicles should be evaluated to meet the long - term emission control objectives. Reductions of lead in gasoline, can, by a great extent, reduce the lead levels in the environment. Further, the catalytic convertors in automobiles should be encouraged to reduce the emission of other pollutants, such as CO and hydrocarbons. Regular monitoring of air quality at several locations in urban areas with high-traffic density and regular collection of epidemiological data in the metropolitan cities also will help reduce the automobile emissions. Finally, mass transportation systems appear to be the ultimate solution to traffic problems in the metropolis, where traffic and pollution are becoming extremely critical problems.



CHAPTER - 15

AIR POLLUTION MONITORING AND MANAGEMENT

The objective of monitoring and management of air-pollution is to protect man and his property. Continuous monitoring of ambient air quality and stack-gas emissions is necessary to develop back-ground concentrations of different pollutants in an area, to evaluate the performance of the air-pollution control measures adopted and finally to check whether the concentrations of pollutants are within the prescribed limits or not. Monitoring meteorological parameters such as wind speed and wind direction, temperature and environmental lapse rate, humidity and precipitation, alongwith the concentrations of pollutants both in stack and in ambient air would help in the successful management of air pollution control problems and in arriving at new air-pollution standards. Air pollution can be reduced by a great extent even before setting up an industry by locating it at a suitable site and by conducting a thorough Environmental Impact Assessment. After commissioning the industry, the pollutants can be minimised by following a good environmental management plan. As air pollution control is often a costly affair with no direct beneficial returns, many industries show little interest in air pollution control management. A thorough monitoring of the air pollutants and a strict implementation of the legislations only can control air pollution and bring air quality to the required standards.

15.1 ENVIRONMENTAL GUIDELINES FOR SITING OF INDUSTRIES

Rapid industrialization significantly contributes towards economic growth. However, industrial progress brings along with it a host of environmental problems. Many of these problems could be avoided if industries are located on the basis of environmental considerations. Injudicious siting of industry can seriously affect the environmental features such as air, water, land, flora and fauna, human settlements and health of people. The industrialist should be fully aware of these implications and he should take necessary steps while setting up the industry so as to minimise the possible adverse effects on the environmental resources and quality of life. Often, an industrialist finds it very costly to instal pollution control equipment and other mitigative measures once the industry is already set up. Thus preventive steps are needed at the time of siting rather than going in for curative measures at a later stage.

Presently, industries are being located on the basis of raw material availability, access to the market, transport facilities and such other techno-economic considerations only without adequate attention to environmental considerations which are now recognised as an important criterion for setting up an industry.

To prevent air, water and soil pollution arising out of industrial projects, the industrial licensing procedure requires that the entrepreneurs before setting up the industry should obtain clearance from Central/State Air and Water Pollution Control Boards. The Central/State Pollution Control Boards stipulate that air (gases) and water (effluents) emanating from the industry should adhere to certain quality standards. However, these stipulations do not prevent the industry from affecting the total environment by wrong siting. Also, the cumulative effect of a number of industries at a particular place is not being studied upon with the result that an industry or an industrial area over a period of time could cause a significant damage in the surrounding environmental and ecological features.

Depending on the nature and location of the project, the entrepreneur will be required to submit comprehensive Environmental Impact Assessment report and Environmental Management Plans and half-yearly progress report on installation of pollution control devices to the respective state pollution control boards.

Environmental Guidelines for Industries

The following environmental guidelines are recommended for siting of industries to ensure optimum use of natural and man-made resources in sustainable manner with minimum depletion, degradation and/or destruction of environment. These are in addition to the directives that are already in existence under the Industries (Development and Regulation) Act.

While siting industries, care should be taken to minimise the adverse impact of the industries on the immediate neighborhood as well as distant places. Some of the natural life sustaining systems and some specific land uses are sensitive to industrial impacts because of the nature and extent of fragility. With a view to protecting such places an industrial site should maintain the following distances from the areas listed:

- a) Ecologically and/or otherwise sensitive areas: atleast 25 kms. These areas include religious and historic places; archeological monument such as identified zone around Taj Mahal; scenic areas; hill resorts; beach resorts; health resorts; coastal areas rich in corals, mangroves and breeding grounds of specific species; gulf areas; biosphere reserves; national parks and sanctuaries; natural lakes and swamps; seismic zones; tribal settlements; areas of scientific and geological interest; defence installations, specially those of security importance and sensitive to pollution; international boarder areas and air ports. Depending on the geo-climatic conditions, the minimum distance to be maintained shall have to be increased by the appropriate agency. State and Central Governments are required to identify such areas on a priority basis.
- b) Coastal areas: atleast 1/2 km. from high tide line.
- c) Flood plain of the riverine systems : atleast 1/2 km. from flood plain or modified flood plain affected by dam in the upstream or by flood control systems.
- d) Transport/communication system: atleast 1/2 km. from highway and railway.
- e) Major settlements (3,00,000 population): distance from settlements is difficult to maintain because of urban sprawl. At the time of siting of the industry if any major settlement or notified area is within 50 km, the spatial direction of growth of the settlement for atleast a decade must be assessed and the industry shall be sited atleast 25 km. from the projected growth boundary of the settlement.

Siting Criteria

The list of polluting industries required to obtain environmental clearance for siting vide press note dated 10th December, 1984 issued by the Department of Industrial Development, Government of India is given below.

1. Primary metallurgical processing industries viz. zinc, lead, copper, aluminium and steel
2. Paper, pulp and newsprint

3. Pesticides / insecticides
4. Refineries
5. Fertilizers
6. Paints
7. Dyes
8. Leather tanning
9. Rayon
10. Sodium/potassium cyanide
11. Basic drugs
12. Foundry
13. Storage batteries (lead acid type)
14. Acids / alkalies
15. Elastics
16. Rubber - synthetic
17. Cement
18. Asbestos
19. Fermentation industry
20. Electro-plating industry

Environmental factors must be taken into consideration in industrial siting. Proximity of water sources, highways, major settlements, markets for products and raw material resources is desired for economy of production, but the above listed systems must be away for environmental protection. Industries are, therefore, required to be sited, striking a balance between economic and environmental considerations. In such a selected site, the following factors must be recognized.

1. No forest area shall be converted into non-forest activity for the sustenance of the industry.
2. No prime agricultural land shall be converted into industrial site.
3. Within the acquired site the industry must locate itself at the lowest location to remain obscured from general sight.
4. Land acquired shall be sufficiently large to provide space for appropriate treatment of wastewater still left for treatment after maximum possible reuse and recycle. Reclaimed (treated) wastewater shall be used to raise green belt and to create water bodies for aesthetics, recreation and if possible, for aquaculture. The green belt shall be 1/2km. wide around the battery limit of the industry. For industry having odour problem it shall be one kilometer wide.
5. The green belt between two adjoining large scale industries shall be 1km.

6. Enough space should be provided for storage of solid wastes so that these could be available for possible reuse.
7. Layout and form of the industry must conform to the landscape of the area without affecting the scenic features of that place.
8. Associated township of the industry must be created at a space having physiographic barrier between the industry and the township.
9. Each industry is required to maintain three ambient air quality measuring stations with 120 degree angle between stations.

15.2 ENVIRONMENTAL IMPACT ASSESSMENT (EIA)

The purpose of Environmental Impact Assessment (EIA) is to identify and evaluate the potential impacts (beneficial and adverse) of development projects on the environmental system. This useful aid of decision making is based on understanding of the environmental implications including social, cultural and aesthetic concerns which could be integrated with the analysis of the project costs and benefits. This exercise should be undertaken early enough in the planning stage of projects for selection of environmentally compatible sites.

The projects for which EIA is necessary, include:

- i) Those which can significantly alter the landscape, land use pattern and lead to concentration of working and service population;
- ii) Those which need upstream development activity like assured mineral and forest products supply or downstream industrial process development;
- iii) Those involving manufacture, handling and use of hazardous materials;
- iv) Those which are sited near ecologically sensitive areas, urban centres, hill resorts, places of scientific and religious importance; and
- v) Industrial estates with constituent units of various types which could cumulatively cause significant environmental damage.

The Environmental Impact Assessment (EIA) should be prepared on the basis of the existing background pollution levels vis-a-vis contributions of pollutants from the proposed plant. The EIA should address to some of the basic factors listed below:

- a) Meteorology and air quality: Ambient levels of pollutants such as sulphur dioxide, oxides of nitrogen, carbonmonoxide, suspended particulate matter, should be determined at the centre and at 3 other locations on a

radius of 10 km with 120 degrees angle between stations. Additional contribution of pollutants at the locations are required to be predicted after taking into account the emission rates of the pollutants from the stacks of the proposed plant, under different meteorological conditions prevailing in the area.

- b) Hydrology and water quality
- c) Site and its surroundings
- d) Occupational safety and health
- e) Details of the treatment and disposal of effluents (liquid, air and solid) and the methods of alternative uses
- f) Transportation of raw material and details of material handling
- g) Impact on sensitive targets
- h) Control equipment and measures proposed to be adopted

15.3 ENVIRONMENTAL MANAGEMENT PLAN

Preparation of environmental management plan is required for formulation, implementation and monitoring of environmental protection measures during and after commissioning of projects. The plans should indicate the details as to how various measures have been or are proposed to be taken including cost components as may be required. Cost of measures for environmental safeguards should be treated as an integral component of the project cost and environmental aspects should be taken into account at various stages of the projects, such as:

- a) Conceptualization: Preliminary environmental assessment.
- b) Planning: Detailed studies of environmental impacts and design of safeguards.
- c) Execution: Implementation of environmental safety measures.
- d) Operation: Monitoring of effectiveness of built-in safeguards.

The management plans should be necessarily based on considerations of resource conservation and pollution abatement, some of which, with reference to liquid, air and land pollutions, are given as under.

1. Effluents from the industrial plants should be treated well to the standards as prescribed by the Central / State Water Pollution Control Boards.
2. Soil permeability studies should be made prior to effluents being discharged into holding tanks or impoundments and steps taken to prevent percolation and groundwater contamination.
3. Special precautions should be taken regarding flight patterns of birds in

the area. Effluents containing toxic compounds, oil and grease have been known to cause extensive death of migratory birds. Location of industrial plants should be prohibited in such type of sensitive areas.

4. Deep well burial of toxic effluents should not be resorted to as it can result in re-surfacing and groundwater contamination. Re-surfacing has been known to cause extensive damage to crop and live stocks.
5. In all cases, efforts should be made for reuse of water and its conservation.
6. The emission levels of pollutants from different stacks, should conform to the pollution control standards prescribed by Central or State Boards.
7. Adequate control equipment should be installed for minimising the emission of pollutants from various stacks.
8. In-plant control measures should be taken to reduce the fugitive emissions.
9. Infrastructural facilities should be provided for monitoring the stack emissions and measuring the ambient air quality (including micro-meteorological data required) in the area.
10. Proper stack height as prescribed by the Central/State Pollution Control Boards should be provided for better dispersion of pollutants over a wider area to minimise the effect of pollution.
11. Community buildings and townships should be built up-wind of plant with 1/2 to 1 kilometer green-belt in addition to physiographical barrier.
12. The site for waste disposal should be checked to verify permeability so that no contaminants percolate into the groundwater or river/lake.
13. Waste disposal areas should be planned down-wind of villages and townships.
14. Reactive materials should be disposed off by immobilising the reactive materials with suitable additives.
15. The pattern of filling disposal sites should be planned to create better landscape and be approved by appropriate agency and the appropriately pretreated solid wastes should be disposed off according to the approved plan.
16. Intensive programmes of tree plantation on disposal areas should be undertaken.
17. Adequate measures should be taken for control of noise and vibrations in the industries.

18. Proper precautionary measures for adopting occupational safety and health standards should be taken.
19. Adequate safety precautions should be taken during preventive maintenance and shut down of the control systems.
20. A system of inter-locking with the production equipment should be implemented where highly toxic compounds are involved.
21. Proper house-keeping and cleanliness should be maintained both inside and outside the industry.
22. Residential colonies should be located away from the solid and liquid waste dumping areas. Meteorological and environmental conditions should be studied properly before selecting the site for residential areas in order to avoid air pollution problems.
23. Persons who are displaced or have lost agricultural lands as a result of locating the industries in the area, should be properly rehabilitated.
24. Proper parking places should be provided for the trucks and other vehicles by the industries to avoid any congestion or blocking of roads.
25. Siting of industries on the highways should be avoided as it may add to more road accidents because of substantial increase in the movements of heavy vehicles and unauthorised shops and settlements coming up around the industrial complex.
26. Spillage of chemicals/substances on roads inside the plant may lead to accidents. Proper road safety signs both inside and outside the plant should be displayed for avoiding road accidents.
27. Efforts should be made to recycle or recover the waste materials to the extent possible. The treated liquid effluents can be conveniently and safely used for irrigation of lands, plants and fields for growing non-edible crops.
28. Industries should plant trees and ensure vegetal cover in their premises. This is particularly advisable for those industries having more than 10 acres of land.
29. Proper disaster planning should be done to fight against any emergency situation arising due to fire, explosion, sudden leakage of gas etc. Fire-fighting equipment and other safety appliances should be kept ready for use during disaster/emergency situation including natural calamities like earthquake/flood.
30. Each industry should identify within its set up a department/section/cell with trained personnel to take up the moral responsibility of environmental management as required for planning and implementation of projects.

15.4 STACK-EMISSION STANDARDS

These are related to a stationary source such as a chimney and are intended to help achieve the desired air quality. They include standards for the physical stack height, equipment design and fuel composition. Table 15.1 presents the maximum permissible process-emission concentrations for some specific substances, Table 15.2 presents the standards for minimum stack height and Table 15.3 presents the stack-gas emission standards for some industries, as framed by the Central Board for Prevention and Control of Water Pollution, India in 1984 and 1985. If an industry falls in an area that is sensitive due to its proximity to national parks, forests, historical monuments such as Taj Mahal and health resorts or if the area is already polluted due to rapid urbanisation/industrialization, the State Pollution Control Boards may adopt more stringent standards. However, they shall not relax the standards.

TABLE 15.1 PERMISSIBLE PROCESS EMISSION STANDARDS FOR SPECIFIC SUBSTANCES

Substance	Maximum permissible concentration, ppm
Chlorine	5
Benzyl chloride	5
Bromine	0.5
Fluorine	0.5
Mercaptans	0.5
Phosgene	0.5
Phosphorus trichloride	2.5
Sulphur monochloride	5
Sulphur pentafluoride	0.1
Acetic anhydride	25
Aniline	25
Cresol	15
Dimethyl amine	30
Trimethyl amine	0.5
Total amines	1
Dimethyl sulfide	0.1
Ethanolamine	10
Formaldehyde	10
Vinyl chloride	500

Ethylene dichloride	150
Formic acid	15
Hydrazine	3
Hydrogen bromide	10
Hydrogen chloride	25
Hydrogen fluoride	10
Hydrogen sulfide	25
Hydrogen cyanide	10
Nitric acid	10
Nitrogen oxides	15
Pyridine	10
Hydrocarbons	25
Sulphurdioxide	15
Acetic acid	50
Ammonia	250
Benzene	30
Carbon disulfide	50
Carbon tetrachloride	30

15.5 STANDARDS FOR MINIMUM STACK HEIGHT

If the height of a stack /chimney is more, the maximum ground level concentration will be less due to an effective dispersion and dilution of pollutants in the atmosphere. The criterion for minimum stack height to be provided in an industry is given in table 15.2.

TABLE 15.2 GUIDE LINES FOR MINIMUM STACK HEIGHT

- For all plants except thermal power plants, $H_{min} = 30\text{ m}$
- For thermal power plants releasing $Q\text{ kg/hour}$ of SO_x emissions per hour, H_{min} is as below.

Boiler size	H_{min}, m
Less than 200 MW	$14 Q^{0.3}$
200 MW to less than 500 MW	220
500 MW and more	275
- If $Q_1\text{ tonnes/hour}$ is the particulate emission rate, $H_{min} = 74 Q_1^{0.27}$
- If the stack height arrived at by using the above criteria are different, then the higher value should be taken as the minimum stack height. However, in no case should the height of the stack be less than 30 m.

TABLE 15.3 STACK GAS EMISSION STANDARDS**1. Cement Industry**

Standard for particulate matter emission		
Capacity	Protected Area	Other Area
200 tpd and less	250 mg/Nm ³	400 mg/Nm ³
Greater than 200 tpd	150 mg/Nm ³	250 mg/Nm ³

2. Thermal Power Plants

Standard for particulate matter emission			
Boiler size	Protected area	Other area	
		Old (before 1979)	New (after 1979)
< 200 MW	150 mg/Nm ³	600 mg/Nm ³	350 mg/Nm ³
≥ 200 MW	150 mg/Nm ³	-	150 mg/Nm ³

3. Iron and Steel Manufacturing

Process	Emission limits for particulates
Sintering plant	150 mg / Nm ³
Coke oven	-
Blast furnace	-
Steel making - during normal operation	150 mg / Nm ³
During oxygen lancing	400 mg / Nm ³

4. Fertilizer (Urea) Industry

Standard for particulate matter emission from prilling tower is 50 mg / Nm³

5. Nitric Acid Manufacturing

Standard for oxides of nitrogen is 3 kg of NO_x per tonne of weak acid (before concentration) produced.

6. Sulfuric Acid Manufacturing

Process	Standard for sulphurdioxide and acid mist emission	
	Sulphurdioxide emission	Acid mist emission
Single conversion-single absorption	10 kg/tonne of concentrated (100%) acid produced	50 mg / Nm ³
Double conversion-double absorption	4 kg tonne of concentrated (100%) acid produced	50 mg / Nm ³

7. Calcium Carbide Industry

Source	Emission limit for particulates
Kiln	250 mg / Nm ³
Arc furnace	150 mg / Nm ³

8. Copper, Lead and Zinc Smelting

Source	Emission standard
Concentrator Smelter and converter	150 mg/Nm ³ for particulate matter Off-gases must go for H ₂ SO ₄ manufacturing No release of SO ₂ /SO ₃ shall be permitted from the smelter or converter.

9. Carbon Black

Standard for particulate matter emission is 150 mg/Nm³

10. Fertilizer (Phosphatic) Industry

Process	Emission limit
Acidification of rock phosphate	25 mg/Nm ³ as total fluoride (F-)
Granulation, mixing, rock grinding	150 mg/Nm ³ of particulate matter from each process.

11. Oil Refineries

Process	SO ₂ Emission limit
Distillation (atmospheric plus vacuum)	0.25 kg/tonne of feed*
Catalytic cracker	2.5 kg/tonne of feed
Sulphur recovery unit	120 kg/tonne of sulphur in the feed

(*Feed indicates the feed for the process under consideration only)

12. Aluminium Industry

	Standard for fluoride and particulate matter
Process	Emission Standard
Calcination	250 mg/Nm ³ of particulate
Aluminium smelting	1 kg (F-) / tonne of aluminium produced & 150 mg / Nm ³ of particulate matter

15.6 AMBIENT AIR QUALITY STANDARDS

The purpose of laying air quality standards is to establish certain maximum limits on parameters of air quality considered desirable for the preservation and enhancement of the quality of air. These standards are designed to protect human health, to prevent injury to plant and animal life, to prevent damage to public and private property, to ensure continued use of natural resources for recreational purposes and to provide opportunities for healthy industrial and agricultural development. The underlying motivation of a study of air pollution is to implement its control and abatement. To be particular, the objective is to control pollutant sources so that ambient pollutant concentrations are reduced to levels considered safe from the standpoint of undesirable effects. Thus, standards define the amount of exposure permitted to the populations or ecological systems and are based on the exposure conditions, the socio-economic situation and the importance of health related problems. Some of the important acts meant for pollution control are:

AIR POLLUTION CONTROL ACTS

1. First Alkali Act (for industries), 1863
2. Public Health Act (w.r.t. smoke), 1936
3. Air Pollution Control Act (first federal legislation), 1955
4. Clean Air Act, U.S.A., 1963
5. Amended Clean Air Act (for cars), 1965
6. Air Quality Act (for ambient air quality), 1967
7. Amended Air Quality Act (emission standards), 1970
8. Water Act, 1974
9. The Air Act, 1981

In India, no systematic or statistical data are available on the health status of the people exposed to air pollution. The nature of damage caused to tropical and subtropical vegetations by air pollution is almost unknown. The information on effects of air pollution on materials is scanty. As the data base is extremely poor, meteorological and epidemiological data, in addition to the air-quality data must be generated at regional levels for an effective air pollution control management.

The ambient air quality standards laid by different pollution control agencies are presented in the following tables.

TABLE 15.4 AMBIENT AIR QUALITY STANDARDS FOR THE UNITED STATES

Contaminant	Exposure	Primary	Secondary
1. Particulates	Annual geometric mean	75	60
	24 hour concentration	260	150
2. SO ₂	Annual arithmetic mean	80	60
	24 hour concentration	365	260
3. NO _x	3 hour concentration	-	1300
	Annual arithmetic mean	100	100
4. CO	Max. 24 hour concentration	10,000	10,000
	Max. 1 hour concentration	40,000	40,000
5. Oxidants as O ₃	24 hour concentration	-	150
	Max. 1 hour concentration	160	-
6. Hydrocarbons (non-methane)	Max 3 hour (6-9am) concentration	160	160

TABLE: 15.5 INDIAN AIR QUALITY STANDARDS

Category	Area	Standard Concentration, µg/m ³			
		SPM	SO ₂	NO _x	CO
A	Industrial & mixed use	500	120	120	5000
B	Residential and rural	200	80	80	2000
C	Sensitive	100	30	30	1000

**TABLE 15.6 AMBIENT AIR QUALITY STANDARDS BY
CENTRAL POLLUTION CONTROL BOARD OF INDIA**

Zone	Exposure	Standard Concentration in µg/m ³		
		SPM	SO ₂	NO _x
Industrial	8 hour	500	120	120
	24 hour	360	80	90
Residential	8 hour	200	80	80
	24 hour	140	60	60
Sensitive	8 hour	100	30	30
	24 hour	70	20	20

Table: 15.7 National Ambient Air Quality Standards Assigned by EPA

Pollutant	Type of Standard	Averaging time	Frequency parameter	Concentration $\mu\text{g}/\text{m}^3$
Carbon monoxide	Primary ^a	1 hr	Annual maximum	40,000
	Secondary ^b	8 hr	Annual maximum	10,000
Hydrocarbons (non methane)	Primay	3 hr	Annual maximum	160 ^c
	Secondary	(6-9 am)	-	
Nitrogen dioxide	Primary and Secondary	1 year	Arithmetic mean	100
	Primary	1 year	Annual maximum	160
Photochemical oxidants(O ₃)	Secondary	24 hr	Annual maximum	260
	Primary	24 hr	Annual geometric	60
Particulate matter	Secondary	24 hr	Annual maximum	150
	Primary	24 hr	Annual geometric	75
Sulphur dioxide	Primary	24 hr	Annual maximum	365
	Secondary	1 hr	Arithmetic mean	80
Lead	Secondary	3 hr	Annual maximum	1,300
	Primary	2 hr	Annual maximum	260
	Primary	3 month	Arithmetic mean	1.5

- a. Primary standards are those required to protect public health (to be achieved regardless of cost within a specified time limit).
- b. Secondary standards are those required to protect public welfare (to safeguard plants, materials and personal comfort).
- c. Not to be exceeded more than once per year.

15.7 STACK EMISSION MONITORING

Stack monitoring is performed by inserting a measuring device into the stack of a particular source to obtain a sample of plume or by obtaining smoke reading of visual emissions from a stationary source. The purpose of stack sampling is to determine the quantity, quality and type of pollutants emitted from a specific source, efficiency of the pollutant collector or control device, to determine emission factors for use in emission inventories, or to determine appropriate design for air pollution control equipment to be installed.

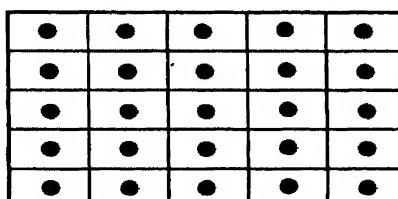
The collection method and collection equipment used for stack sampling mainly depend upon the purpose of the sampling. However, very high temperature operations or extremely moist, dusty and corrosive environments and accessibility of sampling locations can also dictate the type of

sampling equipment. For example using heavy - bulky equipment may not be possible if it is required to scale a difficult stack to obtain a representative effluent sample. It is important to remember that the sample must be collected without physical or chemical alteration and without altering the flow pattern or the concentrations of pollutant at the point of collection of the sample. Also, this sample must be obtained at a point of average gas density and average pollutant concentration. Some considerations for accurate representative sample collection include, the accurate measurement of pressure, moisture, humidity and gas composition and the selection of suitable locations of sampling. Determination of traverse points is required for velocity and temperature profiles across the cross-section of the stack. Isokinetic sampling rate should be maintained while sampling the particulates. Continuous in-stack monitoring systems like 'Pilis-V' can be used for a detailed record of stack emissions. However, the most commonly used system is the stack monitoring kit which is described later.

Location of Sampling Ports and Traverse Points

In a stack or duct, there may be considerable non-uniformity of gas flow and therefore of particle concentration and size. So, location of sampling port and obtaining sufficient number of samples to properly characterise a heterogeneous source are to be properly tackled. The sampling port, wherever possible should be at a distance of 8 diameters down stream and 2 diameters up stream from any such as bends, expansion, flow disturbance, stack exit etc. as shown in figure 15.2.

**Rectangular Stack
(9 - point traverse)**



(Centres of atleast 9 hypothetical squares on minimum of 3 lines)

**Circular Stack
(10-point traverse)**

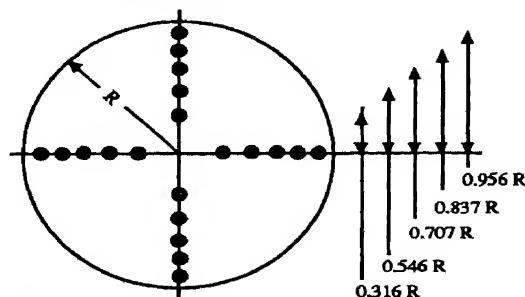


Fig. 15.1 Location of Traverse Points

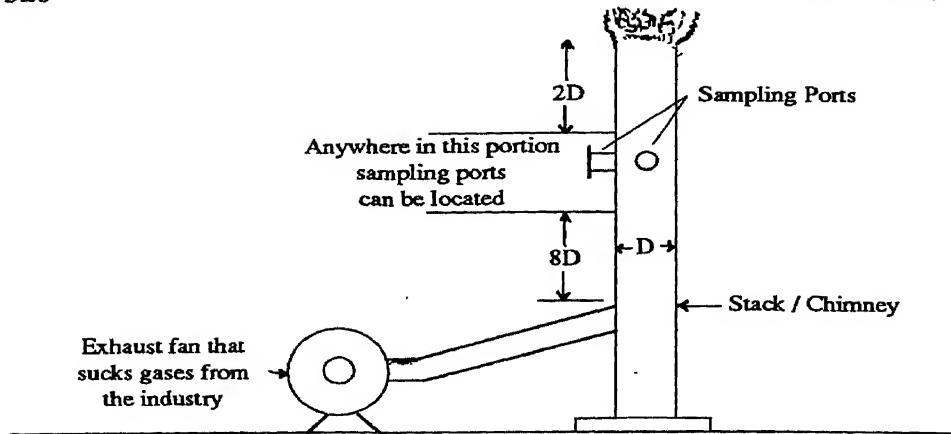


Fig. 15.2 Location of Sampling Ports

The size of sampling port may be made in the range of 7-10 cm in diameter. A blind flange may be riveted so that the opening may be closed during the non-sampling period. The gas stream in a stack is normally under turbulent flow conditions and any flow disturbance would cause non-uniform and unstable gas flow profiles and non-uniform particle concentration patterns. However, in some stacks, it is not always possible to ensure uniform flow and concentration patterns and hence, multiple samples are required to obtain a representative sample. Traverse points have to be located to achieve this. These points, of two sets, 90° apart, are taken in the same plane for circular stacks. The number of traverse points and their distance from inner wall of stack may be found from table 15.8 and table 15.9 respectively.

TABLE 15.8 MINIMUM NUMBER OF TRAVERSE POINTS REQUIRED

Inner diameter of stack, m	No. of points
$D < 0.3$	4
$0.3 < D < 0.6$	8
$0.6 < D < 1.2$	12
$1.2 < D < 2.4$	20
$2.4 < D < 5$	32

In circular stacks, traverse points are located at the centre of equal annular areas across two perpendicular diameters as shown in figure 15.1. While fixing the traverse points, the distances are taken from the inside wall of the stack. Under no circumstances, the traverse point be selected within 25 mm from the inside wall of the stack. In case of rectangular stacks, the sampling port is located by calculating the equivalent diameter according to the following equation.

TABLE 15.9 LOCATION OF TRAVERSE POINTS IN CIRCULAR STACKS

Traverse point number on a diameter	Number of traverse points on a diameter														
	4	6	8	10	12	14	16	18	20	22	24				
1	6.7	4.4	3.3	2.5	2.1	1.8	1.6	1.4	1.3	1.2	1.1				
2	25.0	14.7	10.5	8.2	6.7	5.7	4.9	4.4	3.9	3.5	3.2				
3	75.0	29.5	19.4	14.6	11.8	9.9	8.5	7.5	6.7	6.0	5.5				
4	93.3	70.5	32.3	22.6	17.7	14.6	12.5	10.9	9.7	8.7	7.9				
5		85.3	67.7	34.2	25.0	20.1	16.9	14.6	12.9	11.6	10.5				
6		95.6	80.6	65.8	35.5	26.9	22.0	18.8	16.5	14.6	13.2				
7			89.5	77.4	64.5	36.6	28.3	23.6	20.4	18.0	16.1				
8				96.7	85.4	75.0	63.4	37.5	29.6	25.0	21.8	19.4			
9					91.8	82.3	73.1	62.5	38.2	30.6	26.1	23.0			
10						97.5	88.2	79.9	71.7	61.8	38.8	31.5	27.2		
11							93.3	85.4	78.0	70.4	61.2	39.3	32.3		
12								97.9	90.1	83.1	76.4	69.4	60.7	39.8	
13									94.3	87.5	81.2	75.0	68.5	60.2	
14										98.2	91.5	85.4	79.6	73.9	67.7
15											95.1	89.1	83.5	78.2	72.8
16											98.4	92.5	87.1	82.0	77.0
17												95.6	90.3	85.4	80.6
18												98.6	93.3	88.4	83.9
19													96.1	91.3	86.8
20													98.7	94.0	89.5
21														96.5	92.1
22														98.9	94.5
23														96.8	
24														98.9	

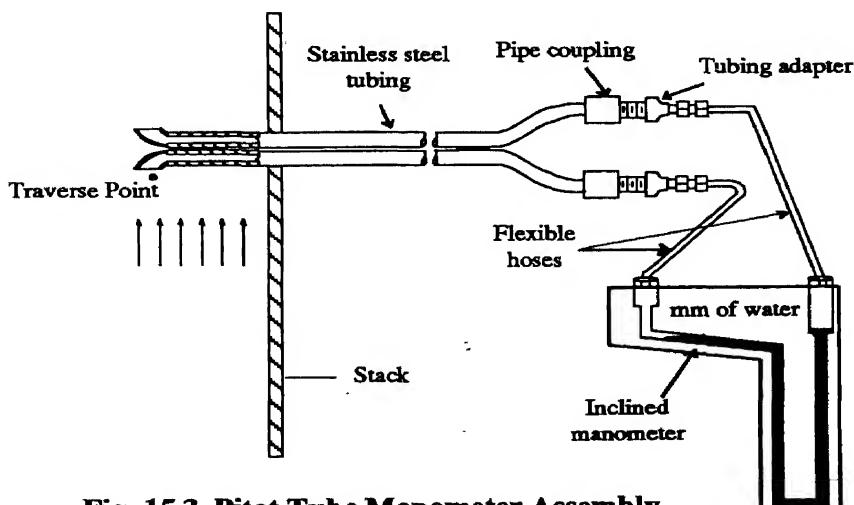


Fig. 15.3 Pitot Tube Manometer Assembly

$$Deq = \frac{4 \times \text{Cross-sectional area of flow}}{\text{Wetted perimeter}} = \frac{2LW}{L+W}$$

The area is divided into 12 to 25 equal parts and the centres of each are fixed. The traverse points are located at the centres of rectangles as shown in figure 15.1. For proper sampling a minimum of 9 traverse points should be selected.

Sampling Train

Stack sampling is carried out by diverting a part of the gas stream through a sampling train. A general arrangement is shown in figure 15.4.

The sampling train comprises of the following essential parts:

1. Nozzle of various sizes (1/4" to 1/2")
2. Sampling probe
3. An efficient collector for removing the particulates from the gas sample.
4. Cooling and or gas collector
5. Gas flow meter (measuring the total volume of gas filtered)
6. A vacuum pump for drawing the gas through sampling nozzle and filter

Nozzle: Nozzle of pre determined and definite diameter should be used to extract a uniform sample of gas and particulates. The nozzle at the end of the probe is normally sharp and tapered and is made of stainless steel with glass or teflon lining. The minimum internal diameter recommended is 7 mm. The size may increase (diameter) depending upon the collection equipment, the velocity in the flue and amount (mass) of sample required.

Sampling Probe: It is made of stainless steel and contains nozzle, thimble holder and a long stainless steel tube which is connected to a flexible hose. For sampling hot gases whose temperatures are above 400°C, these probes are provided with a circulating coolant system to prevent combustion of particulate and to prevent the temperatures from exceeding the maximum allowable temperatures of filtration materials.

Collection Media: The collection media for the particulates will be the thimbles (filter media). For the gases, it is the absorption liquids such as diluted H₂O₂ for SO₂ and diluted NaOH for NOx.

Condenser: The condenser equipped with a dial thermometer should have sufficient storage capacity to hold the liquid required for analysis of sample.

Gas Flow Meter: Dry gas meter attached with temperature and vacuum gauge is used for measuring the sampled gas. The vacuum and the temperature gauges give the measuring conditions of sampled gas. A calibrated rotameter may be used in conjunction with dry gas meter to

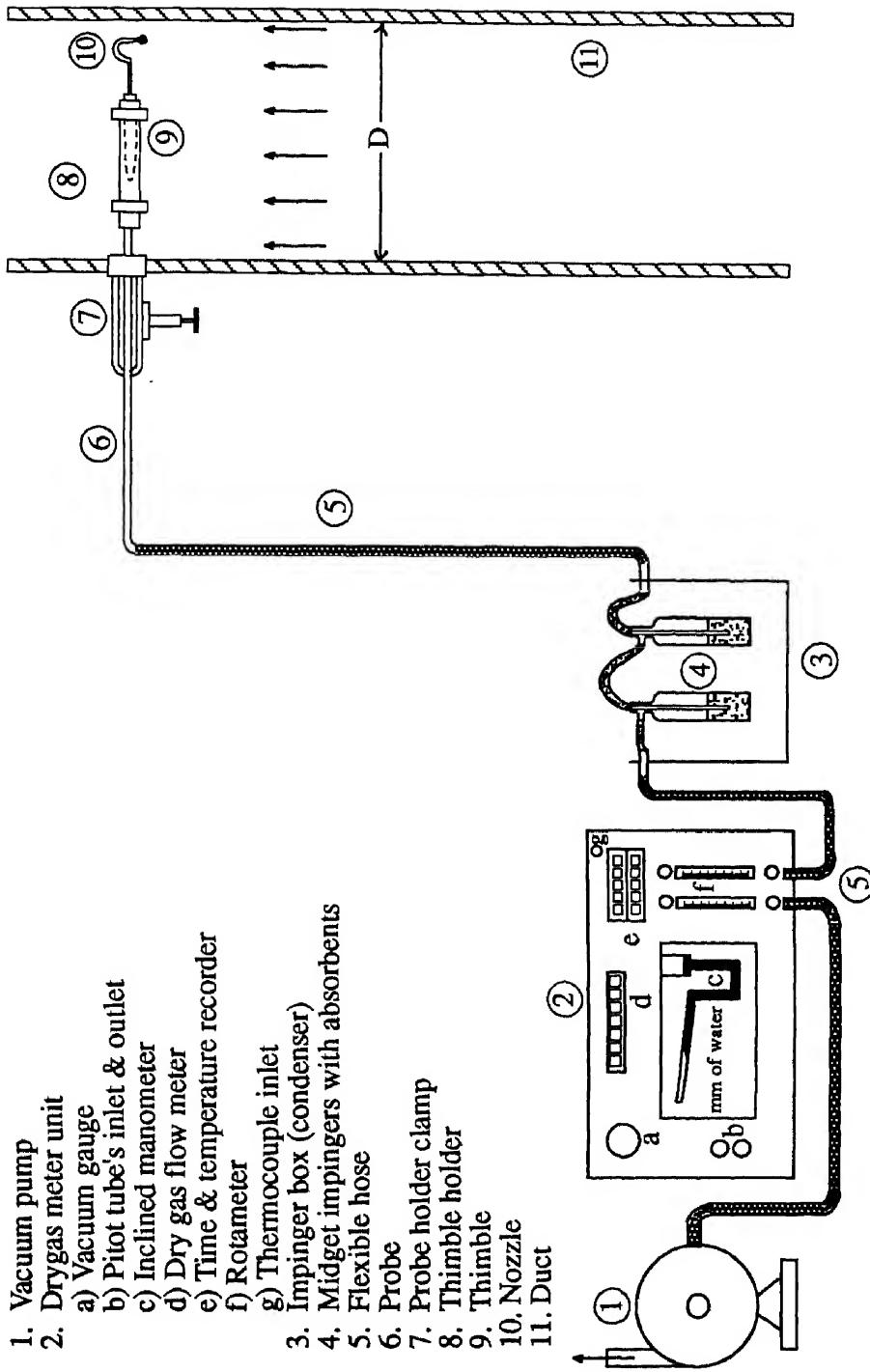


Fig. 15.4 Sampling Train for Stack Monitoring

provide essentially instantaneous flow data for maintaining isokinetic flow at the nozzle.

Vacuum Pump: It consists of a blower, a pump or an ejector to include gas flow through the sampling train. It is necessary to overcome the resistance in the sampling train itself and also the negative pressure present in the flue gas stream. The vacuum pump used should have adequate capacity to provide the desired sample volume rate against total resistance. A valve or other suitable means of control to adjust to the proper flow rate is used. An explosion proof provision will be provided for the pump in plant areas where explosion hazards exist.

Isokinetic Sampling: The determination of the particulate concentration consists essentially of sampling isokinetically a measured amount of gas from the flue and separating the particles from the gas. To obtain a representative sample for analysis of particulates the sampling should be carried out isokinetically, that is, the kinetic energy of the gas stream in the stack should be equal to kinetic energy of the gas stream through the sampling nozzle. To allow for non-uniformity of distribution, samples should be taken at pre-selected number of stated positions (known as traverse points) in the stack cross-sections.

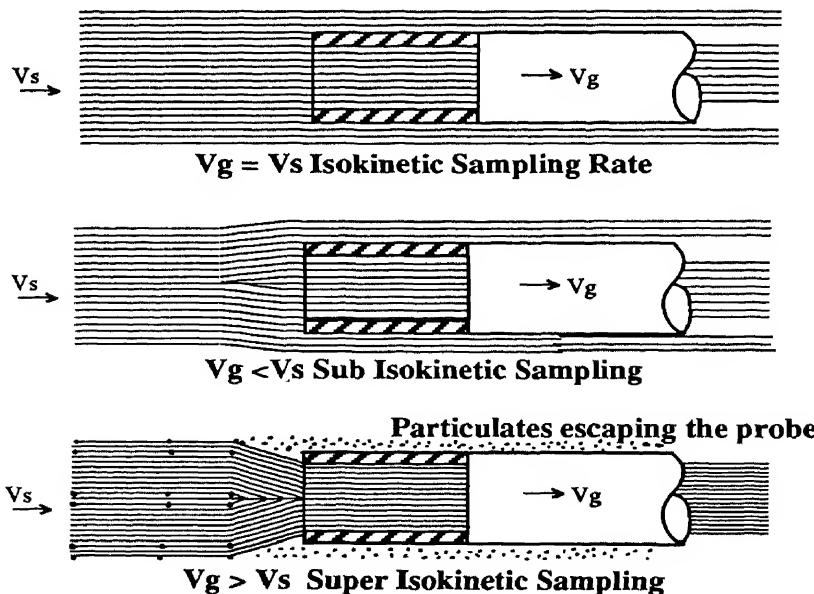


Fig. 15.5 Isokinetic Sampling of Particulates

When a sharp - edged probe is introduced into a stream the flow pattern around the probe may be represented as in the case of a simple pitot tube. The velocity inside the probe is zero and the pressure at the tip of the probe becomes equal to the stagnation pressure.

Depending upon the gas velocity and free stream velocity also the isokinetic sampling can be carried out. If gas velocity (V_g) is less than the free stream velocity (V_s) inside the probe, then the sampling is sub isokinetic. In this case the static pressure at the tip of the probe is greater than the free stream static pressure at the same cross section.

In super isokinetic sampling, the sampling velocity (V_g) is greater than the free stream velocity (V_s). Here the static pressure at the tip of the probe is less than the free stream pressure and too much gas will be sampled in proportion to the probe area. The flow pattern in front of the probe becomes very complicated, when gas stream contains particulate matter. The particles of size $3.5 \mu\text{m}$ or greater have sufficient inertia so that particle-motion may deviate significantly from the gas flow stream - line pattern. In such case, particles are selectively drawn into the probe in a size distribution different from that existing in the duct or flue. It has been observed that if sampling velocity (V_g) is greater than their isokinetic rate (V_s), the sampling will have a lower mass concentration of particulate material than the main stream. Similarly, if the sampling velocity is less than isokinetic rate, the particulate sample has a higher mass concentration than actually present. Thus, isokinetic sampling is essential for collecting particulates. However, for collecting gases it is not necessary. Isokinetic sampling can be achieved by computing the point velocity of the free stream with a pitot tube located as near to the sampling probe as possible without interfering with the free stream and then adjusting the sampling velocity. In this case, rapid adjustment of sampling is required and pitot tube readings and stack temperatures are corrected to equivalent orifice pressure differentials to maintain isokinetic sampling velocities.

Determination of Stack Characteristics

Temperature: The stack gas temperatures are measured by using thermocouple sensor at all pre determined traverse points across the cross-section of the stack. The gas temperature in the flue can be measured by standard mercury thermometer, dial thermometer or thermocouple-pyrometer depending on temperature. If possible, temperature and velocity traverses are taken simultaneously. If there is frequent variation of the gas temperature with time due to process changes, continuous recording of the temperature should be attempted. While measuring temperature, care should be taken in selecting the probe as follows.

Type of probe	Temp. range, °C
Chromel/Alumel	150 to 1250
Copper/Constantan	150 to 350
Iron/Constantan	115 to 1000
Platinum/Rhodium	0 to 1500

Static Pressure: Static pressure can be measured by connecting the static pressure tip of a standard pitot tube to a manometer. If high static pressure is exerted a vertical U-tube mercury filled manometer is used. The manometer should be calibrated in mm of water. The absolute pressure in the flue is equal to the atmospheric pressure plus or minus the static pressure in the flue depending on whether it is under vacuum or pressure.

$$P_u = B_a + P_s \text{, where}$$

$$P_u = \text{Absolute stack pressure in mm Hg}$$

$$B_a = \text{Barometric pressure in mm Hg}$$

$$P_s = \text{Static pressure in stack in mm Hg}$$

The static pressure can also be measured by inserting an inverted piezometer in a beaker of water. If 'h' is the height of water surface in the piezometer above water surface in beaker then the suction pressure inside is 'h' mm of water.

Velocity: The accurate determination of the gas velocity is one of the most important measurement for both sampling rate and total gas flow. Average velocity in the flue is determined by measuring velocity at separate points (i.e. traverse points) and taking arithmetic average of the values.

The standard S-type pitot tube in combination with a differential manometer is the most widely used instrument for the measurement of stack gas velocity. The pitot tube connected to an inclined manometer is placed in the stack with one opening facing upstream and other facing downstream as shown in figure 15.3. The pressure difference read on the manometer in mm of water is equal to the velocity head. While taking the readings, the pitot tube should always point directly into the flow of gas. The central axis of the tube should not exceed 10° inclined to the axis of the chimney.

When the gas velocity is less than 2 m/s, the velocity head is too low to permit accurate measurements with standard inclined manometers. In this case, ultra sensitive micro manometers are used on which the pressures to the nearest 0.025 mm of water can be read or a thermo anemometer of hot wire type are used. But, their use is limited to clear gas streams only. Digital cup type anemometers also can be used to measure velocity provided the temperature of flue gas is less than about 60°C.

Velocity of flue gases at each traverse point can be calculated by using the formula derived for velocity in pitot tube using Bernoulli's theorem.

$V_s = C_p \sqrt{2gh}$ ($S_m/S-1$) where S_m and S are the specific gravities of manometric liquid and gas at stack temperature. It is modified as follows:

$$V_s = K_p \cdot C_p \cdot \left[\frac{T_s \times H}{M \times P_u} \right]^{1/2} \quad \text{where}$$

V_s = flue gas velocity in m/s

K_p = conversion factor = 33.5

C_p = pitot tube coefficient (generally 0.96)

T_s = stack temperature in °K

H = pressure difference measured with pitot tube in mm of water.

M = molecular weight of stack gas measured with the help of Orsat apparatus (may be taken as 30)

P_u = absolute pressure in stack calculated by the equation, $P_u = B_a + P_s$

Gas flow rate and emission rate: The gas flow rate, Q is given by

$$Q \text{ m}^3/\text{sec} = \text{velocity, m/sec} \times \text{area of stack} (\pi D^2/4) \text{ m}^2$$

The emission rate of a pollutant, E in kg/hr is given by

$E, \text{kg/hr} = \text{gas flow rate, m}^3/\text{hr} \times \text{concentration of pollutant, kg/m}^3$

Stack Monitoring Procedure: Stack monitoring is to be executed carefully in the following manner.

1. The sampling port is to be located at 8 diameters from inlet to stack and 2 diameters from exit of stack. It should of size 7 to 10 cm and a strong platform is to be constructed about 1m below the sampling ports.
2. If the above conditions are satisfied, the stack monitoring equipment containing thermo-couple, pitot tube, dry gas meter, impinger box, vacuum pump etc. will be shifted to the platform.
3. Insert the thermo-couple into the stack and record the temperature of gas.
4. Insert the pitot tube upside down and find the static pressure of gas as explained earlier.
5. The inner diameter of stack is noted and the number of traverse points are found. Their locations may be marked on the pitot tube. The inclined manometer reading is noted, the velocity, V_s at each traverse point is calculated by using the formula and the average velocity is found.

$$V_s = K_p \cdot C_p \cdot \left[\frac{(T_s \cdot H)}{M \cdot P_u} \right]^{1/2}$$

5. The gas flow rate through the stack is computed by multiplying the average velocity with area. $Q = Vs \times \pi D^2/4$
7. The different components of the sampling train are assembled as in figure 15.4. If the temperature is more than 150°C, thimble should be of glass fibre and if it is less than 150°C, a cellulose thimble is sufficient.
8. Procedure for particulate sampling: For accurate estimation of particulates (SPM), iso kinetic sampling is essential. Iso kinetic sampling means that the sample is withdrawn at the same velocity as that of stack velocity at the particular traverse point. The basic requirement for it is selection of appropriate nozzle diameter which can maintain about 10-30 LPM of gas flow rate. The sampling rate at meter can be calculated as follows.

$$Q_m = Vs \cdot An \cdot T_m / [(P_{bar} - P_s) / (P_{bar} - P_m)] \times [V_m / (V_m + V_v)] \text{ where}$$

Q_m = flow rate at rotameter

V_s = velocity of flue gas at sampling point, m/s

A_n = area of sampling nozzle, sq.m.

T_m = absolute meter temperature, °K

T_s = absolute stack gas temperature, °K

P_s = stack gas pressure, mm of Hg

P_{bar} = barometric pressure, mm of Hg

P_m = suction at meter, mm of Hg

V_m = volume of gas sampled at meter conditions, m^3

V_v = equivalent vapour volume of condensate at meter conditions, m^3

After proper nozzle and filtering medium have been selected assemble the sample train as shown in figure. The assembly comprises of the nozzle, filter holder, sampling probe, condenser, dry gas meter, rotameter and finally a vacuum pump. Mark the sampling probe (considering nozzle and filter holder also) as explained earlier for locating the traverse points.

The preweighed thimble is placed in clean filter holder and tightened securely. Mark the end of sampling probe to indicate the nozzle tip direction. The sampling train should be checked for leaks by sealing the nozzle tip and switch on the pump or ejector with the control valve shut. The vacuum should hold steady if there are no leaks.

When the equipment is ready in all respects, record the initial dry gas meter reading and push the sampling probe carefully and properly into the stack and start the vacuum pump. The flow rate should be adjusted to the isokinetic flow rate by throttling the control valve fitted to the rotameter. As the test proceeds, dust packing in the thimble will increase the amount of suction

required to maintain the proper meter rate and the valves should be adjusted accordingly. Record the meter volume, pressure and temperature at 5 minute intervals during the test. When sampling at one point has been completed, move the sampler to the next point as quickly as possible. The total sampling duration is continued for atleast one hour or minimum of 1.6m^3 gas collection. If possible carry out sampling for atleast 10 minutes at each traverse point.

At the completion of test, close the control valve, turn the sampler so that the sampling nozzle is facing downstream and record the final gas volume and time. The rubber tubes should not be disconnected until the sample has been withdrawn from the flue, because if it is under considerable suction, a reverse flow would be set up through the thimble which might cause some of the material to be drawn out through the sampling nozzle and lost.

After sampler has cooled brush down the dust on the inside of the nozzle carefully into the thimble using a small brush and then weigh the thimble carefully. The difference of the weights gives the dust collected for the given volume of gas. Particulate matter, in mg/m^3

$$= \text{Weight of dust collected, mg} + \text{Volume of gas collected, m}^3$$

The values converted to normal conditions (i.e. 25°C & 760 mm of Hg) are expressed in mg / Nm^3 . Total emission rate can be calculated as:

Dust emission rate, $\text{mg/hr} = \text{dust concentration, mg/m}^3 \times \text{flow rate, m}^3/\text{hr}$

Safety considerations: Stack sampling is a difficult process as an equipment weighing about 50 - 100 kg is to be lifted upto a small platform, sometimes of height more than 50m. The stack is uninsulated and the location is exposed to atmosphere. Some of the safety considerations to be taken are:

- Respiratory equipments are to be provided while sampling toxic gases.
- An explosion proof electrical equipment is to be provided.
- Long sleeves, trousers and asbestos gloves are to be worn by sampling personnel.

Gaseous sampling: Gaseous sampling from stack emissions is similar to that employed in sampling of particulate matter. However, in this case, the sampling is much easier because it is not necessary to sample at isokinetic conditions. The sample can be withdrawn from the stack at a constant rate independent of the flow rate in the stack.

The sampling must have a trap i.e. filtering media on upstream of the collecting system to prevent down stream line plugging as well as to minimize

losses of gaseous pollutants due to reaction with particulates on cooling. It is useful to point the probe downstream to minimize the amount of particulates that are pulled into the sampling train.

Stainless steel is usually an acceptable probe material and in some special applications teflon is preferred to avoid reaction with the gas to be measured. If moisture is present in stack gases it could get condensed in the sampling line and dissolve the gaseous constituents. To prevent the losses resulting from condensation, the sampling line may be heated.

A known volume of the gas from the stack is sucked by the vacuum pump through a series of absorbents which remove the constituent gases selectively. The gas flow rate is measured with a flow meter in LPM. Normally sampling range is from half an hour to 8 hours depending upon the expected concentration of the pollutant or as shown below.

Period of sampling	Rate of sampling
30 min	2 LPM
1 hour	1 LPM
1-4 hours	0.5 LPM
8 hours	0.2 LPM

The gases are analysed in the laboratory and their concentrations in ppm or mg/m³ are found. The stack gas emission rate in mg/hr is equal to

$$\text{gas flow rate in m}^3/\text{hr} \times \text{gas concentration in mg / m}^3$$

15.8 AMBIENT AIR QUALITY MONITORING

The ambient air quality in cities, near industrial establishments, roads etc., has to be assessed for knowing the level of air pollution. This is a basic requirement for policy makers, industrial managers, research workers and others to decide various alternatives to be adopted to suit the local conditions. One of the major air pollutants to be considered as primary pollutant is suspended particulate matter (SPM), commonly called as dust.

Apart from SPM other hazardous gases like SO₂, NOx etc. are also present in the ambient air which if present in large concentrations can cause several problems to man, material and vegetation. Assessment of ambient air quality is very important because any future planning of industrial and residential areas can be done carefully based on this assessment knowledge only. The sampling should be carried out long enough and at a rate that allows collection of an analytically measurable and prominently representative sample. High volume air sampler is used to collect particulate matter as well as gaseous pollutants such as NOx, SO₂ etc.

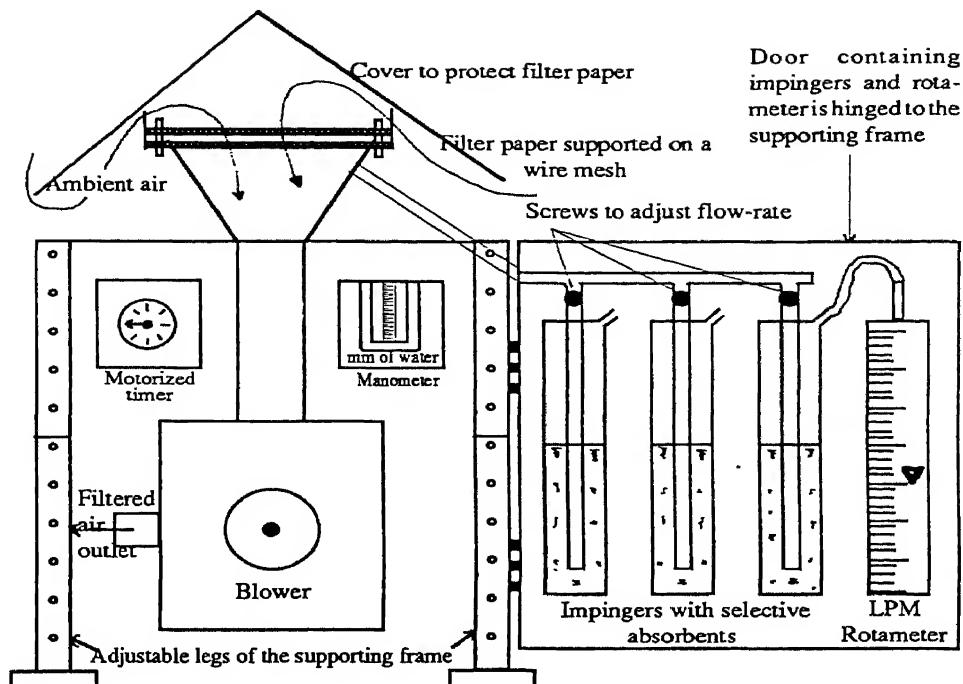


Fig. 15.6 A Typical High Volume Air Sampler

Location of Stations

One of the objectives which should be given profound importance in any air sampling exercise is trying to obtain a genuine and representative sample. Hence the site of sampling should be able to meet all the conditions which the particular study demands. The necessary number of sampling stations, and their locations depend on several factors including the objectives of the programme, the size of the study area, the proximity of sources of pollution, topographical feature and weather, and the fact that concentrations of pollutants vary with altitude. For example, the results shown by sampling on the roofs of tall buildings may differ substantially from conditions at ground or breathing level.

Duration of Sampling Period

Fixing of duration of sampling is one of the important decisions concerning actual sampling procedure. Duration of sampling should be selected in such a way that the information required for each specific problem can be provided. Some of the important factors governing the choice of sampling

period are nature of the compound under study and its stability to oxidation, light or other factors such as sensitivity, accuracy and precision of the analytical method to be used for the measurement of pollutant. Depending upon the extent of surveys, the frequency of sampling is fixed and generally a 24 hour sampling period is prescribed to determine the average pollutant concentration.

SPM Sampling

Particulate pollutants in the atmosphere are grouped generally into those that settle out due to the force of gravity and those that remain suspended as aerosols. Large particles of size greater than $10\text{ }\mu\text{m}$ diameter can be collected using sedimentation techniques, whereas suspended particles of smaller size are collected by more sophisticated techniques like filtration, impingement and electrostatic and thermal precipitation.

Out of these, high volume filtration method is popular for measurement of the mass concentration of SPM smaller than $10\text{ }\mu\text{m}$. The sampler is universally known as "Hi-Vol".

A known volume of air is sucked by a high speed blower through a fine filter paper free from defects like pinholes, external damage, particles etc. Such filter paper is folded twice by keeping the rough side facing up and then dried in a hot air oven at (105°C) for about 30 minutes. It is then cooled and weighed. The pre weighed filter paper should be placed in the sampler keeping rough surface upwards, only at the site just before starting the high-volume sampler in order to avoid the deposition of dust and damage during transportation.

The sampling is done for 24 hours and during this time over 2000 m^3 of air is sucked through the filter. Keeping the rotameter reading constant at 2 LPM the manometer reading is recorded every hour throughout the sampling period. For each manometric reading ($H = H_1 - H_2$, in mm of H_2O) the corresponding flow rate in m^3/min is found out from the calibration curve supplied by the equipment manufacturer and the average flow-rate is found.

The filter paper, after sampling, is removed gently and transferred carefully to the laboratory. Final weight is taken after drying at 105°C for half an hour.

Gaseous Sampling

There are several methods available for collection of gaseous air pollutants such as SO_2 and NO_x from ambient air. The most common methods are grab sampling and absorption in liquid. Absorption separates the desired pollutants from air either through direct solubility in the absorbing media or by chemical reaction. Many different types of collectors are available for high

degree of gas liquid contact.

Mostly, the midget impinger is used as the collector in which the gas stream impinges at a high velocity onto a flat surface providing good contact between gas and liquid. The absorbing solutions used for SO_2 and NO_x are H_2O_2 (3%) and NaOH (4 g/lit) respectively. These solutions are bubbled at a rate of 2 LPM for 4 hrs. These solutions, after sampling, are taken to laboratory for analysis.

15.8 AMBIENT AIR QUALITY SURVEY

A technical air pollution study of a community or industrial city usually requires considerable number of personnel and large amounts of laboratory and field equipment for a year or longer. These studies are essential to determine the origin, magnitude, and causes of air pollution and its effects on vegetation, public health and property and to recommend effective action for control. Although considerable progress has been made in this type of research, there is still insufficient understanding of the processes involved in the formation, accumulation, diffusion, dispersion and decay of air pollutants.

When a general air pollution survey is to be undertaken in a city, the following factors should be taken into consideration.

1. Generally, air pollution will be maximum during the winter months (October to March) and hence observations should be made particularly during this period. The complete duration of survey should be a minimum of two to three years.
2. The minimum number of sampling stations selected should be six. While selecting the stations various factors like population density, concentration of industries and intensity of traffic should be taken into account. An additional station set up a few kilometers outside the city limits in semi-rural surroundings helps in comparing the pollution levels at the stations within the city.
3. The air sampling stations should not be located near buildings liable to obstruct free flow of air movements or just close to the source of emission of pollutants to be estimated.
4. The selection of major pollutants for the purpose of the survey depends upon the major industrial plants in the area and other human activities constituting the pollution. Generally, in urban areas, the important pollutants are SO_2 , NO_2 , H_2S , oxidants and dust. Depending on the type of industries in the specific areas, other pollutants like HC, mercaptans, mercury, ammonia, lead, chlorine etc. also may be included.

5. After sampling stations have been selected, the sampling instruments should be installed. In addition to this, some meteorological instruments should also be installed for measurement of meteorological variables such as wind speed, wind direction, environmental lapse rate, relative humidity etc.
6. The cumulative samples are collected over a period of one month and these samples are used for measurement of dust and SO_x . The short-term samples are collected for smaller periods during different times of the day i.e. morning, noon, evening and night. In this manner, atleast two sets of samples taken on two days every month from each of the station, are collected and analysed over a period of 2-3 years to get representative data. From such data, the average daily and monthly concentrations and the maximum concentration over a period can be found out at the end of the survey.
7. The daily average concentration is determined either by continuous sampling or by intermittent sampling. In case of intermittent sampling, sampling is done every two or four hours. For this sampling the preferable timing is between 6.00 AM and 10.00 AM because the air turbulence is low during this period. If the survey is to determine the pollutants which irritate the mucous membranes of the eye or respiratory tract, the short-time samples (20 minutes) are usually taken once in a day during the period when the air pollution is likely to be maximum.

15.9 SMOKE MONITORING BY RINGLEMANN-CHARTS

Ringlemann charts are used for estimating the density of the smoke emerging from a stack. The Ringlemann scale consists of a black rectangular pattern super imposed on a white card. The lines are of definite width and spacing such that in different sections of the card the ratio of the black to white changes gradually. Shades of gray vary by five equal steps between white and black. The details about the width of black lines, width of white spaces, and percentage of black is given in table 15.10.

Professor Ringlemann devised this visual assessment method for smoke emissions. Ringlemann scale is a visual measure of the quality of the flue gas as it leaves the chimney. However it is not only dependent on the optical density of the flue gas but is also a function of the brightness and colour of the sky immediately behind the chimney plume and other factors such as the colour of the emission.

The chart should be mounted so as to be held firmly without creasing or bending. The portion of any holder adjoining the viewing edge of the chart shall be neutral in colour. It has been found that aluminium is a suitable

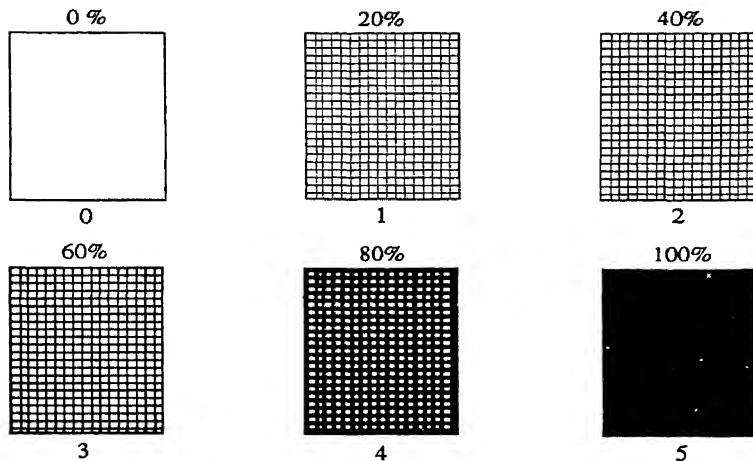


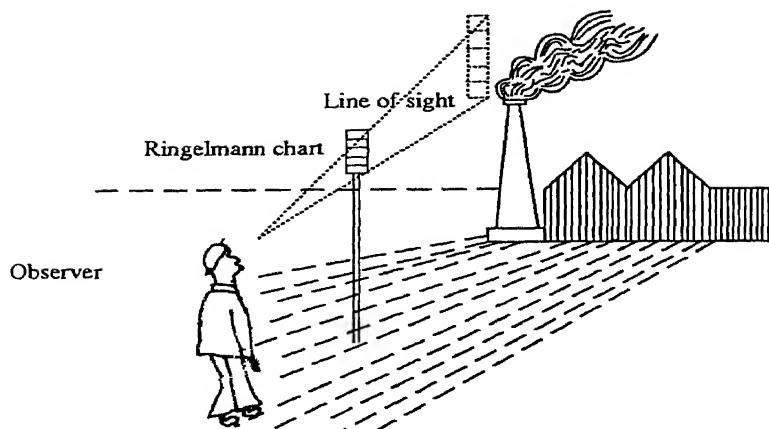
Fig. 15.7 Ringelmann's Smoke Charts

Table 15.10 Spacing of Lines of Ringelmann's Charts

Ringelmann Chart No.	Width of black line (mm)	Width of white space (mm)	Percent black
0	0	All white	0
1	1	9	20
2	2.3	7.7	40
3	3.7	6.3	60
4	5.5	4.5	80
5	All black	0	100

material for this purpose. No protecting cover shall be applied to chart in use. If the chart is attached to a board or other support, the fixing medium should not impair the luminance of the working surface of the chart.

Method of Use: The chart shall be used under day light conditions and held or fixed facing the observer in a vertical plane as shown in fig 15.8. The chart shall be in line with the top of the chimney and placed so that the chart and the smoke have a similar sky background. The chart should be at a sufficient distance from the observer for the lines to appear to merge until each square forms a uniform shade. For most observers this is about 15m. Observations shall be carried out as far as practicable under conditions of uniform general illumination from the sky. However, if the observations are made with the sun shining, or sky bright, on one side, the bright source of illumination shall be



15.8 Method of using Ringelmann's Chart

approximately at right-angles to the line of vision and not in front or behind the observer. Under hazy conditions, readings shall not be taken at extreme distance as there is a tendency for the readings to be low. It is desirable that the angle of view of the chart and the smoke shall be as low as possible. Observations at a steep angle shall be avoided. The darkness of the smoke at the point while it leaves the chimney shall be compared with the shades of the charts. The number of the shade which appears most closely to match the darkness of the smoke and the corresponding time of duration during which they match are noted. The darkness of smoke which is intermediate between two shades may be estimated to the nearest quarter Ringlemann number in favourable conditions.

The readings obtained are reduced to the total equivalent of No.1 smoke as a standard. The percentage density of the smoke for the entire period of observation is calculated by the following formula.

Percentage smoke density =

$$\frac{\text{Equivalent units of No.1 smoke} \times 0.20}{\text{Number of observations}} \times 100$$

Alternatives to Ringlemann's Charts

The Ringlemann's charts are very simple but are very much subjective. They cannot be used during night time and during cloudy and windy conditions. The use of standard chart generally requires the services of a helper to hold the chart for the observer. The miniature smoke chart has overcome these demerits. Here, everything is same except that the chart is placed at arm's length or at a maximum of 1.5m so that a holder or a person to hold the chart

is avoided. But the values obtained by the miniature smoke chart are not as accurate as those of Ringlemann's smoke charts. Now-a-days photochemical and photographic methods also are used. 'Smoke scope' is another instrument that finds smoke density based on principles of optics.

Problem 15.1: Find the % smoke density from the following observations recorded for one hour at every half minute interval for 2 hours on Ringlemann's charts.

Data given :

- 10 Units of No.5
- 6 Units of No.4
- 25 Units of No.3
- 70 Units of No.2
- 6 Units of No.1
- 3 Units of No.0

Answer : The total equivalent No.1 smoke units are:

$$(10 \times 5) + (6 \times 4) + (25 \times 3) + (70 \times 2) + (6 \times 1) + 0 = 295$$

Total number of observations = 120

$$\begin{aligned} \% \text{ smoke density} &= \frac{\text{Equivalent of No.1 Smoke} \times 0.20}{\text{No. of observations}} \times 100 \\ &= \frac{295 \times 0.20}{120} \times 100 = 48.3\% \end{aligned}$$



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