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Air Pollution Control Lectures

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CHAPTER 2

Air Pollution: Sources and Effects

2.1 DEFINITION AND SCALES OF CONCENTRATION

Air pollution may be defined as any atmospheric condition in which certain substances are present in such concentrations that they can produce undesirable effects on man and his environment. These substances include gases (sulphur oxides, nitrogen oxides, carbon monoxide, hydrocarbons etc.), particulate matter (smoke, dust, fumes, aerosols), radioactive materials and many others. Most of these substances are naturally present in the atmosphere in low (background) concentrations and are usually considered to be harmless. The background concentrations of various components of dry air near sea level and their estimated residence times are given in Table 2.1. Thus, a particular substance can be considered an air pollutant only when its concentration is relatively high compared with the background value and causes adverse effects. For example, sulphur dioxide, if present in the atmosphere in concentrations greater than the background value of 2×10^{-4} ppm and causes measurable effects on humans, animals, plants, or property, then only it is classified as an air pollutant.

The concentration of a pollutant in the atmosphere can be expressed in a number of ways involving units of weights or volume per unit weight or volume of air. Four concentrations scales are generally used to describe the concentrations of either gaseous or particulate pollutants.

The first is the mass concentration, ω_p, defined as the ratio of the mass of pollutant to the mass of air plus mass of pollutant:

$$\omega_p = \frac{m_p}{m_a + m_p} \qquad \text{...(2.1)}$$

where m_p is the mass of the pollutant and m_a is the mass of pure air in a given volume of air-pollutant mixture. The second concentration scale is the volume concentration, y_p, defined as the ratio of the volume of pollutant to the volume of air plus volume of pollutant:

$$y_p = \frac{v_p}{v_a + v_p} \qquad \text{...(2.2)}$$

The third concentration scale is the volume concentration in parts per million (ppm), y_{ppm}:

$$y_{\text{ppm}} = y_p \times 10^6 \qquad \text{...(2.3)}$$

Table 2.1 Composition of clean, dry atmospheric air

Component	*Concentration* (ppm)*	*Estimated residence time (ref.1)*
Nitrogen	78.09×10^4	Continuous
Oxygen	20.94×10^4	Continuous
Argon	93×10^2	Continuous
Carbon dioxide	3.2×10^2	2-4 years
Neon	18	Continuous
Helium	5.2	~2 million years
Krypton	1.0	Continuous
Xenon	8×10^{-2}	Continuous
Carbon monoxide	1×10^{-1}	0.5 years
Methane	1.2	4-7 years
Nitrous oxide	25×10^{-2}	4 years
Nitric oxide	6×10^{-4}	5 days
Ammonia	6×10^{-4}	7 days
Hydrogen sulphide	2×10^{-4}	2 days
Sulphur dioxide	2×10^{-4}	4 days
Hydrogen	5×10^{-1}	?**
Ozone	2×10^{-2}	~60 days

*Single values for concentrations, instead of ranges of concentrations, are given to indicate order of magnitude, not specific and universally accepted concentrations.

**Little is known about the residence time.

Finally, the fourth concentration scale is the mass-volume concentration, ρ_p, defined as the ratio of the mass of the pollutant to the volume of air and pollutant combined:

$$\rho_p = \frac{m_p}{v_a + v_p} \qquad \text{...(2.4)}$$

The concentration of a pollutant whether it be gaseous or particulate is at present commonly expressed in terms of ρ_p, usually as micrograms of pollutant per cubic metre of air and pollutant combined, (μg/m^3). A number of relationships can be developed among these concentrations, but the conversion between y_{ppm} and ρ_p in μg/m^3 for gaseous pollutants is of special interest. Combining Eqs. (2.2), (2.3) and (2.4) we get,

$$\rho_p = \frac{m_p}{v_p} y_{\text{ppm}} 10^{-6} \qquad \text{...(2.5)}$$

Assuming that the perfect gas law holds for pollutants that are usually formed in the atmosphere, we can express the mass density of the pure component pollutant, m_p / v_p, in units of μg/m^3 as,

$$\frac{m_p}{v_p} = \frac{P\hat{M}_p\left(10^9\right)}{\left(8.314 \times 10^{-2}\right)T} \qquad \text{...(2.6)}$$

where P is the total pressure in bars, $\hat{M}_p$ is the molecular weight of the pollutant, T is the absolute temperature in K, and 8.314×10^{-2} is the value of the universal gas constant expressed in units of m^3-bar/kg mol-K. At the standard temperature (25 °C) and pressure (1.0133 bars), Eq. (2.6) reduces to,

$$\frac{m_p}{v_p} = \frac{\hat{M}_p\left(10^9\right)}{24.45} \qquad \text{...(2.7)}$$

Substituting Eq. (2.7) into Eq. (2.5), we get the relation between ρ_p (μg/m^3) and y_{ppm}:

$$\rho_p = \frac{\hat{M}_p y_{\text{ppm}}\left(10^3\right)}{24.45} \qquad \text{...(2.8)}$$

The constant in the denominator becomes 22.4 at 0 °C and 1 atm pressure.

Example

Carbon monoxide (CO) is present in standard atmospheric air at a concentration of 50 ppm. Compute y_p, ρ_p and ω_p values for the CO concentration in the atmosphere.

Solution

From the statement of the problem, $y_{\text{ppm}} = 50$. The air density at standard condition is 1.185 kg/m^3, and the molecular weight $\hat{M}_p$ is 28. From Eq. (2.3),

$$y_p = y_{\text{ppm}} 10^{-6} = 0.00005$$

From Eq. (2.8), the mass volume concentration, ρ_p, is

$$\rho_p = \frac{\hat{M}_p y_{\text{ppm}}\left(10^3\right)}{24.45} = \frac{28(50)10^3}{24.45}$$

$$= 57.26\left(10^3\right)\mu\text{g/m}^3 = 57.26\left(10^{-6}\right)\text{kg/m}^3$$

The mass concentration, ω_p, can be calculated as follows:
Dividing Eq. (2.1) by (2.2), we have

$$\frac{\omega_p}{y_p} = \frac{m_p}{v_p}\left(\frac{v_a + v_p}{m_a + m_p}\right)$$

But the term $(m_a + m_p / v_a + v_p)$ can be written as

$$\frac{m_a+m_p}{v_a+v_p}=\frac{m_a}{v_a}(1-y_a)+\frac{m_p}{v_p}\cdot y_p$$

Taking the density of air, ρ_a, as equal to m_a/v_a, we get

$$\omega_p=\frac{\left(\frac{m_p}{v_p}\right)y_p}{\rho_a\left(1-y_p\right)+\frac{m_p}{v_p}\cdot y_p}$$

Substituting the relation $\rho_p=\left(\frac{m_p}{v_p}\right)y_p$ in the above equation, we get

$$\omega_p=\frac{\rho_p}{\rho_a\left(1-y_p\right)+\rho_p}$$

Substituting the values of ρ_p, ρ_a and y_p into the above equation, we get the mass concentration,

$$\omega_p=\frac{57.26\left(10^{-6}\right)}{1.185(1-0.00005)+57.26\left(10^{-6}\right)}$$

$$=0.000048$$

2.2 CLASSIFICATION AND PROPERTIES OF AIR POLLUTANTS

2.2.1 Classification

The variety of matter emitted into the atmosphere by natural and anthropogenic sources is so diverse that it is difficult to classify air pollutants neatly. However, usually they are divided into two categories of primary pollutants and secondary pollutants. The primary pollutants are those that are emitted directly from the sources. Typical pollutants included under this category are particulate matter such as ash, smoke, dust, fumes, mist and spray; inorganic gases such as sulphur dioxide, hydrogen sulphide, nitric oxide, ammonia, carbon monoxide, carbon dioxide, and hydrogen fluoride; olefinic and aromatic hydrocarbons; and radioactive compounds. The secondary pollutants are those that are formed in the atmosphere by chemical interactions among primary pollutants and normal atmospheric constituents. Pollutants such as sulphur trioxide, nitrogen dioxide, PAN (peroxyacetyl nitrate), ozone, aldehydes, ketones and various sulphate and nitrate salts are included in this category.

Of the large number of primary pollutants emitted into the atmosphere, only a few are present in sufficient concentrations to be of immediate concern. These are the five major types—particulate matter, sulphur oxides, oxides of nitrogen, carbon monoxide, and hydrocarbons. Carbon dioxide is generally not considered an air pollutant but, because of cide dusts and certain fumes released from chemical plants also contain organic compounds. Hydrocarbons themselves can coalesce into aerosol droplets that constitute one kind of particulate matter. The most harmful components of incomplete combustion are generally grouped as particulate polycyclic organic matter (or PPOM). These materials are derivatives of benz-α-pyrene, a potent carcinogen.

Of all the different types of particulates in the atmosphere, the presence of trace elements such as cadmium, lead, nickel and mercury may constitute the greatest health hazard. Many of the trace metals are toxic and are concentrated in the finest of particulate matter in a variety of combined forms such as oxides, hydroxides, sulphates and nitrates.

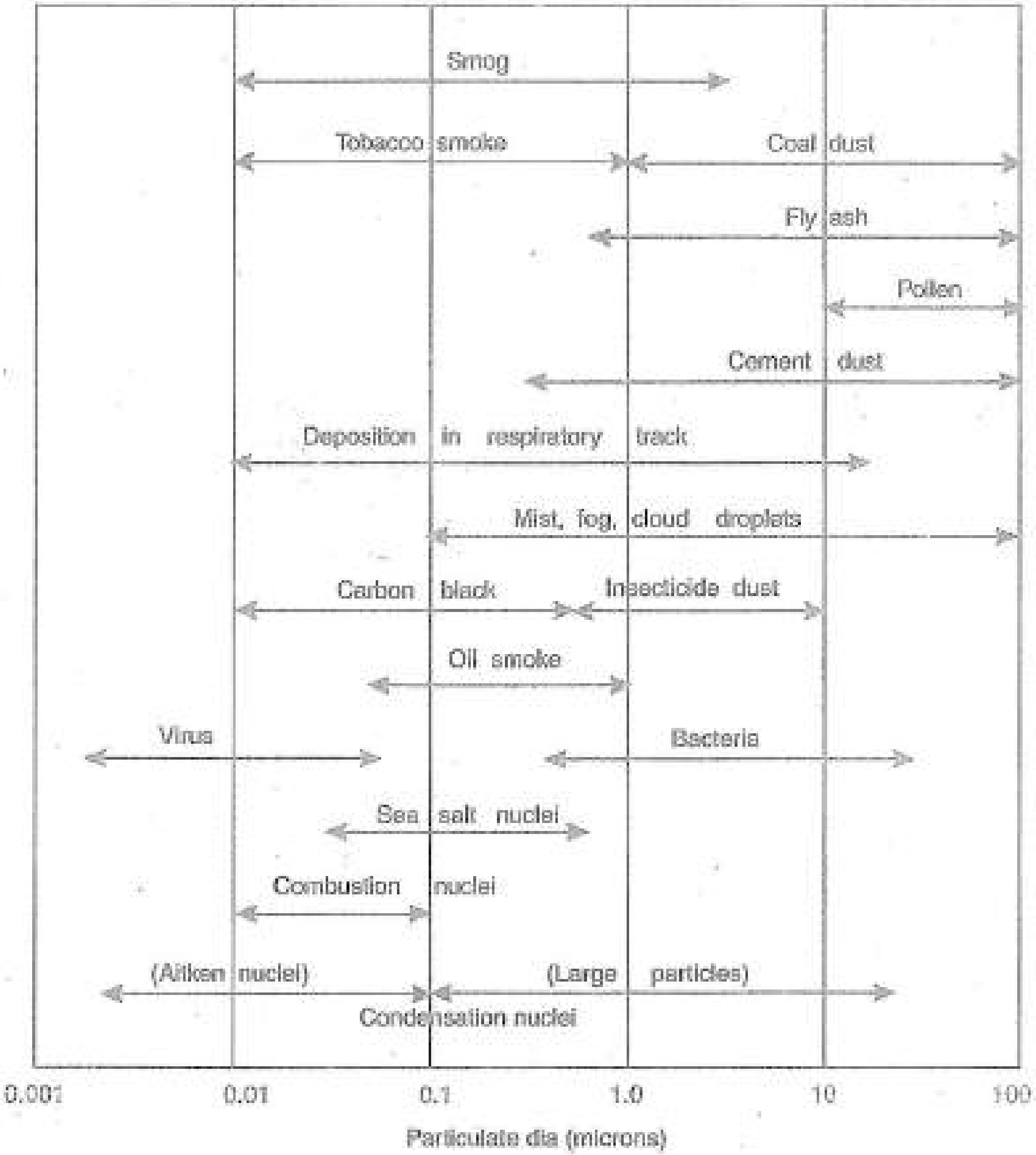


Fig. 2.1 Sizes of atmospheric particulate matter

Oxides of Sulphur

The most important oxide emitted by pollution sources is sulphur dioxide (SO_2). SO_2 is a its increased global background concentration, its influence on global climatic patterns is of great concern. The radioactive pollutants are of specialised nature and they are beyond the scope of this book. The interested reader may refer to Hodges[2].

Secondary pollutants are formed from chemical and photochemical reactions in the atmosphere. The reaction mechanisms and various steps involved in the process are influenced by many factors such as concentration of reactants, the amount of moisture present in the atmosphere, degree of photoactivation, meteorological forces, and local topography.

2.2.2 Properties of Air Pollutants

Particulate Matter

In general the term "particulate" refers to all atmospheric substances that are not gases. They can be suspended droplets or solid particles or mixtures of the two. Particulates can be composed of inert or extremely reactive materials ranging in size from 100 μm down to 0.1 μm and less. The inert materials do not react readily with the environment nor do they exhibit any morphological changes as a result of combustion or any other process, whereas the reactive materials could be further oxidised or may react chemically with the environment.

The classification of various particulates may be made as follows:

Dust: It contains particles of the size ranging from 1 to 200 μm. These are formed by natural disintegration of rock and soil or by the mechanical processes of grinding and spraying. They have large settling velocities and are removed from the air by gravity and other inertial processes. Fine dust particles act as centres of catalysis for many of the chemical reactions taking place in the atmosphere.

Smoke: It contains fine particles of the size ranging from 0.01 to 1 μm which can be liquid or solid, and are formed by combustion or other chemical processes. Smoke may have different colours depending on the nature of material burnt.

Fumes: These are solid particles of the size ranging from 0.1 to 1 μm and are normally released from chemical or metallurgical processes.

Mist: It is made up of liquid droplets generally smaller than 10 μm, which are formed by condensation in the atmosphere or are released from industrial operations.

Fog: It is the mist in which the liquid is water and is sufficiently dense to obscure vision.

Aerosol: Under this category are included all air-borne suspensions either solid or liquid; these are generally smaller than 1 μm.

Particles in the size range 1-10 μm have measurable settling velocities but are readily stirred by air movements, whereas particles of size 0.1-1 μm have small settling velocities. Those below 0.1 μm, a submicroscopic size found in urban air, undergo random Brownian motion resulting from collisions among individual molecules. Fig. 2.1 compares the sizes of atmospheric particulates from various sources. Most particulates in urban air have sizes in the range 0.1-10 μm. The finest and the smallest particles are the ones which cause significant damage to health.

The chemical composition of particulate pollutants varies over a wide range. The actual composition is very much dependent upon the origin of the particulate. Particles from soils and minerals primarily contain calcium, aluminium and silicon compounds. Smoke from combustion of coal, oil, wood, and solid waste contains many organic compounds. Insecticolourless gas with a characteristic, sharp, pungent odour. It is moderately soluble in water (11.3 g/100 ml) forming weakly acidic sulphurous acid (H_2SO_3). It is oxidised slowly in clean air to sulphur trioxide. In a polluted atmosphere, SO_2 reacts photochemically or catalytically with other pollutants or normal atmospheric constituents to form sulphur trioxide, sulphuric acid and salts of sulphuric acid.

Sulphur trioxide (SO_3) is generally emitted along with SO_2, at about 1-5 per cent of the SO_2 concentration. SO_3 rapidly combines with moisture in the atmosphere to form sulphuric acid which has a low dew point. Both SO_2 and SO_3 are relatively quickly washed out of the atmosphere by rain or settle out as aerosols. This is the reason why SO_2 mass in clean dry air is so small compared to annual emissions from anthropogenic sources (Table 2.2).

Table 2.2 Comparison of the amounts of anthropogenic pollutants with the amounts naturally present in dry, clean air

Pollutant	*Amount (millions of tonnes)*	
	Anthropogenic (per year)	*Dry, Clean air*
Particulates	269	–
SO_2	132	2
NO_2	48	8
CO	400	500

Nitrogen Oxides

Of the six or seven oxides of nitrogen, only three—nitrous oxide (N_2O), nitric oxide (NO), and nitrogen dioxide (NO_2)—are formed in any appreciable quantities in the atmosphere. Often NO and NO_2 are analysed together in air and are referred to as NO_x.

Nitrous oxide is a colourless, odourless nontoxic gas present in the natural atmosphere in relatively large concentrations (0.25 ppm). The major source of N_2O in the atmosphere is the biological activity of the soil and there are no significant anthropogenic sources. It has a low reactivity in the lower atmosphere and is generally not considered an air pollutant.

Nitric oxide is a colourless, odourless gas produced largely by fuel combustion. It is oxidised to NO_2 in a polluted atmosphere through photochemical secondary reactions. Nitrogen dioxide is a brown pungent gas with an irritating odour which can be detected at concentrations of about 0.12 ppm. It absorbs sunlight and initiates a series of photochemical reactions. Small concentrations of NO_2 have been detected in the lower stratosphere; NO_2 is probably produced by the oxidation of NO by ozone. Nitrogen dioxide is of major concern as a pollutant; it is emitted by fuel combustion and nitric acid plants.

Carbon Monoxide

It constitutes the single largest pollutant in the urban atmosphere. CO is colourless, odourless, and tasteless, and has a boiling point of –192 °C. It has a strong affinity towards the hemoglobin of the bloodstream and is a dangerous asphyxiant. The rate of oxidation of carbon monoxide to carbon dioxide in the atmosphere seems to be very slow; mixtures of CO and O_2 exposed to sunlight for several years have been found to remain almost unchanged. Carbon monoxide is present in small concentrations (0.1 ppm) in the natural atmosphere and has a residence time of about six months. The main sources of CO in the urban air are smoke and exhaust fumes of many devices burning coal, gas or oil.

Hydrocarbons

The gaseous and volatile liquid hydrocarbons are of particular interest as air pollutants. Hydrocarbons can be saturated or unsaturated, branched or straight-chain, or can have a ring structure as in the case of aromatics and other cyclic compounds. In the saturated class, methane is by far the most abundant hydrocarbon constituting about 40 to 80 per cent of the total hydrocarbons present in an urban atmosphere. The unsaturated class includes alkenes (olefins) and acetylenes. Among the alkenes the prominent pollutants are ethylene and propene. The first member of the aromatic class is benzene, but some of its substituted derivatives such as toluene and *m*-xylene are usually present in larger concentrations in the urban atmosphere. Terpenes are a particular class of volatile hydrocarbons emitted largely by natural sources. These are cyclic non-aromatic hydrocarbons found in pine tar and in other wood sources.

The hydrocarbons in air by themselves alone cause no harmful effects. They are of concern because the hydrocarbons undergo chemical reactions in the presence of sunlight and nitrogen oxides forming photochemical oxidants of which the predominant one is ozone. Methane has very low photochemical activity as compared to that of other hydrocarbons. For this reason, it is the non-methane hydrocarbon concentration that is of interest while considering air pollution.

2.3 EMISSION SOURCES

The sources of air pollutants are numerous. They can be grouped according to a variety of methods, including type of source, number and spatial distribution of sources and type of emissions[3].

2.3.1 Classification According to Source Types

Source type refers to natural and anthropogenic sources, as well as to additional subclassifications within each group. Natural sources include wind-blown dust, pollen, sea salt nuclei, volcanic ash and gases, smoke and trace gases from forest fires, and terpenes from forests. Anthropogenic sources cover a wide spectrum of types. Table 2.3 includes a list of major anthropogenic air pollution sources, and their characteristic emissions. The most important of these with regard to quantity are the products of combustion. The combustion of fossil fuels results in the emission of a variety of pollutants into the atmosphere of which the major ones are SO_2, NO_x, CO and particulate matter such as fly ash. Also emitted are small quantities of water vapour and trace metal oxides, e.g. oxides of mercury, lead and cadmium. Incineration of solid combustible wastes and refuse gives off a wide variety of pollutants depending upon waste composition and combustion conditions. These pollutants include aldehydes, benz-α-pyrene, CO, NO_x, SO_2, hydrocarbons, ammonia and particulates.

Next to combustion systems, the major sources of air pollutants are chemical and metallurgical industries. Thus, a major, and often quite concentrated source of sulphur dioxide is the roasting and subsequent treatment of nonferrous sulphide minerals, principally lead, zinc, and copper ores. In addition to SO_2 emission, these operations usually produce dust and fumes of primary metal oxides and small quantities of trace metals.

Table 2.3 Classification of anthropogenic air pollution sources

Source type	*Category*	*Important sources*	*Typical pollutants*
Combustion	Stationary	Power plants, industrial boilers, diesel generators, municipal or industrial incineration, refuse burning	Oxides of sulphur, NO_x, CO, smoke, flyash, trace metal oxides
	Mobile	Motor vehicles, air craft	CO, hydrocarbons, NO_x, SO_2 particulates
Roasting and heating processes	Non-ferrous metallurgical	Roasting, smelting and refining operations	Dust, smoke, metal fumes (Cu, Pb and Zn) oxides of sulphur
	Ferrous metallurgical	Materials handling, ore sintering and pelletising, coke ovens, blast furnace, steel furnaces	Smoke, fumes, CO, odours, H_2S, organic vapour, fluorides
	Non-metallic minerals	Crushed stone, gravel, and sand processing, cement, glass, refractories, and ceramics manufacture, coal-cleaning	Mineral and organic particulates, SO_2, NO_x dust fumes
Chemicals, petroleum, pulp and paper	Petroleum refining	Boilers, process heaters, catalyst regenerators, flares, reactors, storage tanks, compressor engines	Oxides of sulphur, hydrocarbons, NO_x, particulate matter, CO, aldehydes, ammonia, odours
	Inorganic chemicals	Sulphuric acid plants, fertiliser manufacture, nitric acid and ammonia plants, phosphoric acid manufacture	SO_2, HF, H_2S, NO_x, NH_3, particulate matter, H_3PO_4 etc.
	Organic chemicals	Plastics, paint and varnish manufacture, synthetic rubber, rayon, insecticide, soap and detergent manufacture, methanol, phenol etc.	Particulate matter, odours, SO_2, CO, organic intermediates product gases and vapours, solvent vapours etc.
	Pulp and paper (Kraft process)	Digester blow system, pulp washers, recovery furnace, evaporators, oxidation towers	Particulate matter, odourous sulphur compounds (H_2S, methyl mercaptan, dimethyl sulphide) and SO_2 (sulphite process)
Food and agriculture	Food processing	Drying, preserving, packaging	Vapours, odours, dust.
	Crop spraying and dusting	Pest and weed control	Organic phosphates, chlorinated HC, arsenic, lead
	Field burning	Refuse burning	Smoke, flyash and soot

In the case of iron and steel industry, air pollution originates from large scale high temperature processing of coal and iron ore. The major emission sources include ore sintering, coke ovens, waste water quenching of hot coke and furnace effluents. Some of the significant emissions are dust, fumes, hydrocarbons, tars, H_2S and SO_2. In non-metallic mineral industries like cement, glass, ceramics and refractories, the operations of mining, crushing, transport and storage of the materials result in the emission of large quantities of hazardous dust.

The chemical process industries are the source of a wide variety of air-pollutants emissions associated with raw material processing, reaction products and their purification. Some of the pollutants emitted from inorganic chemical industries are SO_2 gas, SO_3—H_2SO_4 mist, NH_3, NO_2, hydrogen fluoride, HCl gas and H_2S. Synthetic organic chemical industries emit a variety of hydrocarbon compounds and solvents like C_6H_6, $C_6H_5CH_3$ and CCl_4 into the atmosphere.

Petroleum refining operations are a major source of air pollution, emitting such pollutants as oxides of sulphur and sulphur containing vapours from various stages of the refining process, particulates from catalyst regeneration and recycling, H_2S and mercaptans which are stripped from lighter grades of fuel and hydrocarbons from leaks in valves, pipelines and storage tanks.

Pulp and paper industry is a notorious source of many air-pollutants emissions into the atmosphere. Sulphur bearing malodourous gases such as H_2S, methyl mercaptan, and methyl sulphides are emitted from blow tanks, evaporators and recovery furnace. In addition, combustion of wood waste results in large particulate emissions into the atmosphere.

Food processing covers a wide range of activities including drying, preservation of food materials and packaging. These activities produce such pollutants as dusts from grinding, milling and handling operations, and odours associated with biological decay of food materials. Use of agricultural chemicals for improvements in crop yield, for control of weeds and insects result in emission of pollutants like nitrates and phosphates, pesticides, arsenic and lead particulates into the atmosphere.

2.3.2 Other Methods of Grouping Air Pollution Sources

Air pollution sources can also be grouped according to number and spatial distribution. These include single or point sources such as steel mills, power plants, oil refineries, and pulp and paper mills etc., multiple or area sources such as an entire residential area, and line sources which include highways carrying moving vehicles. Another source grouping is by the type of emissions with particulate and gaseous emissions being the two major divisions.

2.3.3 Major Emissions from Global Sources

The estimated magnitudes of major air pollutants emitted from various global sources are given in Table 2.4. As seen from the from the table the total global emission of particulate matter is estimated to be 2365 million tonnes per year. Of this total emission the natural emissions from both primary and secondary sources account for 2096 million tonnes and anthropogenic sources account for 269 million tonnes. Among the primary sources of natural emissions, sea spray is the largest single contributor, amounting to 908 million tonnes per year with soil dust making up most of the remaining amount.

Table 2.4 Estimated global emissions of major air pollutants (refs. 4, 5, 6, 7, 8)

Pollutant		*Emissions (millions of tonnes/year)*			
		Natural		*Anthropogenic*	
Particulate matter					
	Primary particle production	Sea salt spray	908		84
		Soil dust	182		
		Volcanic and forest fires	7		
			1097		
	Gas-to-particle conversion	Sulphate from H_2S	182	Sulphate from SO_2	133
		Nitrate from NO and NO_2	390	Nitrate from NO_x	27
		Ammonium	245	Photochemicals from HC	25
		Terpenes	182		
			999		185
Sulphur dioxide		Emissions expressed as S		Coal	92
		Biological decay (H_2S)	90	Petroleum	26
		Sea spray (sulphates)	40	Smelting	14
			130		132
Nitrogen oxides		NO:455[a]		*Emissions expressed as NO_2*	
		N_2O: 537		Coal combustion	24.4
				Petroleum refining	0.6
				Gasoline combustion	6.8
				Other oil combustion	12.8
				Natural gas combustion	1.9
				Other combustion	1.4
					47.9
Carbon monoxide		Oxidation of CH_4 and formaldehyde	3000		400
		Decay and synthesis of chlorophyll	90		
		Photochemical oxidation of terpene	54		
		Oceans	220		
			3364		
Hydrocarbons		CH_4:1450 Terpenes:170			88

[a] Most NO, whether from natural or anthropogenic sources, is oxidised to NO_2 within a few days; thus, the distinction made here is somewhat arbitrary.

The secondary sources of natural particulate emissions are gas phase chemical reactions. Such reactions involving H_2S, NO_x, NH_3 and terpenes account for the annual production of 999 million tonnes of particulates. In contrast, global particulate emissions of anthropogenic origin by chemical reaction between gaseous pollutants come to around 185 million tonnes per year. This is about 19 per cent of the amount of natural particulates produced by the same process. The direct introduction of (primary) particulates into the atmosphere resulting from the combustion of fuels, cement manufacturing, agricultural burning, and solid-waste disposal operations amounts to 84 million tonnes per year.

Sulphur dioxide is emitted into the atmosphere either directly (e.g., from fuel combustion, petroleum refining and smelting operations, etc.), or through oxidation of H_2S obtained from decomposition of organic matter. The natural sources such as biological decay and sea spray emit about 130 million tonnes of sulphur per year and the anthropogenic sources such as coal combustion, petroleum and smelting operations release an additional 132 million tonnes of SO_2 annually into the atmosphere. The largest single contribution to the total anthropogenic emissions, about 70 per cent, is made by coal combustion. No major natural sources of SO_2 are known, although a small amount is probably present in gases emitted through volcanic activity.

Both natural and anthropogenic sources contribute to the emission of nitrogen oxides to the atmosphere. Global natural emissions, mainly due to bacterial activity in the soil, are estimated to be 455 million tonnes of NO per year. Combustion of coal, oil or natural gas in power plants or the internal combustion engines is the major source of anthropogenic emission of nitrogen oxide. It is estimated that 48 million tonnes of these oxides are emitted per year into the atmosphere from these activities. The amount reported is based on NO_2 since most of the NO is oxidised to NO_2 within a few days. However, it should be noted that it is NO and not NO_2 which enters the atmosphere predominantly.

The major sources of carbon monoxide in the environment are incomplete combustion of carbonaceous fuels, oxidation of methane and formaldehyde derived from biological activity, the decay of chlorophyll in plants, the algae and other biological sources in oceans, and the photochemical oxidation of terpenes. As seen from the Table 2.4 the natural sources far exceed the anthropogenic sources in CO emission. Global emissions from natural sources amount to an estimated 3364 million tonnes per year and these are approximately eight times more than the CO emissions from all human activities. About 88 per cent of this total comes from atmospheric oxidation of CH_4 and formaldehyde and the remaining from other sources.

The major sources of hydrocarbons emissions into the atmosphere are the natural sources. Swamps, marshes and other water bodies generate an estimated 1450 million tonnes of methane per year into the atmosphere. Plants are also natural sources of atmospheric hydrocarbons. They emit an estimated 170 million tonnes of terpene-type hydrocarbons into the atmosphere. The significant anthropogenic sources are incineration operations, evaporation of solvents in industrial coating and cleaning, and incomplete combustion of coal, oil and wood. The largest source of airborne hydrocarbons, however, is the entire cycle consisting of processing and using of petroleum. On a worldwide basis, the annual anthropogenic hydrocarbon emissions amount to an estimated 88 million tonnes.

Importance of Anthropogenic Sources

It is evident from Table 2.4, the pollutant emission from natural sources is much greater than that from anthropogenic sources. Fortunately, the former are distributed throughout the world and eventually they reach a sink such as the ocean or the soil. Thus, the atmosphere can cleanse itself from the pollutants given sufficient time. On the other hand, anthropogenic sources of pollutants are concentrated in specific locations, such as urban areas and reach very high levels in the atmosphere. For example, 95 to 98 per cent of the atmospheric carbon monoxide in an urban area comes from human activities and the resulting levels of CO are commonly 50 to 100 times higher than the characteristic global values of 0.1 to 0.5 ppm. The emission of these pollutants is at such massive rates that they overwhelm the capacity of the environment to cleanse itself.

The extent of man's contribution to global pollution is evident from Table 2.2 where a comparison of the total amount of anthropogenic generation of pollutants is made with their amounts present in dry, clean air. Thus, the influence of anthropogenic sources is quite significant and the air pollutants not only threaten the health and well-being of population in a particular locality, but could also produce adverse effects on a global scale.

2.3.4 Emission Sources in India

Air pollution sources in India may be grouped into rural and urban sources. The rural sources are those emitted mainly from burning of biofuels and the urban sources originate primarily from the use of fossil fuels. The biofuels used in rural areas include fuelwood, dry cattle dung and vegetable wastes. Burning of these unprocessed fuels generate air pollutants such as carbon monoxide, NO_2, SO_2 and hydrocarbons. Women in the households who use these fuels are exposed to high concentrations of air pollutants. The nature of these pollutants and their health effects are not well-known despite the long experience rural women have had with these fuels. Another reason could be that these emissions are localised and have little impact on the environment beyond their immediate premises.

The combustion of fossil fuels and their products is responsible for a sizable amount of air pollution in urban areas and coal was the greatest contributor to air pollution followed by fuel oils and mobile sources. In addition to burning of fossil fuels, major industries like steel, paper and pulp, textiles, cement and fertilisers contribute relatively small but significant amounts of air pollutants to the nation's atmosphere. Since most of the industries are located in major cities, these significantly add to the pollution burden of the metropolitan areas.

However, the air pollution scene in urban areas has changed drastically with the liberalisation policies of the government of India, allowing more car manufacturers to enter the Indian market in 1990s. Now it is not factories but motor vehicles—cars, buses, trucks, 3-wheelers and 2-wheelers—which contribute nearly 65-70 per cent to the total air pollution burden of the cities. For example, Bangalore had 1,00,000 vehicles in 1976-77 but by 1996, this number has increased to nearly 9,00,000 vehicles which released a pollution-load of 1145 tonnes/day of CO, hydrocarbons and NO_x. Of the total daily pollution load, two and three wheelers contributed 57 per cent and four wheelers contributed nearly 30 per cent. But in a span of just two years, the contribution of 2 and 3-wheelers had increased to nearly 75 per cent.

Similarly Delhi's vehicular pollution contributes about 70-80 per cent of the overall pollution load in the city. Even with the implementation of control measures and considering the present trend of growth of vehicles, it has been estimated that the load of all major pollutants in the city will increase more than two-fold by the end of 2005 from their 1991 levels (Table 2.5). Pollutants of concern emitted in substantial quantity by moving vehicles include CO, NO_x and HCs, which contributed nearly 94 per cent of the total pollution load in 1991. This ratio has remained fairly unchanged in 2005 which indicates the continued increase in the concentration of these pollutants.

Table 2.5 Major annual pollutant emissions in Delhi (ref. 25)

	1991	*2005 (estimated)*
	(10^3 tonnes)	
Carbon monoxide	243	600
Hydrocarbons	82	198
Nitrogen oxides (NO_x)	139	330
Sulphur dioxide	10	23
Suspended particulate matter (SPM)	10	44

According to the Maharashtra Pollution Control Board, the amount of air pollution in Mumbai due to auto exhaust in 1999 was 501 tonnes of the total 818 tonnes per day. The concentration levels of NO_2, respirable suspended particulate matter (RSPM or PM10) and CO has exceeded the air quality standards promulgated by the Central Pollution Control Board except in residential areas where only SPM levels had exceeded standards. Particulate matter of less than 10 μm has a high morbidity rate and these comprise about 40 per cent of the total suspended particulate matter (SPM).

2.4 BEHAVIOUR AND FATE OF AIR POLLUTANTS

Although large amounts of pollutants are discharged annually into the atmosphere, the very fact that their ambient levels have remained very much the same throughout the world suggests that there are certain pathways of exchange from the atmosphere to the Earth, whereby the pollutants are continually removed. These pathways or the scavenging processes, as they are called, may be grouped as follows for both particulates and gases:

Particulates: (*a*) Wet removal by precipitation.
(*b*) Dry removal by sedimentation, impaction and diffusion.

Gases: (*a*) Wet removal by precipitation.
(*b*) Chemical reaction in the atmosphere to produce aerosols and/or absorption on aerosols with subsequent removal.
(*c*) Absorption or reaction at land and ocean surfaces.

2.4.1 Wet Precipitation

Wet precipitation has two distinct mechanisms—"rainout" and "washout". The first includes various processes taking place inside clouds, where the contaminants serve as condensation nuclei on which droplets condense. The second mechanism refers to the removal of pollutants below the cloud level by falling rain. Wet precipitation is one of the most effective scavenging processes for both particulate and gaseous pollutants in a global sense. The rainout mechanism is particularly effective for Aitken particles whose size is less than 0.1 μm. These particles are captured by cloud droplets by Brownian diffusion, and the cloud droplets (typically 30 μm) in turn grow in size by coalescence and precipitate. Washout is most effective in removing particles larger than 2 μm. Its scavenging efficiency, however, is influenced by the rain-drop cross-sectional area and the intensity of rain fall. Particles smaller than 2 μm are not usually collected by rain drops (typically 500 μm) because they are brushed aside by the diverging air ahead of the drop.

The scavenging of gaseous pollutants by wet precipitation is more complex and is less well understood. Soluble gas molecules such as SO_2 can migrate to the rain drop by Brownian motion or to the surface of the cloud droplets by diffusion due to the concentration gradient of the gas across the liquid-air interface. However, wet precipitation is very effective in removing the acid droplets and sulphate particles formed after chemical reactions in the atmosphere.

Dry Deposition

Particulate matter smaller than 0.1 μm often coagulates through mutual collisions and forms larger aggregates which are effectively removed by gravitational settling. Brownian motion is the major mechanism of coagulation, although atmospheric turbulence is particularly effective for coagulating larger particles whose Brownian motion is less pronounced. The rate of settling of the particles depends on their settling velocities according to the Stokes' law:

$$v_t = \frac{g d_p^2}{18\mu_a}(\rho_p - \rho_a)\left(1 + \frac{2C}{d_p p}\right) \qquad \text{...(2.9)}$$

where v_t = terminal settling velocity

d_p = particle diameter

ρ_p and ρ_a = density of particle and air, respectively

μ_a = viscosity of air

p = air pressure

and C = constant [when p is given in millibars and d_p in centimeters $C = 0.0084$ (ref. 9)]

From the above equation, it is seen that the rate of sedimentation is strongly influenced by the particle size. Particles larger than 10 μm have high settling rates and, hence have short residence time in the atmosphere. The terminal velocity is also related to the particle's density, but only by a less sensitive linear dependence. Deviations from the Stokes' law occur due to irregular particle shapes, turbulence in the wake of large particles, and atmospheric vertical velocities; but it is clear that small particles must aggregate to form larger ones if they are to be removed efficiently from the atmosphere.

In addition to sedimentation, the mechanisms of inertial impaction and diffusion also contribute to the removal of particulate matter. In inertial impaction, wind-borne particles strike an obstacle and are deposited; whereas in diffusion small particles migrate to land and ocean surfaces. Dry deposition accounts for about 20 per cent of the total particulate removal from the atmosphere.

2.4.2 Interaction at the Earth's Surface

Gaseous pollutants can be transported to the Earth's surface by atmospheric turbulence where they interact with the ocean surface, vegetation and upper layers of the soil, and are removed by absorption or chemical reaction. Assimilation at these surfaces depends on many factors about which little is known for many pollutants. Two major pollutants, about which some information is available, are sulphur dioxide and carbon monoxide.

At the ocean surface, SO_2 first diffuses through the gas phase, crosses the gas-liquid interface, and finally diffuses into the bulk of the ocean where it is absorbed. Vegetation and upper layers of the soil also act as sinks for SO_2. Hence the mode of transfer involved is adsorption. SO_2 first diffuses to the external surface of the solid, penetrates into the pores of the solid, and is subsequently adsorbed on the pore site. An estimated removal of 4×10^7 tonnes of SO_2 per year has been calculated for oceanic absorption[10] and the solid surfaces account for 5.6×10^7 tonnes per year[11]. The importance of these sinks can be seen when their performance is compared with the estimated emission of 14×10^7 tonnes per year SO_2 from the anthropogenic sources.

For carbon monoxide, biological action in soils seems to be an important sink; the role played by soil in the removal of CO has been firmly established[12]. It is theorised that the soil contains certain bacteria which can make use of CO in their metabolism, producing either CO_2 or CH_4:

$$CO + \frac{1}{2}O_2 \rightarrow CO_2 \qquad \text{...(2.10)}$$

$$CO + 3\,H_2 \rightarrow CH_4 + H_2O \qquad \text{...(2.11)}$$

Nitrogen dioxide also seems to be absorbed by the ocean and other surface waters, but the extent of the contribution of this sink to the overall removal of nitrogen oxides is not clearly established.

2.4.3 Chemical Reactions in the Atmosphere

Many of the gaseous pollutants undergo chemical reactions within the atmosphere and form either new compounds or aerosols. This mode of removal is of great importance for sulphur dioxide. A large part of SO_2 in the atmosphere is oxidised to sulphur trioxide which quickly combines with moisture to form sulphuric acid mist. The overall reaction is represented as:

$$2SO_2 + 2H_2O + O_2 \rightarrow 2H_2SO_4 \qquad \text{...(2.12)}$$

This process has been shown[13] to be catalysed by metal salts such as iron and manganese, commonly formed in the flyash. These particles serve as nucleation sites for droplet formation and the sulphuric acid droplet may in turn react with metal salts (such as NaCl from sea salt particles), metal oxides such as MgO, Fe_2O_3, ZnO and Mn_2O_3, or ammonia to produce sulphates:

$$2NaCl + H_2SO_4 \rightarrow Na_2SO_4 + 2HCl \qquad \text{...(2.13a)}$$

$$MgO + H_2SO_4 \rightarrow MgSO_4 + H_2O \qquad \text{...(2.13b)}$$

$$2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4 \qquad \text{...(2.13c)}$$

With these reactions, the sulphuric acid droplet is neutralised and the solubility of SO_2 in the droplets is further increased thereby enhancing the oxidation process. Both the acid droplets and the sulphate particles are rapidly removed from the atmosphere primarily by wet precipitation.

Similarly, a major process of removal of nitrogen oxides appears to be through their conversion to form nitric acid; however, the mechanism of such a conversion has not been clearly determined. The direct conversion of NO_2 to HNO_3 in the presence of moisture appears to be too slow to account for the observed rate of removal:

$$2NO_2 + H_2O \rightleftharpoons HNO_3 + HNO_2 \qquad \text{...(2.14a)}$$

$$3HNO_2 \rightarrow HNO_3 + 2NO + H_2O \qquad \text{...(2.14b)}$$

or

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO \qquad \text{...(2.14c)}$$

Since the direct conversion of sulphur dioxide to sulphur trioxide and nitrogen dioxide to nitric acid is slow, other mechanisms have been postulated, based mainly on theoretical conjecture and to a lesser extent on experimental observations. These mechanisms involve the oxidation by reactive species such as radicals, atomic oxygen, ozone, and hydroxyl radicals.

The first step in the oxidation of SO_2 is the photoexcitation of the SO_2 molecule through its absorption of solar radiation:

$$SO_2 + h\nu \rightarrow SO_2^* \qquad \text{...(2.15)}$$

where SO_2^* represents an excited SO_2 molecule. These molecules in their excited state react more readily with molecular oxygen[14]. Then several reactions follow to complete the oxidation of SO_2 to SO_3:

$$SO_2^* + O_2 \rightarrow SO_4^{2-} \qquad \text{...(2.16a)}$$

$$SO_4^{2-} + O_2 \rightarrow SO_3 + O_3 \qquad \text{...(2.16b)}$$

$$SO_2 + O_3 + h\nu \rightarrow SO_3 + O_2 \qquad \text{...(2.16c)}$$

A three-body reaction with atomic oxygen has also been suggested as a possible mechanism:

$$O_2 + h\nu \rightarrow 2O \qquad \text{...(2.17a)}$$

$$SO_2 + O + M \rightarrow SO_3 + M \qquad \text{...(2.17b)}$$

The third body, *M*, is required in order to carry off excess energy of reaction.

A proposed rapid mechanism for the conversion of NO_2 to HNO_3 is the reaction of NO_2 with atmospheric ozone to give nitrogen trioxide:

$$NO_2 + O_3 \rightarrow NO_3 + O_2 \qquad \text{...(2.18)}$$

In addition, NO_3 can be formed by reaction with atomic oxygen

$$NO_2 + O + M \rightarrow NO_3 + M \qquad ...(2.19)$$

The NO_3 radical is removed by reaction with NO_2 forming N_2O_5, which in the presence of moisture forms nitric acid:

$$NO_3 + NO_2 \rightarrow N_2O_5 \qquad ...(2.20a)$$

$$N_2O_5 + H_2O \rightarrow 2HNO_3 \qquad ...(2.20b)$$

The HNO_3 so formed in then washed out of the atmosphere in the form of nitrate salts by precipitation.

For carbon monoxide, its reaction with atmospheric oxygen in the presence of sunlight is found to be very slow and accounts for the removal of only 0.1 per cent of available CO for each hour of sunlight. Of major interest as an atmospheric sink for CO is the relatively fast reaction of CO with hydroxyl radicals present in the atmosphere.

$$CO + OH^{*} \rightarrow CO_2 + H^{*} \qquad ...(2.21)$$

The above mechanism may account for the removal of a substantial portion of CO from the troposphere depending upon the concentration of OH^{*} radicals. Another possible mechanism is the migration of CO into the stratosphere, where the oxidation to CO_2 may subsequently take place by the hydroxyl radicals. In fact, all these gaseous pollutants, including the hydrocarbons, inter-react by photochemical processes in the phenomenon known as the *photochemical smog*.

2.4.4 Photochemical Smog

Photochemical smog was first observed in Los Angeles, U.S.A. in the mid-1940's and since then the phenomenon has been detected in most major metropolitan cities of the world. The conditions for the formation of photochemical smog are air stagnation, abundant sunlight, and high concentrations of hydrocarbon and nitrogen oxides in the atmosphere. In India, Bombay and Calcutta are ideal candidates for the formation of photochemical smog, but it may be masked by smoke and sulphur dioxide.

Smog arises from photochemical reactions in the lower atmosphere by the interaction of hydrocarbons and nitrogen oxide released by exhausts of automobiles and some stationary sources. This interaction results in a series of complex reactions producing secondary pollutants such as ozone, aldehydes, ketones and peroxyacyl nitrates. The reaction mechanisms are complex and are not fully understood.

A broad outline of the principal reactions that occur in a photochemical process are illustrated in Fig. 2.2. The starting mechanism is the absorption of ultraviolet light from the Sun by NO_2. This causes the nitrogen dioxide to decompose into nitric oxide and highly reactive atomic oxygen.

$$NO_2 + h\nu \rightarrow NO + O \qquad ...(2.22)$$

The atomic oxygen initiates oxidizing processes or quickly combines with molecular oxygen to form ozone, which itself is reactive and acts as an oxidant:

$$O + O_2 + M \rightarrow O_3 + M \qquad ...(2.23)$$

$$O_3 + NO \rightarrow NO_2 + O_2 \qquad ...(2.24)$$

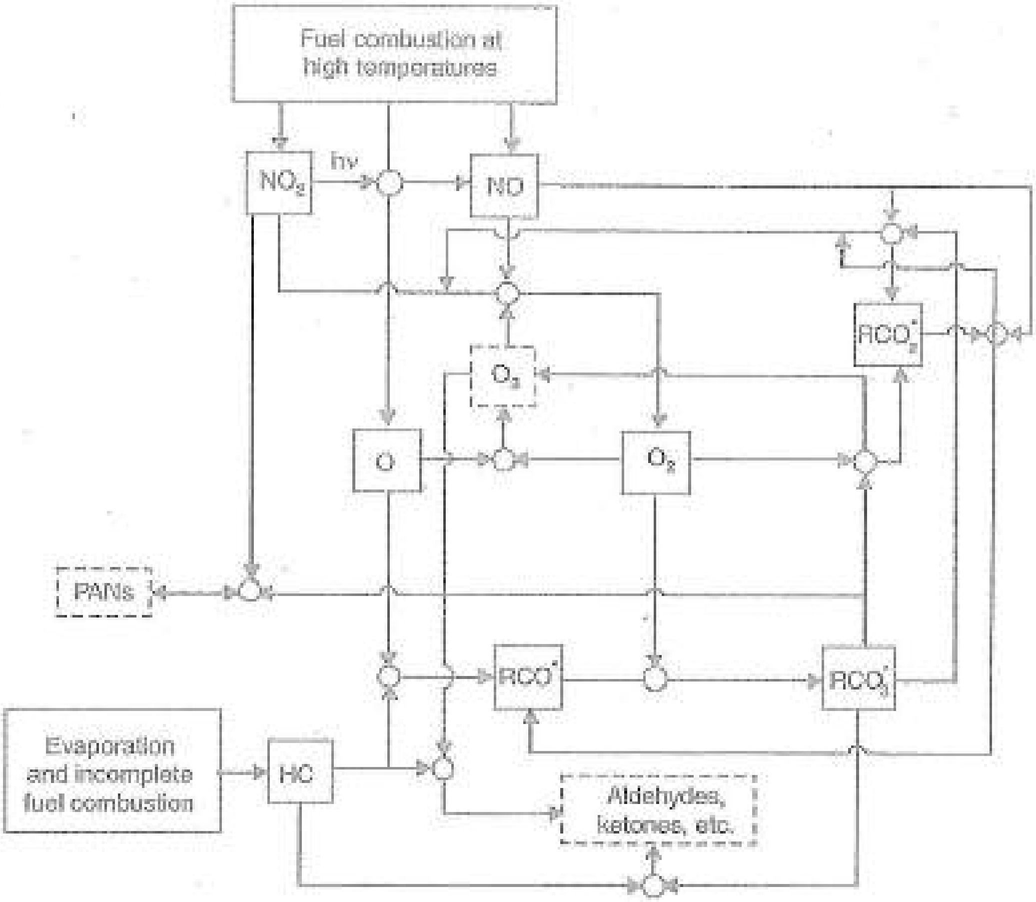


Fig. 2.2 A schematic representation of the formation of photochemical smog

In Eq. (2.23) as energy-absorbing molecule or particle (*M*) is required to stabilise O_3 or else it will rapidly decompose. Under normal conditions, the ozone formed will be quickly removed by reaction with NO to provide NO_2 and O_2 according to Eq. (2.24); however, when hydrocarbons are present in the atmosphere this mechanism is partially eliminated as NO reacts with the hydrocarbon radical peroxyacyl (RCO_3^*) according Eq. (2.28), and as a result ozone concentration builds up to dangerous levels.

Hydrocarbons, indicated by symbol HC, compete for free oxygen released by NO_2 decomposition to form oxygen-bearing free radicals such as the acyl radical.

$$HC + O \rightarrow RCO^* \text{ (acyl radical)} \qquad ...(2.25)$$

This radical takes part in a series of reactions involving the formation of still more reactive species, which in turn react with O_2, hydrocarbons and nitric oxide.

$$RCO^* + O_2 \rightarrow RCO_3^* \text{ (peroxyacyl radical)} \qquad ...(2.26)$$

$$RCO_3^* + HC \rightarrow RCHO\text{(aldehydes)}, R_2CO\text{(ketones)} \qquad ...(2.27)$$

$$RCO_3^* + NO \rightarrow RCO_2^* + NO_2 \qquad ...(2.28)$$

$$RCO_3^* + O_2 \rightarrow RCO_2^* + O_3 \qquad ...(2.29)$$

Reactions represented by Eq. (2.27) are termination reactions forming aldehydes an ketones; however, in Eqs. (2.28) and (2.29) the peroxyacyl radial reacts with NO and O_2 t produce another oxidised hydrocarbon radical (RCO_2^*) as well as more NO_2 and O_3. Furthe the acylate radical (RCO_2^*) can react with NO to generate even more NO_2.

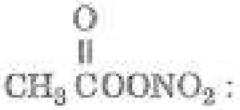
$$RCO_2^* + NO \rightarrow RCO^* + NO_2 \qquad ...(2.30$$

The NO level in the atmosphere eventually drops off with the accumulation of NO_2 an O_3. When reactions such as these increase the NO_2 level sufficiently, another reactio begins to compete for the peroxyacyl radical.

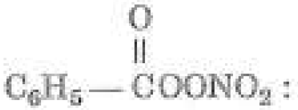
$$RCO_3^* + NO_2 \rightarrow RCO_3NO_2\,(PANS) \qquad ...(2.31$$

The end products are known a peroxyacyl nitrates or PANS. Numerous PANS could b formed, corresponding to the different possible R groups. Three of the common member of PAN family are:

$$H\overset{O}{\overset{\|}{C}}OO\,NO_2:$$ Peroxyformyl nitrate (PFN)



$$CH_3\,\overset{O}{\overset{\|}{C}}OONO_2:$$ Peroxyacetyl nitrate (PAN)



$$C_6H_5-\overset{O}{\overset{\|}{C}}OONO_2:$$ Peroxybenzoyl nitrate (PBzN)

The ozone formed according to Eqs. (2.23) and (2.29) reacts with the hydrocarbons t generate more aldehydes and ketones.

$$HC + O_3 \rightarrow RCO_2^* + RCHO,\ R_2CO \qquad ...(2.32$$

The above equations represent in a broad sense the nature of the overall photochemica reactions leading to formation of smog and they are by no means the only importan mechanisms. It has been observed that carbon monoxide and sulphur dioxide also play significant part in the process of formation of smog by strongly interacting with man species present in the smog and accelerate the oxidation processes. For example, carbo monoxide does this through a series of reactions whose net effect is to convert CO, NO, an O_2 into CO_2 and NO_2 thus accelerating the oxidation of NO. First, CO is oxidised to CO by the OH^* radical (Eq. 2.21). In the smogy atmosphere the OH^* radical may be produce when aldehydes are attacked by atomic oxygen.

$$O + CH_3CHO \rightarrow CH_3CO + OH^* \qquad ...(2.33$$

$$CO + OH^* \rightarrow CO_2 + H^* \qquad ...(2.21)$$

$$H^* + O_2 + M \rightarrow HO_2^* + M \qquad ...(2.34$$

The $H^{\bullet}$ radical reacts with O_2 to form the hydroperoxyl radical $HO_2^{\bullet}$ which is a principal agent for the rapid conversion of NO into NO_2 (ref. 15)

$$HO_2^{\bullet} + NO \rightarrow OH^{\bullet} + NO_2 \qquad ...(2.35)$$

The overall reaction is

$$CO + O_2 + NO \rightarrow CO_2 + NO_2 \qquad ...(2.36)$$

This sequence of reactions provides another route for the oxidation of NO without the participation of O_3 (Eq. 2.24).

Similarly, the reaction of SO_2 with the $HO_2^{\bullet}$ radical may be an important step in the mechanism of the oxidation of SO_2 to SO_3.

$$HO_2^{\bullet} + SO_2 \rightarrow OH^{\bullet} + SO_3 \qquad ...(2.37)$$

In addition, the hydrocarbon radicals may give off an oxygen atom to SO_2 to form SO_3, which in turn in converted to H_2SO_4 droplets resulting in the formation of haze.

Smog Behaviour

The formation of photochemical smog is a dynamic process whose nature is illustrated in Fig. 2.3. In the morning, the NO and hydrocarbon levels increase followed quickly by

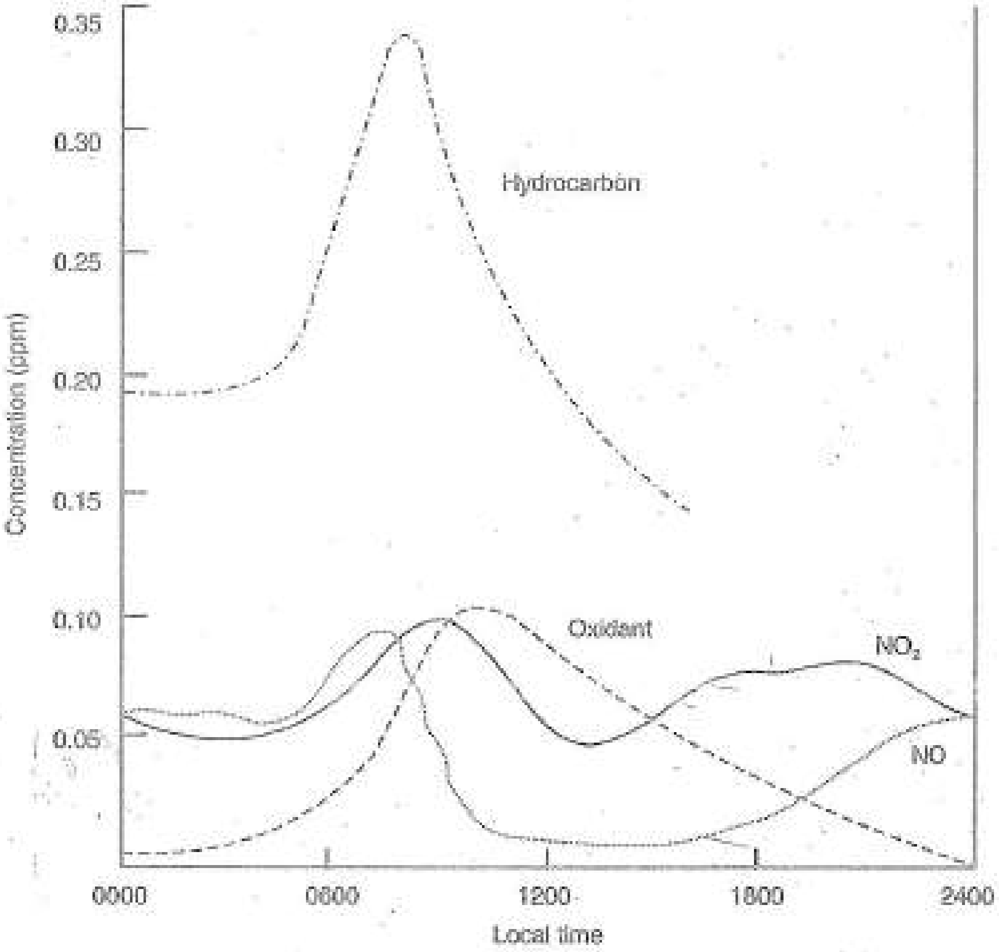


Fig. 2.3 Dynamic behaviour of photochemical smog (ref. 14)

increase in NO_2. NO_2 reacts with the sunlight leading to various chain reactions and ultimately to the production of ozone and other oxidants.

Ozone concentration now increases until, sometime in the afternoon, it reaches a maximum, and then decreases gradually. NO_2 concentration diminishes from its peak as ozone concentration builds up and is usually low by later afternoon. The typical smog episode occurs in hot, sunny weather under low humidity conditions. The characteristic symptoms of the smog are the brown haze in the atmosphere, reduced visibility, eye irritation, respiratory distress and plant damage.

The control of photochemical smog may require a substantial reduction in NO_x produced in urban areas. At the same time it is necessary to control the release of hydrocarbons from numerous mobile and stationary sources.

2.5 EFFECTS OF AIR POLLUTION

In the previous section the scavenging mechanisms for the major air pollutants were examined. But often the pollutants are discharged into the atmosphere in such high quantities and concentrations as to overwhelm the natural scavenging ability of the atmosphere. As a result, the concentrations of the pollutants persist at levels which are much higher than the allowable background levels. This is particularly true for urban and other industrial regions where the pollutants adversely affect the health of humans and animals, and cause plant and material damage. The global effects of air pollution on climate due to increased levels of carbon dioxide and particulates, and the role of SO_2 in producing acid rain were discussed in Chapter 1. These problems are less apparent than the community-wise problems but they may be of great importance in the long run. In this section the main emphasis will be on the effects of those pollutants which cause community-wise problems and these are presented with particular attention to six ubiquitous pollutants, namely, particulates, sulphur oxides, carbon monoxide, nitrogen oxides, hydrocarbons and photochemical oxidants.

2.5.1 Human Health

Adverse effects of air pollution may be divided into two classes—acute and chronic effects. Acute effects manifest themselves immediately upon short-term exposure to air pollutants at high concentrations, and chronic effects become evident only after continuous exposure to low levels of air pollution. The chronic effects are very difficult to demonstrate and are consequentially less obvious. Therefore, much of our knowledge of the effects of air pollution on people comes from the study of acute air pollution episodes. Deaths from these episodes are measured by comparing the number of deaths normally associated with the area and period in question with those that occur during the episode. The difference is referred to as "excess deaths".

In 1930, the Meuse Valley in Belgium was trapped by an inversion in which pollutants accumulated for about five days resulting in the death of about 60 people. Similar stable meteorological conditions occurred in 1948 in Donora, U.S.A., where 20 people died and about 6000 of the Town's 14,000 population became ill. The notorious London episode of 1952 took place under heavy continuous smog conditions and caused an estimated 4000 excess deaths. The episode of 1962, although shorter in duration was very much similar to that of 1952, but the excess deaths were lower. Table 2.6 outlines some of the major air pollution disasters. Most of these were associated with temperature inversions lasting for several days. The general and most wide-spread effects were caused by high concentrations of smoke and SO_2 and in particular by the synergistic action of the two, where the combined influence of the two pollutants is greater than the sum of their individual effects experienced separately.

Table 2.6 Major air pollution disasters (ref. 16, 17, 18)

Location	*Conditions and causes*	*Symptoms and effects*
Meuse Valley, Belgium, Dec 1920	Inversion; smoke, SO_2(9.6-38.4 ppm), H_2SO_4 mist	60 excess deaths, thousands ill, eye and nasal irritation, cough
Donora, U.S.A., Oct. 1948	Inversion and fog; SO_2 (0.5-2 ppm), smoke, zinc particles H_2SO_4 mist	20 excess deaths, 6000 of town's 14000 population became ill, irritation of eyes, nose and respiratory tract, breathlessness; nausea
Poza Rica, Mexico, Nov. 1952	Shallow inversion, fog and calm conditions. H_2S release due to burner failure	22 excess deaths, 320 hospitalised, irritation of the respiratory tract
London, England Dec., 1952	Low temperature inversion, thick fog, stagnant air; smoke (4500 μg/m^3) and SO_2 (1.4 ppm) accumulation.	Estimated 4000 deaths, thousands hospitalised for respiratory and heart diseases, chronic bronchitis, bronco-pneumonia.
London, England Jan 1956	Extended fog conditions, similar to 1952 episode, particulates (3250 μg/m^3), SO_2 (0.57 ppm)	1000 excess deaths
London, England Dec. 1962	Shallow inversion, thick fog, smoke (2000 μg/m^3), SO_2 (1.26 ppm)	700 excess deaths, increased illness.
New York, U.S.A Nov. 1966	SO_2, particles	168 excess deaths.
Seveso, Italy July, 1976	Reactor explosion releasing dioxin plume and cloud settled over an area of 1430 hectares	No excess deaths, 187 cases of skin chloracne, 32 official abortions, 15 cases of deformed births and 6 premature offspring, dizziness, diarrhea.
Bhopal, India, Dec. 1984	Release of 30 tonnes of deadly methyl isocynate gas from storage tanks due to alleged failure of vent scrubber system	Estimated deaths more than 2500; 1,00,000 people severely affected, vomiting, violent coughing, chemical conjunctivitis; suffocation, cardiac failure.

In this context, it is interesting to compare London episodes of 1952 and 1962. Compared to those in the 1952 episode, the SO_2 levels in 1962 changed relatively little while the particulate concentration decreased by more than 50%. The mortality decrease was al substantial, possibly indicating either a dominating role of particulates or the availabili of better medical facilities in 1962. The synergistic damage to health was particular severe on the aged people who had been suffering from previously existing cardio-respirato diseases.

The air pollution disasters of Poza Rica, Mexico, Seveso, Italy and the worst ev disaster in Bhopal, India, are examples of so called industrial pollution accidents. Bhop provides an example of the failure in handling a toxic material in large-scale chemic processing and the consequences that have to be faced by a city in a short time. Th disaster struck Bhopal on December 3, 1984 when a pesticide manufacturing plant r leased a potent toxicant, methyl isocyanate gas, into the atmosphere due to the allege functional failure of 'vent scrubber' outlet. About 30 tonnes of the gas escaped from unde ground storage tanks resulting in the death of about 2500 people and severe disability an additional 1,00,000 of the city's population. The chief causes of deaths and casualtie were vomiting, violent coughing, eye infections (chemical conjunctivitis), suffocation, ca diac failure and pulmonary disorders. The full consequences are not yet known.

The greatest impact of air pollutants on human health, however, results from contin ued exposure to low concentrations under unexceptional conditions. These are chroni effects. It is believed that these effects occur through continued irritation by pollutant which interact with other environmental or biological factors to initiate disease or inten sify previously existing diseases. There are two general approaches to studying the chroni effects. One is epidemiological and the other is toxicological.

Epidemiological studies are statistical surveys on the effects of air pollution on huma populations under natural conditions. Such studies are extremely important, but due t the multiplicity of unknown factors it is not possible to establish a cause-effect relationshi Toxicological studies are conducted in the laboratory under controlled conditions. Th effect of several variables such as pollutant concentration, exposure duration, temperature humidity etc. can be experimentally studied. Even though these experimental studies ca clearly demonstrate a direct cause-effect relationship between certain pollutants an sickness or death, their relevance to natural setting is sometimes questionable.

Respiratory Effects

Pollutants may enter the body by a number of ways. They can cause eye and skin irritation; certain particulates may be swallowed as a result of internal respiratory cleanin action or certain pollutants could even be ingested. But the primary mode of pollutan transfer into the human body is through the respiratory system.

The respiratory system is composed primarily of two lungs and the air passages which lead to them. The air passages begin at the nose and mouth, and include the windpipe (trachea) and its two branches known as bronchi. The bronchi divide into five main branches (the lobor bronchi) and then subdivide, finally, reaching the terminal bronchi (or respiratory bronchioles) deep within the lungs. At the end of bronchioles are the countless tiny air sacs known as alveoli. Alveoli are the functional units of the lung; it is across their membranes that oxygen diffuses from the air to the pulmonary capillaries and carbon dioxide diffuses in the opposite direction. The total surface area of all the alveoli within the lungs is about 50 square metres.

Particulate matter inhaled may be deposited in various regions of the respiratory system depending on particle size. Particles above 10 μm are almost wholly retained in the nose. Those below 10 μm escape entrapment and generally pass through the upper respiratory system. Fine particles in the size range 0.5 to 5 μm are deposited as far as bronchioles, but few reach the alveoli. The walls of the bronchi and bronchioles are lined with fine hair-like structures called cilia (Fig. 2.4). These are responsible for removing such fine particles along with the mucous by moving them upto the larynx where they may be eliminated by swallowing. The health risk is primarily from the deposition of the particles smaller than 0.5 μm in the alveoli where they cause damage to the respiratory organs.

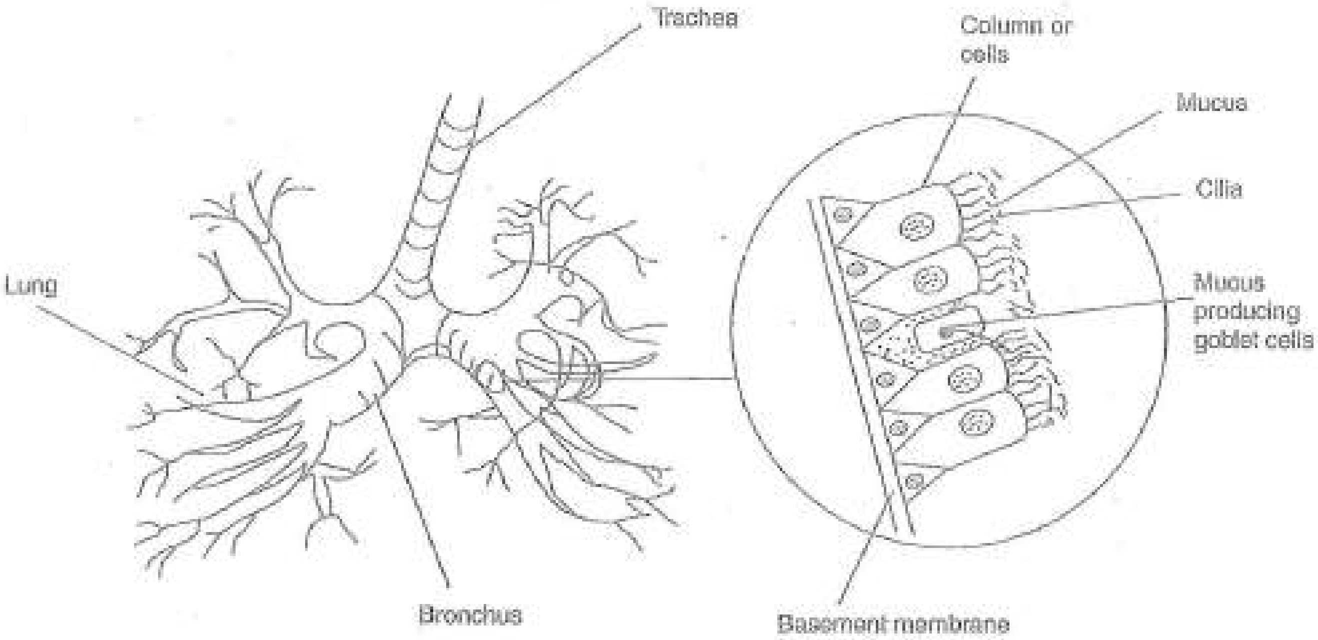


Fig. 2.4 Lower respiratory system showing bronchial lining

Particulate Matter

The toxic effect of particles can be grouped into three categories:

(*a*) *Interference of inert particles with the clearing mechanisms of the respiratory tract:* The effect includes a slowing of ciliary beat and mucus flow in the bronchial tree.

(*b*) *Particles act as carriers of adsorbed toxic gases such as SO_2 and produce synergistic effects:* A summary of some observed relations between particulates and SO_2 levels and the physiological responses is given in Table 2.7.

(*c*) *Particles may be intrinsically toxic because of their physical or chemical characteristics:* Such particles belong to metals which are usually found in the atmosphere in trace quantities but may constitute a great health hazard because of the possibility of their concentrations increasing beyond normal levels (0.01 to 3.0 per cent of all particulate air pollution). Of all the trace metals found in the atmosphere, the one present in largest concentration is lead. In addition to lead, cadmium, nickel and mercury represent known and widespread health hazards. Their sources and the possible effects are summarised in Table 2.8.

Table 2.7 Observed relations between particulates and SO_2 levels and health effects (ref. 19)

Condition	Effects
1. Particulate level of 750 μg/m^3 with SO_2 at 715 μg/m^3 (0.25 ppm), both 24-h mean	Increased daily death rate; substantial increase in illness of persons with bronchitis
2. Low particulate level with SO_2 levels ranging between 300 and 500 μg/m^3 (0.11-0.19 ppm), both 24-h mean	Increased hospital admissions of elderly people respiratory disease cases; increased absenteeism among older workers
3. Particulate level of 300 μg/m^3 with SO_2 level of 600 μg/m^3(0.21 ppm), both 24-h mean	Worsening of symptoms in persons suffering from chronic bronchitis.
4. Particulate level of 185 μg/m^3 with SO_2 levels ranging between 105 and 265 μg/m^3 (0.04-0.09 ppm), both annual mean	Increased frequency of respiratory symptoms and lung disease
5. Particulate level of 100 μg/m^3 with SO_2 level of 120 μg/m^3 (0.05 ppm), both annual mean	Increased incidence of respiratory disease among school children

Table 2.8 Major toxic metals and their effects

Element	Sources	Health effects
Lead	Auto exhaust (from gasoline), paints, storage bacteries, pipes	Neurotoxin, effects blood system, behavioural disorders, death
Cadmium	Coal, zinc mining, incineration of plastic containers, refining of metals, tobacco smoke	Cardiovascular disease and hypertension, interference with zinc and copper metabolism, kidney damage
Nickel	Combustion of coal, diesel and residual oils, tobacco smoke, chemicals and catalysts, steel and non-ferrous alloys manufacture	Respiratory symptoms, lung cancer (as nickel carbonyl)
Mercury	Combustion of fossil fuels, evaporation from ore mining, exhausts from metal smelters, chloralkali cells, paints, pharmaceuticals	Nerve and brain damage, kidney damage

Lead

The poisonous effects of lead on humans have long been recognised. Lead is a neurotoxin whose poisoning results in convulsions, delirium, coma, severe and irreversible brain damage, and death. Inhaled lead is far more serious than the ingested lead. The fine particles emitted by automobile are retained within the lungs and are absorbed by body with an efficiency of about 40 per cent. Extensive measurements of the size of lead particles in automobile exhaust have shown extremely small mean particle size (0.02 μm) besides the highways and much larger size (0.3-2.0 μm) in busy urban areas. About 80 per cent of the smallest particles are deposited in the lungs whereas only 20 per cent of the larger particles (0.5 µm) are retained.

The body maintains about 15-25 µg of lead per 100 g of whole blood. The body responds to any increase in the lead intake by excreting it in the urine as much as possible and the remainder is stored primarily in the bones. At elevated blood lead levels the production of hemoglobin is impaired resulting in oxygen starvation and anemia. High lead levels in the blood may also produce behavioural disorders in children and adults.

Cadmium

Cadmium is a potential health hazard due to its presence in urban atmosphere and cigarettes smoke. Cigarette smoking constitutes a major source for cadmium accumulation in the body. The natural cadmium levels in air vary from 0.002 µg/m^3 to much higher values of about 0.3 µg/m^3 found near zinc smelters. Cadmium inhibits the performance of certain enzymes thereby producing hypertension in humans. Exposure to fumes or oxides of cadmium is known to cause cardiovascular diseases. In addition, cadmium can interfere with proper zinc and copper metabolism in the body.

Very little is known about the fate and distribution of cadmium in the environment. It has a very long biological half-life and, therefore, tends to accumulate in the human body. Some of the chronic effects are kidney and liver damage and even death.

Nickel

The adverse effects of nickel are caused mainly due to nickel carbonyl which is formed when finely divided nickel is emitted into an atmosphere containing carbon monoxide. Nickel carbonyl is also formed in tobacco smoke. Within the lung the carbonyl complex breaks down and deposits finely divided nickel, which may be the main cause of cancer in the lungs. Nickel carbonyl has been shown to cause changes in the alveoli of the lungs, resulting in respiratory damage symptoms.

Mercury

Mercury in the atmosphere is only a small part of the overall mercury burden of the environment. It is present in gaseous form in the atmosphere because of its relatively high vapour pressure. The gaseous mercury is washed from the air by rain; a portion of it enters the aquatic systems and the remaining is bound to the soil over the land. In both cases the inorganic mercury is generally converted into its methyl or dimethyl compounds by the action of bacteria.

The physiological effects of mercury poisoning include neurological damage, chromosomal aberrations, and even death. Methylmercury can penetrate the membranes separating the bloodstream from the brain, causing injury to cerebellum and the cortex. The effects are blurring of vision and numbness. Another insidious effect of methylmercury is that it can cross the placental barrier in pregnant woman. High levels of mercury can build up in the fetus without the mother showing any signs of illness. The effects are congenital birth defects or the death of the fetus.

Other Toxic Substances

Apart from the four major toxic substances already discussed there are many other substances whose presence in the atmosphere due to industrial activities constitutes a health hazard. Two such substances which may be classified as occupational pollutants are beryllium and asbestos.

Most beryllium emissions are in the form of metallic powder or beryllium oxide particulates. Acute beryllium exposure is a very serious occupational problem affecting the mucus membranes of the eyes and lungs. A chronic condition known as berylliosis is thought to be caused by beryllium concentrations as low as 0.01 to 0.10 μg/m^3. Berylliosis is a systemic poisoning which starts with progressive shortness of breath, weight loss and cough, and finally affects many organs including the heart. When inhaled as dust, it can also cause lung cancer, but this has not been conclusively proved for humans. Major sources of beryllium emissions into the atmosphere are ceramic industry, processing plants which convert the ore into beryllium powder, rocket motor test facilities, coal combustion, and nuclear power industry.

"Asbestos" is an industrial term for a number of hydrated silicates which separate into strong flexible fibres upon crushing and processing. The most abundant type of asbestos is known as chrysolite, which is the main fibre used in asbestos textiles. Inhalation of asbestos dust or fibres can cause a disabling lung disease known as asbestosis. The disease is characterised by shortness of breath and pleural calcification. Asbestos has also been implicated in lung cancer. The fibres line the membranes of the lungs and abdomen and this can lead to mesothelioma, an incurable and fatal cancer. It has been observed that the frequency of cancer is eight times higher among asbestos workers who smoke compared to that among non-smoking workers. Asbestos in the atmosphere comes from many uses of asbestos products which include insulating materials, asbestos cement and brake linings.

Gaseous Pollutants

The effects of gaseous pollutants on the respiratory system depend on the concentration, period of exposure, and the solubility. Highly soluble gases such as sulphur dioxide are absorbed in the upper part of the respiratory system whereas relatively insoluble gases like CO, NO_2 and ozone penetrate deep and reach the alveoli of the lungs. Some of the adverse effects of these pollutants include pulmonary edema, emphysema, and prevention of oxygen transfer to blood.

(a) Sulphur Dioxide

There is considerable evidence that SO_2 aggravates existing respiratory diseases in humans and contributes to their development. Even healthy individuals experience broncho-constriction when exposed for a few minutes to levels of 1.6 ppm. This condition is accompanied by shallow breathing and an increased respiratory rate. The acute irritant effects of the gas are confined to the upper respiratory tract where more than 95 per cent of inhaled SO_2 is absorbed. The chronic effects resulting from extended exposure to low concentrations include incidence of respiratory infection in children. Table 2.9 summarises the effects of SO_2 at various concentrations.

The primary threat of SO_2 to urban atmospheres may arise not from SO_2 itself but from the changes it undergoes in the atmosphere, such as the formation of H_2SO_4 and sulphate aerosols. The sulphate particles can be carried deep into the lungs, causing even more severe health problems. SO_2 can also be absorbed on small particulates such as the salts of iron, manganese and vanadium present in the atmosphere and thus enter the alveoli. There, in the presence of moist air, SO_2 is oxidised to H_2SO_4 and the particulates act as catalysts in enhancing the oxidation process.

Table 2.9 Effects of sulphur dioxide on humans (ref. 8)

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 irritation
10	Eye irritation
20	Immediate coughing

(b) Carbon Monoxide

Carbon monoxide, when inhaled, passes through the lungs and diffuses directly into the blood stream where it combines with the red blood pigment called hemoglobin forming carboxyhemoglobin, 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 and death could result by asphyxiation (lack of oxygen). In addition, the presence of COHb in the blood retards the dissociation of remaining oxyhaemoglobin, so the tissues are further deprived of oxygen.

Table 2.10 summarises the effects of various concentrations of COHb in the blood. These are the expected signs and symptoms of exposure to carbon monoxide in healthy individuals and those suffering from heart disease.

The equilibrium level of COHb may be estimated for concentrations of CO below 100 ppm in the inhaled air by using the approximate equation[21]:

$$\%\text{COHb in blood} = 0.16\ (\text{ppm.CO}) + 0.5 \qquad \text{...(2.38)}$$

The equilibrium levels are not established instantaneously and it requires at least 8 hrs. before the maximum level of COHb in the blood is attained. The time span can decrease considerably with increase in physical activity.

Carbon monoxide levels in cities are usually between 10 to 40 ppm on an annual 8-hr average basis and occasional short term concentrations may exceed 100 ppm. These levels can easily lead to COHb concentration in blood of approximately 2 to 8 per cent. Table 2.11 lists typical concentrations in various urban areas. A concentration of upto 500 ppm in the air, when inhaled for 1 hr produces no observable symptoms but a similar exposure to 1000 ppm can be dangerous. Concentrations of 4000 ppm and above are fatal, usually within 1 hr. Increased COHb in the blood deprives oxygen supply to various vital organs, especially the brain. This leads to impairment of mental performance, visual acuity and other functions.

Table 2.10 Health effects of COHb blood levels (ref. 20) .

COHb blood levels (%)	*Effects on healthy individuals*	*Effects on heart patients*
1-5	Blood flow to certain vital organs increases to compensate for reduction in oxygen carrying capacity of blood	Heart patients may lack sufficient cardiac reserve to compensate
5-9	Visual light threshold increased	Patients with angina pectoris require less exertion to induce chest pain
16-20	Laboured respiration during exertion, visual evoked response abnormal	May be lethal for patients with severe cardiovascular disease
20-30	Headache, nausea	
30-40	Severe headaches; nausea and vomiting, dizziness	
40-50	Slurring of speech; tendency to collapse	
50-60	Convulsion; coma	
60-70	Fatal coma if not treated	

Table 2.11 Carbon levels in urban areas

City	*Maximum 1 hour CO values, ppm*
London	58
Chicago	46
Los Angeles	43
New York	27
Kolkata	35

The chronic effects of carbon monoxide are not fully known but they may induce heart and respiratory disorders. The long term studies are complicated by the presence of other pollutants such as NO_2 in the atmosphere. 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.

(c) Oxides of Nitrogen

The major oxides of nitrogen which affect human health are nitric oxide (NO) and nitrogen dioxide (NO_2). NO is not an irritant and at concentrations that occur in the atmosphere it does not show any adverse health effects. However, its main toxic potential results from its oxidation to NO_2.

NO_2 is relatively insoluble and upon inhalation can reach the moisture-filled alveoli of the lungs. There it is converted to nitrous and nitric acids which are highly irritating and cause damage to the lung tissues. Long term exposure to concentrations of the order of

1 ppm could lead to symptoms resembling emphysema and biochemical alterations in blood. Other observed effects on humans are given in Table 2.12. In addition to the direct effects mentioned therein, NO_2 in combination with hydrocarbons acts as the initiator of photochemical smog leading to the production of secondary pollutants like the oxidants. These oxidants are the ones that cause most damage to human health.

Table 2.12 Effects of atmospheric NO_2 (ref. 22)

Effect	*NO_2 Conc. (ppm)*	*Exposure*
Increase in acute respiratory disease	0.06-0.1	2-3 years
Increase in acute bronchitis in school children	upto 0.1	6 months
Human olfactory threshold	0.12	< 24 hrs.
Increase in airway resistance	5	10 min
Pulmonary edema	90	30 min.

(d) Hydrocarbons and Photochemical Oxidants

At the concentrations usually found in urban air, the hydrocarbons cause no adverse effects on human health. Aliphatic hydrocarbons produce undesirable effects only at concentrations 10^2 to 10^3 times higher than those usually found in the atmosphere. No effects have been observed for levels below 500 ppm. Aromatic hydrocarbons are more reactive than aliphatic ones and cause irritation of the mucous membranes.

The major oxidant produced in photochemical smog is ozone. Contrary to the popular belief, ozone appears to have no effect on the eyes at usual urban concentrations. The respiratory system, however, may respond to very low concentrations. There is a definite increase in airway resistance in some people exposed to concentrations as low as 0.1 ppm. Many other oxidants produced in photochemical smog, particularly the peroxyacyl nitrates, cause eye irritations. Oxidants such as peroxyacetyl nitrate and peroxybenzoyl nitrate irritate the nose and throat, and cause chest constriction. The one with the lowest threshold is peroxybenzyl nitrate, having a value of 0.005 ppm for five-minute exposure. Table 2.13 summarises the effects of ozone and total photochemical oxidants on humans.

Table 2.13 Effects on health of ozone and total photochemical oxidants (ref. 23)

Effects	*Conc. ppm*	*Exposure*
Ozone		
Increased airway resistance	0.1-1.0	1 hour
Extreme fatigue, lack of coordination	1.0-3.0	2 hours
Severe cough	2.0	2 hours
Pulmonary edema	9.0	Unknown
Total oxidants		
Eye irritation	0.1	Instantaneous
Aggravation of asthma	0.050-0.06	1 hour
Impaired performance of athletes	0.03-0.3	1 hour

2.5.2 Air Pollution Effects on Vegetation

The most obvious damage caused by air pollutants to vegetation occurs in the leaf structure. The surface of a leaf is covered by a waxy layer known as the *cutile*. In between the waxy layer is the epidermis, a single layer of cells forming the surface skin of the leaf (Fig. 2.5). It's chief functions are the protection of the inner tissues from excessive moisture loss and the admission of carbon dioxide and oxygen to these internal tissues.

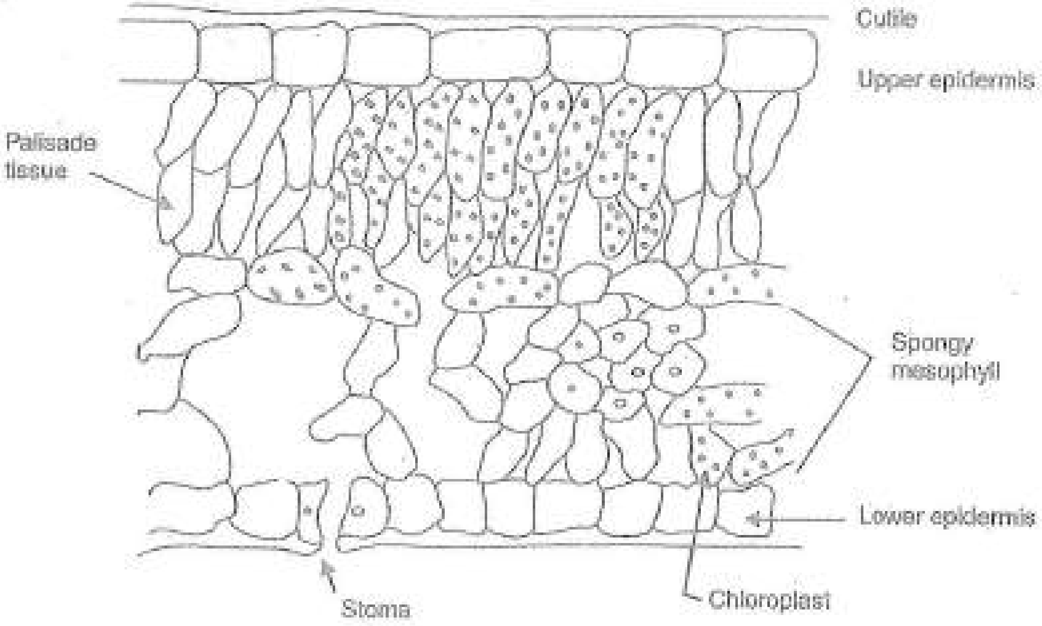


Fig. 2.5 Cross section of a common leaf

The leaf surface is penetrated by a large number of openings called the stomata. Each stoma is protected by a pair of guard cells, which control the opening and closing of the stoma. The internal tissues of the leaf are the palisade, the spongy mesophyll, and the conducting tissues, or veins, which carry water, minerals and food. Of particular interest with regard to air pollution are the stomata through which gases diffuse to the surface of the cells within the leaf.

The damage caused by air pollutants is of several types like necrosis, chlorosis and epinasty. The dead areas on a leaf structure are referred to as necrosis. Chlorosis is the loss or reduction of chlorophyll and leads to the yellowing of the leaf. Epinasty is a downward curvature of the leaf due to higher rate of growth on the upper surface, and the dropping of leaves is called *abscission*. Few plant species are spared damage on exposure to one or more of the principal air pollutants. In general, the pollutants enter the inner tissues through the stomata, where they destroy the chlorophyll and disrupt photosynthesis. The adverse effects range from reduction in growth rate to death of the plant.

The effect of particulates on vegetation is not well known. However, some specific dusts have been observed to cause damage. Cement dust deposited on leaves, on combination with mist or light rain, forms incrustations. Plugging of stomata may occur, resulting in plant damage. Chemicals such as arsenic and fluorides when deposited on the leaves can poison animals. The effects of specific pollutants on vegetation are summarised in Table 2.14.

Table 2.14 Effects of specific air pollutants on vegetation

Pollutant	*Level (ppm) and exposure*	*Effects*
SO_2	0.3 to 0.5 for several days	Bleached spots, chlorosis, chronic injury to spinach, and other leafy vegetables
NO_2	0.25 for 8 months	Increased abscission and reduced yield in citrus plants
	0.5 for 10-12 days	Suppressed growth of tomatoes
	3.5 for 21 hours	Spots of mild necrosis on cotton and bean plants
	25 to 1 hour	Acute leaf injury
Ozone	0.03 for 8 hours, time effect reduced if low level SO_2 is also present	Fleck on upper surface; Necrosis and bleaching; damage to tobacco leaves at O_3 = 0.027 ppm and SO_2 = 0.24 ppm after 2 hours of exposure
Peroxyacetyl nitrate (PAN)	0.01 to 0.05 for a few hours	Glazing or bronzing of underside of leaf; damage to sensitive plants; young leaves more susceptible to damage
HF	0.001 for 7-21 days can be significant; cumulative effect	Necrosis of leaf tip, grapes are particularly susceptible
Ethylene	0.1 for several hours or 0.05 for several weeks	Epinasty; leaf abscission, flower droppings

2.5.3 Effects of Air Pollution on Materials

The damage caused by atmospheric pollutants to materials is a well-known phenomenon. Particulates such as soot, dust and fumes soil painted surfaces, fabrics and buildings, and because of their abrasive nature, particulates can cause damage to exposed surfaces when they are driven by wind at high velocities. Through their own corrosiveness or in the presence of SO_2 and moisture, they can accelerate the corrosion of steel, copper, zinc and other metals.

The most notorious pollutant responsible for metallic corrosion is sulphur dioxide. It has been reported that corrosion of hard metals such as steel begins at annual mean concentrations of 0.02 ppm (52 $\mu g/m^3$). At levels of 0.09–1 ppm, SO_2 affects fabrics, leather and paint. SO_2 is readily absorbed by leather and causes its disintegration. Paper is also discoloured by SO_2 and becomes brittle and fragile. Sulphuric acid mist in the atmosphere causes deterioration of structural materials such as marble and limestone. Many priceless marble sculptures and buildings have suffered damage in the last 30 years as a result of increased SO_2 content in the atmosphere.

Ozone is a very reactive substance. Much of the degradation of materials, such as fabrics and rubber, now attributed to "weathering" is caused primarily by ozone. Ozone causes the cracking of synthetic rubbers at atmospheric levels of 0.01 to 0.02 ppm (20-40 $\mu g/m^3$). It also attacks fabric fibres and the adverse effects increase in the order: fibres made of cotton, acetate, nylon and polyester. The fading of fibres and the cracking of rubber are attributed to ozone's oxidising ability. Nitrogen oxides, although less widely publicised than ozone, are known to cause fading in acetate, cotton and rayon fibres at levels of 0.6-2 ppm over 2-3 month period. It has been observed that particulate nitrates attack and damage nickel-brass alloys in the presence of moisture.

2.5.4 Damage to Health, Vegetation and Materials in India

In India no systematic or statistical data are available on the health status of the people exposed to air pollution. Firstly, the data base is extremely poor. According to one estimate, as many as 60 million people are affected in one way or the other by air pollution[24]. Epidemiological data should be collected at the regional and national levels on the effects of air pollutants on human health. The nature of damage caused to tropical and subtropical vegetations by air pollution is almost unknown. Reports of SO_2 damage to plants like banana, grapes, papaya, coconut etc., are scattered, and no systematic assessment is available. Most of the information available in literature is applicable to countries of moderate climate in Europe and North America, and it is of very little use for assessing the damage to tropical broad-leaved plants.

The information on materials damage due to air pollution is very scanty. However, the information on corrosive effects of acid precipitation on metals is available for a few cities. Due to high concentration of industrial discharges and salinity and humidity in the air, corrosion rates in Mumbai are reported to be 3 to 6 times higher than those in other similar coastal areas of the country.

2.6 AIR POLLUTION LAWS AND STANDARDS

The main objective of enacting any pollution law is to control pollutant sources so that ambient pollutant concentrations are reduced to levels considered safe. The oldest antipollution law in India is the "Smoke Nuisance Act" enacted as early as 1920 by the then Bombay Government. The act was originally applicable to Bombay city, but was later extended to cover the entire state. It laid down rules and regulations concerning the size and height of chimneys and boilers in textile mills, besides listing measures to be effected for treatment of smoke. Similarly, a few other states in the country came up with their own smoke nuisance acts. Further, almost all the states have a clause on nuisance control in their municipal corporation acts. However, these acts have either loopholes or they are outdated in context of the development of numerous chemical, metallurgical and power plants. Hence, the need for strict monitoring of air pollutants and their control through detailed regulations is very essential. The Central Air (Prevention and Control of Pollution) Act, 1981 is a significant development in this direction.

The act provides an integrated approach to tackling of problems related to pollution. It empowers the Central Board for Prevention and Control of Water Pollution, constituted under the Water (Prevention and Control of Pollution) Act, 1974, to exercise the powers and perform the functions of the Central Board for the Prevention and Control of Air Pollution also. The main functions of Central Board include the following:

(a) Advise the government of India on matters concerning the prevention, control or abatement of air pollution.

(b) Coordinate the activities of the State Boards and provide technical assistance and guidance to them.

CHAPTER

EIGHT

METEOROLOGY AND NATURAL PURIFICATION PROCESSES

Pollution problems arise from the confluence of atmospheric contaminants, adverse meteorological conditions, and, at times, certain topographical conditions. The air pollution episodes mentioned in the previous chapter all involved meteorological conditions that restricted dispersion of contaminants, causing them to accumulate at harmful levels.

Because of the close relationship that exists between air pollution and certain atmospheric conditions, it is necessary for the environmental engineer to have a thorough understanding of meteorology. Even the most cursory exploration of the conditions which prevail in the greater Los Angeles basin, in the metropolitan Denver area, in Athens, or in any smog-troubled city will give a fair understanding of the cause-effect relationship between meteorological and topographical conditions and air pollution. That relationship will be explored in depth here, with special emphasis being given to the effect of meteorological elements on the dispersion of pollutants in the atmosphere and, conversely, to the influence of atmospheric contaminants on meteorological conditions.

Elemental Properties of the Atmosphere

The preceding chapter discussed the composition and structure of the earth's atmosphere. The source of all meteorological phenomena is a basic, but variable, ordering of the elemental properties of that atmosphere—heat, pressure, wind, and moisture. All weather, including pressure systems, wind speed and direction, humidity, temperature, and precipitation, ultimately results from variable relationships of heat, pressure, wind, and moisture.

8-1 SCALES OF MOTION

The interaction of these four elements may be observed on several different levels or scales. These *scales of motion* are related to mass movements of air which may be global, continental, regional, or local in scope. According to their geographic range of influence, the scales of motion may be designated as *macroscale, mesoscale*, or *microscale*. [8-30]

Macroscale

Atmospheric motion on the macroscale involves the planetary patterns of circulation, the grand sweep of air currents over hemispheres. These phenomena occur on scales of thousands of kilometers and are exemplified by the semipermanent high- and low-pressure areas over oceans and continents.

The sun's rays heat the earth near the equator to a greater extent than at the poles. If the rotation of the earth were discounted, the heated air at the equator would rise, and cool air from the poles would move in to take its place. This would set up two theoretical cells, involving only longitudinal motion [8-18], as shown in Fig. 8-1.

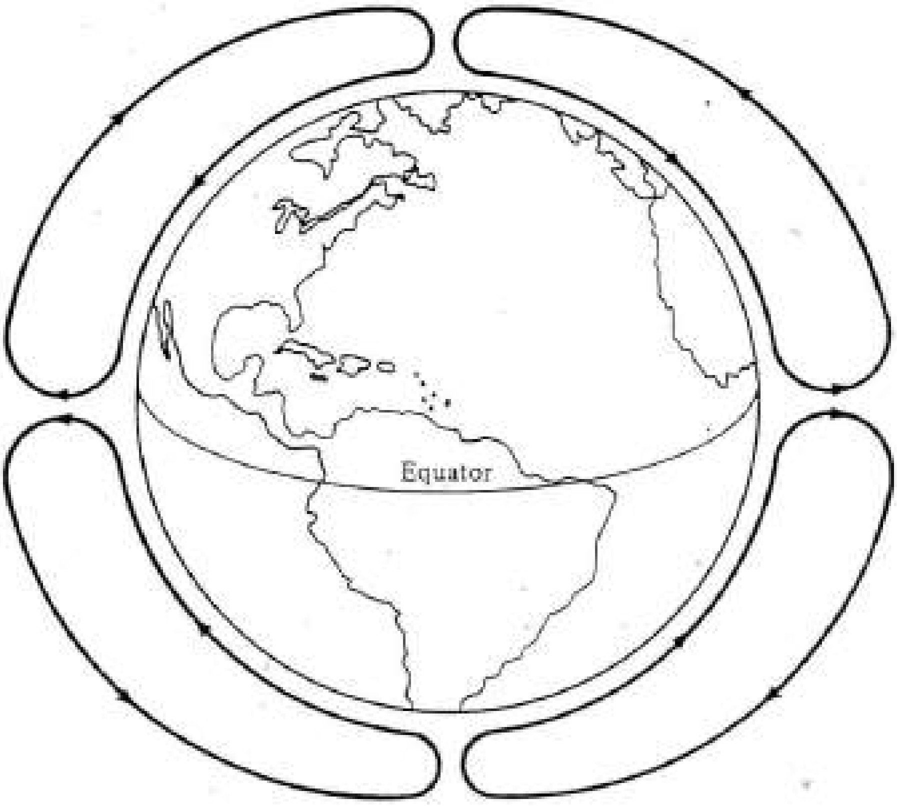


Figure 8-1 Halley's suggestion for general global circulation. (*From Linsley* [*8-18*].)

However, the west-to-east rotation of the earth must be taken into account, since it has a profound effect on air currents, deflecting the winds to the right in the 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*, and this force has major significance in the formation of weather. [8-7]

Thus, air movement on the global scale is not simply in longitudinal directions, for the dual effect of heat differential between poles and equator and of the rotation of the earth along its axis establishes a more complicated pattern of air circulation. As indicated in Fig. 8-2, the general global circulation pattern (macroscale) is composed of three cells of air movement in each hemisphere. [8-18] It is under this dual influence of thermal convection and the Corolis force that high- and low-pressure areas, cold or warm fronts, hurricanes, and winter storms are formed.

One of the primary elements influencing air mass movement on this scale is the distribution of land and water masses over the surface of the earth. The great variance between conductive capacities of land and ocean masses accounts for the development of many of our weather systems. Over land masses, atmospheric temperature rises rapidly in the presence of solar radiation (day), then drops with

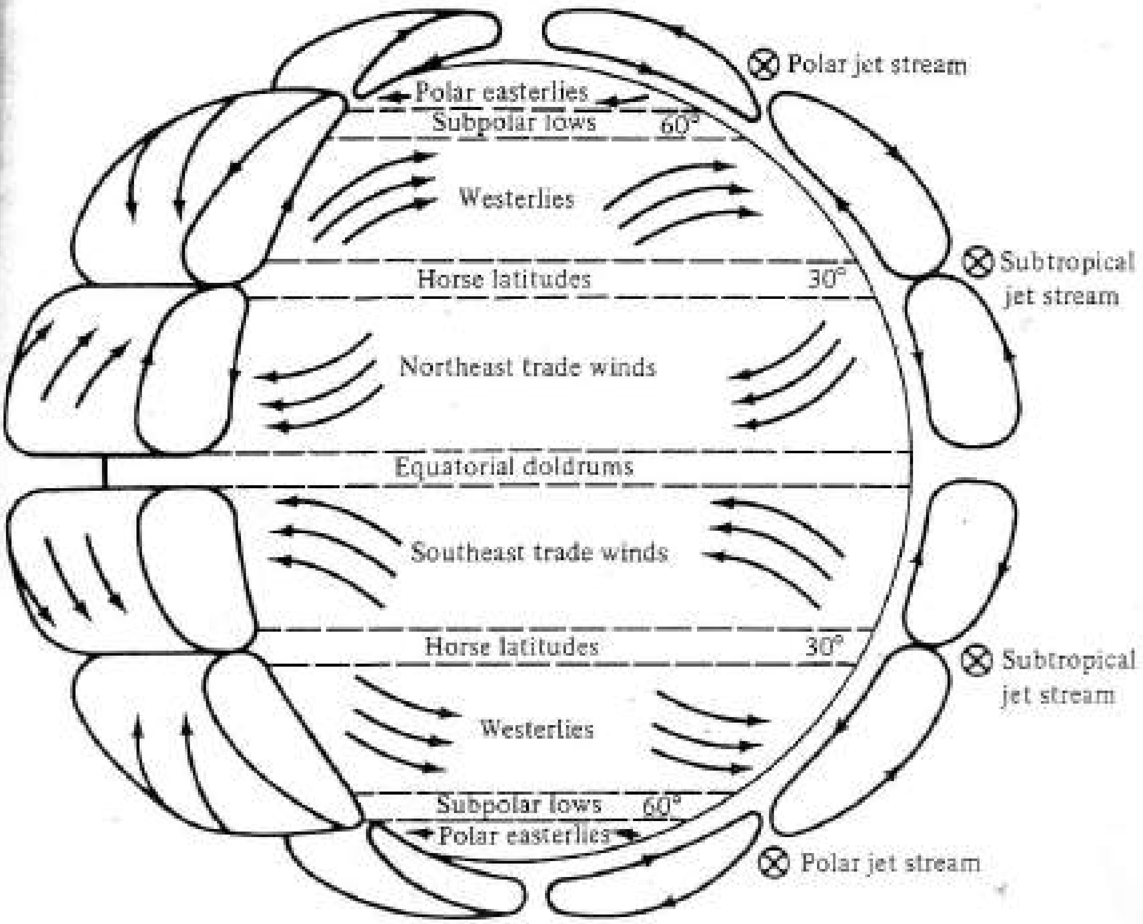


Figure 8-2 Schematic representation of general circulation. (*From Linsley* [*8-18*].)

equal rapidity in its absence (night), since landmasses quickly reradiate heat into the atmosphere. Conversely, air temperature over water rises and falls more slowly, since heat energy received by water penetrates to deeper layers than heat absorbed by land and is reradiated in lesser amounts.

Mesoscale

Secondary, or mesoscale, circulation patterns develop over regional geographic units, primarily because of the influence of regional or local topography. These phenomena occur on scales of hundreds of kilometers. Air movement on this scale is affected by the configuration of the earth's surface—the location of mountain ranges, of oceanic bodies, of forestation, and of urban development. Land or sea breezes, mountain or valley winds, migratory high- and low-pressure fronts, and urban heat islands are typical of the peculiarly local phenomena observable on this scale. [8-30]

Microscale

Microscale phenomena occur over areas of less than 10 k and can be exemplified by the meandering and dispersion of smoke plumes from industrial stacks. Phenomena on this scale occur within the *friction layer*, the layer of atmosphere at ground level where effects of frictional stress and thermal changes can cause winds to deviate markedly from a standard pattern. The frictional stress encountered as air moves over and around irregular physical surfaces such as buildings, trees, bushes, or rocks causes mechanical turbulence which influences the pattern of air movement. Radiant heat from stretches of urban asphalt and concrete, desert sands, or other such surfaces causes thermal turbulence that also influences air movement patterns. [8-13]

Macroscale circulation patterns have little direct influence on air quality in most cases. Noted exceptions are Los Angeles, California, and Santiago, Chili, two cities whose air quality is directly affected by the presence of high-pressure cells related to circulation patterns of macroscale.

It is the movement of air on mesoscale and microscale levels that is of vital concern to those charged with the control of air pollution. A study of air movement patterns over relatively small geographic regions can help determine how well pollutants will be dispersed into the upper atmosphere in those regions.

8-2 HEAT

Heat is the critical atmospheric variable, the major catalyst of climatic conditions. The heat energy in the atmosphere comes from the sun as short-wave radiation (about 0.5 μm), mostly in the form of visible light. The earth emits much longer waves (average of 10 μm) than it receives, mostly in the form of nonvisible heat radiation.

Some of the solar rays never reach the earth at all but are reflected back to space by individual particles in the air and by clouds. Solar rays may also be reflected back to space by the ground itself, with surface characteristics being a major factor in the rate of reflection. For example, desert sands, snow, and ice have a high rate of reflection, while forests and cultivated fields have a low rate.

Some of the sun's rays are scattered by intervening air molecules. It is this scattering of rays of different wave lengths that gives a clear sky its deep blue color. Scattering is more intense as the sun moves near the horizon, and it is this phenomenon that produces red sunrises and sunsets.

Some of the sun's rays are absorbed by ozone, water vapor, carbon dioxide, dust, and clouds of the lower atmosphere, but the earth's surface is the prime absorber of solar energy. Thus the troposphere is heated primarily from the ground, not from the sun. [8-29]

Tropospheric Heating

Four important ways in which heat transfer occurs in the troposphere are through the "greenhouse effect", the condensation-evaporation cycle, conduction, and convection.

Greenhouse effect As noted earlier, solar energy (light radiation) absorbed by the earth is converted to heat energy and emitted into space as long-wave (heat) radiation. Although water vapor and carbon dioxide are transparent to short-wave radiation, they are nearly opaque to long-wave radiation. Thus, much of the earth's reradiation is retained, raising the temperature of the atmosphere. This phenomenon is known as the *greenhouse effect*, taking its name from the principle of greenhouse construction, where glass operates in a fashion similar to carbon dioxide and water vapor, allowing solar rays to pass unhindered into the greenhouse, but blocking reverse radiation. [8-29]

Evaporation-condensation cycle Evaporation of water requires expenditure of energy, and the needed energy is absorbed from the atmosphere and stored in water vapor. Upon condensation, this heat energy is released. Because evaporation usually takes place on or near the earth's surface, while condensation normally occurs in the upper regions of the troposphere, the evaporation-condensation process tends to move heat from lower regions to higher regions.

On the macroscale, latent heat is transported from latitude belts where there is substantial precipitation. Below about 22° latitude, water vapor and latent heat are carried equatorward, while at higher latitudes they are carried poleward. [8-2]

Conduction Transfer of heat from earth to atmosphere is also accomplished through the process of *conduction*, heat transfer by direct physical contact of air and earth. As parcels of air move downward, they come into contact with the warmer ground and take heat from the earth into the atmosphere.

Convection *Convection*, a process initiated by the rising of warm air and the sinking of cold air, is a major force in transferring heat from earth to troposphere. As can be seen in Fig. 8-2, convection is a primary factor in movement of air masses on the macroscale.

Temperature Measurement

Maximum, minimum, and average temperatures are generally recorded at weather stations, and normal daily temperatures for a specific region can be calculated by averaging daily temperatures over a 10-, 20-, or 30-yr period. A temperature designation of particular interest to the environmental engineer is the *degree-days* of an area, since this figure is a measure of heating and fuel requirements and hence of air pollution potential from the burning of fossil fuels. The heating-degree-day of a region is calculated by subtracting the average daily temperatures for a year from a preselected "comfortable" temperature usually 18°C. The number of degrees by which the average daily temperature falls below this standard temperature yields the heating-degree-days for that region. [8-2]

Lapse Rates

In the troposphere, the temperature of the ambient air usually decreases with an increase in altitude. This rate of temperature change is called the *lapse rate*. This rate can be determined for a particular place at a particular time by sending up a balloon equipped with a thermometer. The balloon moves *through* the air, not with it, and the temperature gradient of ambient air, which the rising balloon measures, is called the *ambient lapse rate*, the *environmental lapse rate*, or the *prevailing lapse rate*. [8-2]

A specific parcel of air whose temperature is greater than that of the ambient air tends to rise until it reaches a level at which its own temperature and density equal that of the atmosphere that surrounds it. Thus, a parcel of artificially heated air (e.g., stack gas or automobile exhaust) rises, expands, becomes lighter, and cools. The rate at which the temperature decreases as the parcel gains altitude (the lapse rate) may be considerably different from the ambient lapse rate of the air through which the parcel moves. Thus, it is necessary to distinguish between the temperature decrease associated with the ambient lapse rate and the internal temperature decrease which occurs within a rising parcel of air or other gas.

The lapse rate for the rising parcel of air may be determined theoretically.* For calculation purposes, the cooling process within a rising parcel of air is assumed to be *adiabatic* (i.e., occurring without the addition or loss of heat). Under adiabatic conditions, a rising parcel of air behaves like a rising balloon, with the air in that distinct parcel expanding as it encounters air of lesser density until its own density

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* See Petterssen [8-27], p. 106, for a discussion of the adiabatic lapse rate.

is equal to that of the atmosphere which surrounds it. This pe[illegible]ssumed to occur with no heat exchange between the rising parcel and the ambient air.

Expansion of air against its surroundings, like all other work, requires energy. As long as the rising parcel is very close to the earth's surface, it may receive some heat energy from the earth. As soon as it rises beyond that energy source, it must rely on its own store of heat for energy. An internal cycle is thus established; temperature within the air parcel decreases as heat energy is expended. [8-2] Since this process involves no transfer of heat from the rising parcel to the atmosphere which surrounds it, it is called *adiabatic cooling*.

Utilizing two basic concepts of physics, the ideal-gas law and the law of conservation of energy, it is possible to establish a mathematical ratio expressing temperature change against altitude gain under adiabatic conditions. [8-27] This rate of decrease is termed the *adiabatic lapse rate*. Dry air, expanding adiabatically, cools at 9.8°C per kilometer, the dry adiabatic lapse rate. [8-32] In wet, as in dry adiabatic process, a saturated parcel of air rises and cools adiabatically, but a second factor affects its temperature. Latent heat is released as water vapor condenses within the saturated parcel of rising air. Temperature changes of the parcel are then due to liberation of latent heat as well as to expansion of the air. Wet adiabatic lapse rate (6°C/km) is thus less than dry adiabatic lapse rate. [8-27] Since a rising parcel of effluent gases would seldom be completely saturated or completely dry, the adiabatic lapse rate generally falls somewhere between these two extremes.

Stability

Ambient and adiabatic lapse rates are a measure of atmospheric stability. Since the stability of the air reflects the susceptibility of rising air parcels to vertical motion, consideration of atmospheric stability or instability is essential in establishing the dispersion rate of pollutants.

The atmosphere is said to be *unstable* as long as a rising parcel of air remains warmer (or descending parcel remains cooler) than the surrounding air, since such a parcel will continue to accelerate in the direction of the displacement.

Conversely, when a rising parcel of air arrives at an altitude in a colder and denser state than the surrounding air, the resultant downward buoyancy force pushes the displaced parcel of air earthward and away from the direction of displacement. Under such conditions, the atmosphere is said to be *stable*. [8-2]

Stability is a function of vertical distribution of atmospheric temperature, and plotting the ambient lapse rate against the adiabatic lapse rate can give an indication of the stability of the atmosphere. Though dry, moist, or wet adiabatic lapse rates may be used in such a comparison, the dry adiabatic lapse rate (9.8°C/km) is used in Fig. 8-3 as the measure against which several possible ambient lapse rates are plotted. Thus, in Fig. 8-3, the boundary line between stability and instability is the dry adiabatic lapse rate.

When the ambient lapse rate exceeds the adiabatic lapse rate, the ambient lapse rate is said to be *superadiabatic*, and the atmosphere is highly unstable. When

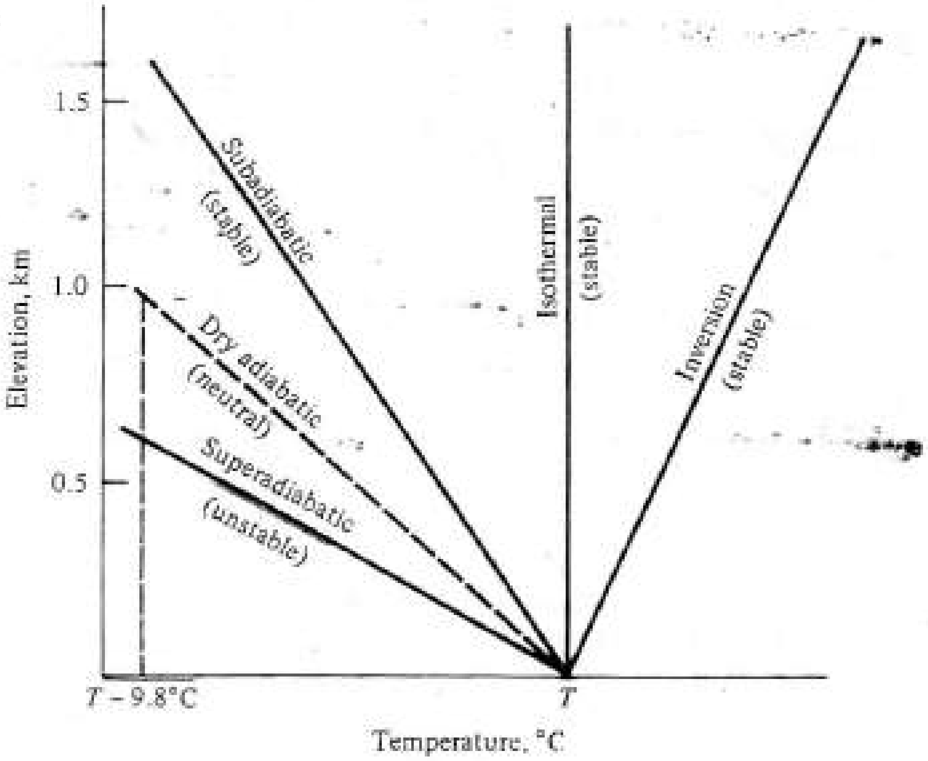


Figure 8-3 Relationship of the ambient lapse rates to the dry adiabatic rate.

the two lapse rates are exactly equal, the atmosphere is said to be *neutral*. When the ambient lapse rate is less than the dry adiabatic lapse rate, the ambient lapse rate is termed *subadiabatic* and the atmosphere is stable. If air temperature is constant throughout a layer of atmosphere, the ambient lapse rate is zero, the atmospheric layer is described as *isothermal*, and the atmosphere is stable. [8-2]

When temperature of the ambient air increases, rather than decreases, with altitude, the lapse rate is negative, or inverted, from the normal state. Negative lapse rate occurs under conditions commonly referred to as an *inversion*, a state in which warmer air blankets colder air. Thermal or temperature inversions represent a high degree of atmospheric stability. [8-2]

There are two types of inversions. The first is a *radiation inversion*, a phenomenon arising from the unequal cooling rates of the earth and the air above the earth. This type of inversion may extend a few hundred meters into the friction layer and is characteristically a nocturnal phenomenon that breaks up easily with the rays of the morning sun. A radiation inversion prompts the formation of fog and simultaneously traps gases and particulates, creating a concentration of pollutants.

The second type of inversion is the *subsidence inversion* that is usually associated with a high-pressure system. Such an inversion is caused by the characteristic sinking motion of air in a high-pressure cell. Air circulating around a stationary high descends slowly. As the air descends, it is compressed and heated, forming a blanket of warm air over the cooler air below and thus creating an inversion that prevents further vertical movement of air. This type of inversion may extend through the friction layer to heights of over 1500 m.

8-3 PRESSURE

In addition to heat, pressure is an important variable in meteorological phenomena. Because air has weight, the whole atmosphere presses down upon the earth beneath it. This pressure is commonly measured with a mercury barometer, an instrument which measures the weight, over a unit area, of a column of air extending to the top of the atmosphere. On the average, the atmosphere at latitude 45° and at a temperature of 0°C (32°F) is equivalent to a column of mercury 760 mm (29.9 in) high, and this, by international agreement, is called *one standard atmosphere*, or roughly one *bar*. Meteorologists usually express pressure in *millibars*, and one standard atmosphere is 1103 millibars. [8-29]

On weather maps such as the one shown in Fig. 8-4 pressure distribution throughout the atmosphere is represented by *isobars*, lines connecting points of equal atmospheric pressure. These lines delineate high- and low-pressure cells that influence the development of major weather systems.

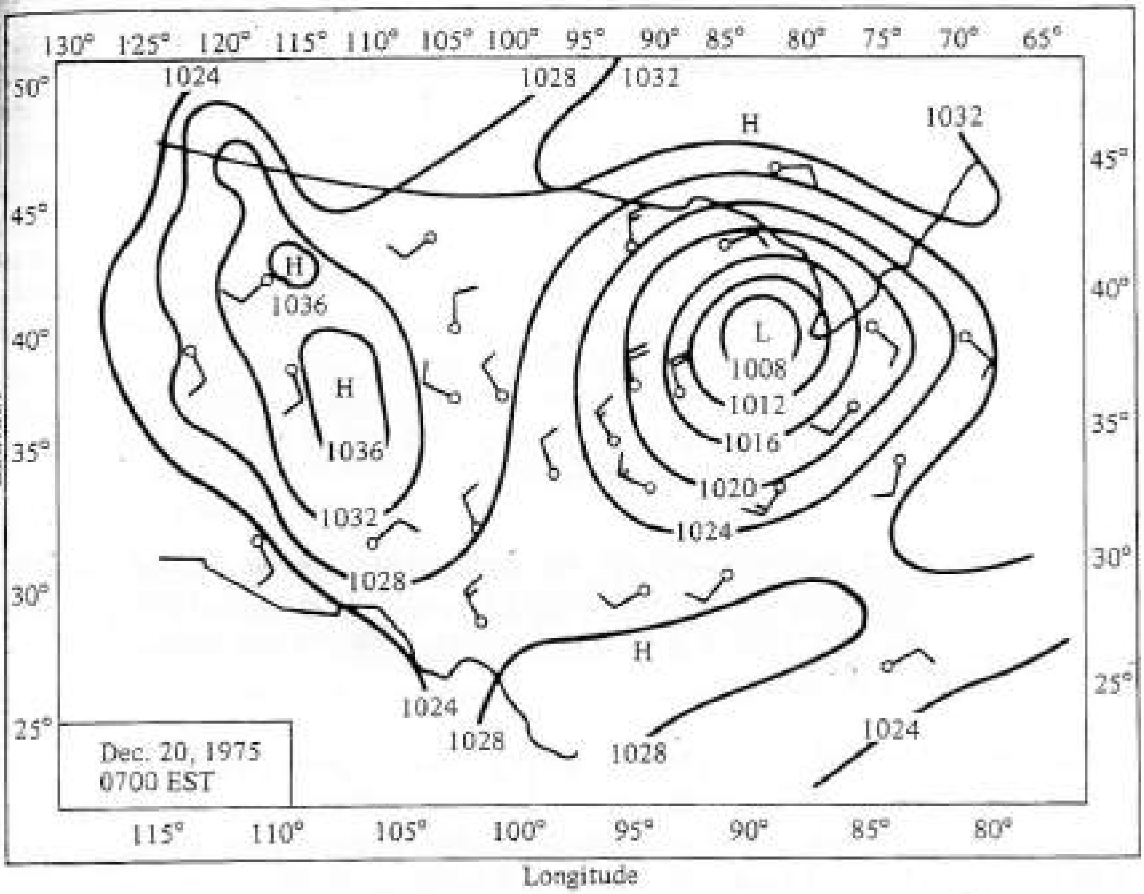


Figure 8-4 Sea-level isobars over the United States and observed wind velocities at selected stations. (*From Battan* [8-2].)

Pressure Systems

Pressure patterns over the earth are in constant flux as air pressure rises in some regions and falls in others. The 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 or cells. The circulation or movement of these high- and low-pressure systems is responsible for many weather changes. [8-36]

High-pressure systems High-pressure systems are related to clear skies, light winds, and atmospheric stability. In a typical high-pressure system in the northern hemisphere, the vertical motion of air is downward and the horizontal motion is clockwise. High-pressure systems reflect the relative uniformity of air masses. Under such stable conditions, temperature and humidity vary little over great areas, and any weather change is gradual. Under these stable conditions, dispersion is restricted and pollutants are likely to build to undesirable levels.

Low-pressure system In a typical low-pressure system in the northern hemisphere, horizontal air movement is counterclockwise and vertical movement is upward. Low-pressure systems are usually associated with cloudy skies, gusty winds, atmospheric instability, and the formation of fronts. Under such unstable conditions, dispersion of pollutants is likely, and air pollution problems are minimal. [8-36]

Fronts

Frequently two masses of air develop sharp boundaries with respect to temperature. When air masses having different properties come together, they do not mix readily. Warmer, less dense air tends to override the colder, denser air. The sloping, wedge-shaped zones of transition between two air masses of different density are called *fronts*. A front, either cold or warm, typically moves around its host low-pressure cell in a counterclockwise direction.

Warm fronts Warm fronts occur when warm air advances while cold air retreats. The warm air, being lighter, rises over the cold air, and a wide band of precipitation results. The precipitation is heavy at the beginning of the lift, but decreases as the warm air progresses. [8-16]

Cold fronts When cold air advances on a cell of warmer air, the resulting weather system is called a 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. [8-29]

When the transition zone between warm and cold air does not move one way or the other, that zone is called a *stationary front*. [8-2]

8-4 WIND

Wind is simply air in motion. On the macroscale, the movement originates in unequal distribution of atmospheric temperature and pressure over the earth's surface and is significantly influenced by the earth's rotation. The direction of wind flow is characteristically from high pressure to low, but the Coriolis force tends to deflect air currents out of these expected patterns.

On the mesoscale and microscale, topographical features critically influence wind flow. Surface variations have an obvious effect on the velocity and direction of air movement. Monsoons, sea and land breezes, mountain-valley winds, coastal fog, windward precipitation systems, urban heat islands—all are ready examples of the influence of regional and local topography on atmospheric conditions.

Wind channeling in river valleys is a phenomenon affecting many large urban areas. Updraft or up-mountain breezes, which predominate during warmer portions of the day, and nocturnal downdraft are weather phenomena peculiar to mountain valleys.

The variance of the conductive capacity of land and water accounts for another effect of topography on wind direction. Because land warms and cools more rapidly than neighboring bodies of water, the characteristic coastal winds fall into a pattern of daytime sea breezes and evening land breezes.

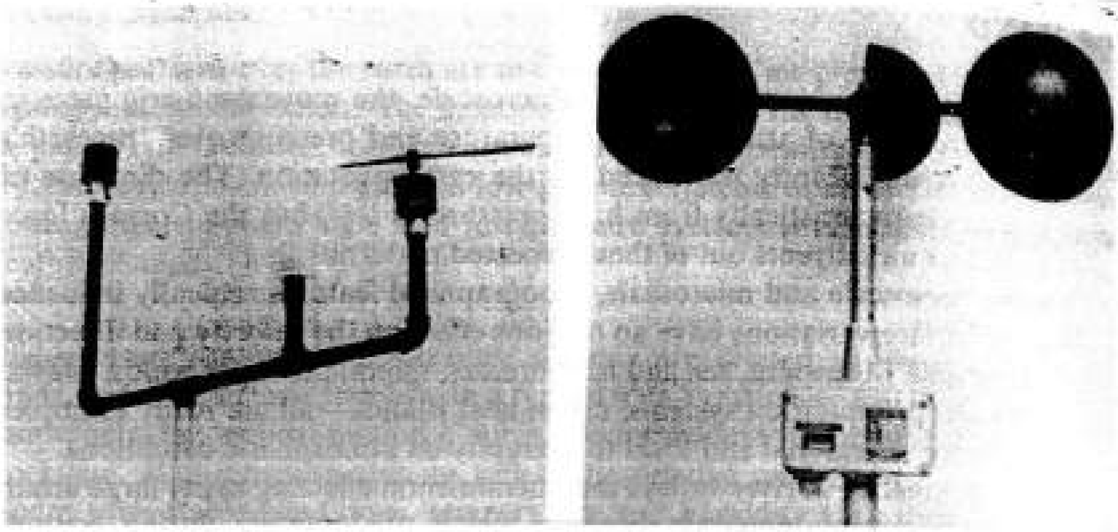
In the friction layer at the earth's surface, winds are often gusty and changeable, primarily due to locally generated mechanical or thermal turbulence. [8-15] Once free of the impediments of the friction layer, velocity of air movement generally increases, and winds aloft usually blow more steadily and more parallel to the isobars than do those in lower regions. An empirical formula relating wind speed to height in the friction layer, that zone of air beneath 700 to 1000 m (2,000 to 3000 feet), is

$$\frac{v}{v_0} = \frac{z^k}{z_0} \tag{8-1}$$

where v = wind speed at height z, m/s
v_0 = wind speed at anemometer level z_0, m/s
k = coefficient, approximately $\frac{1}{7}$

Wind speed is usually measured by an anemometer, an instrument typically consisting of three or four hemispherical cups arranged around a vertical axis. The faster the rate of rotation for the cups, the higher the speed of the wind. A three-cup anemometer and a wind vane for observation of wind direction are shown in Fig. 8-5.

When data for wind speed and direction are placed on a *wind rose*, they yield a graphic picture of the direction, frequency, and velocity of the winds in a particular location. For example, the wind rose shown in Fig. 8-6 indicates that the greatest percentage of winds in that month were from the southwest and that speeds of up to 8 m/s were recorded for winds from that direction. Relatively infrequent easterly winds were occasionally as high as 8 m/s. [8-38]



(a) (b)

Figure 8-5 Wind measurement instruments: (a) three-cup anemometer and wind vane; (b) close-up of three-cup anemometer.

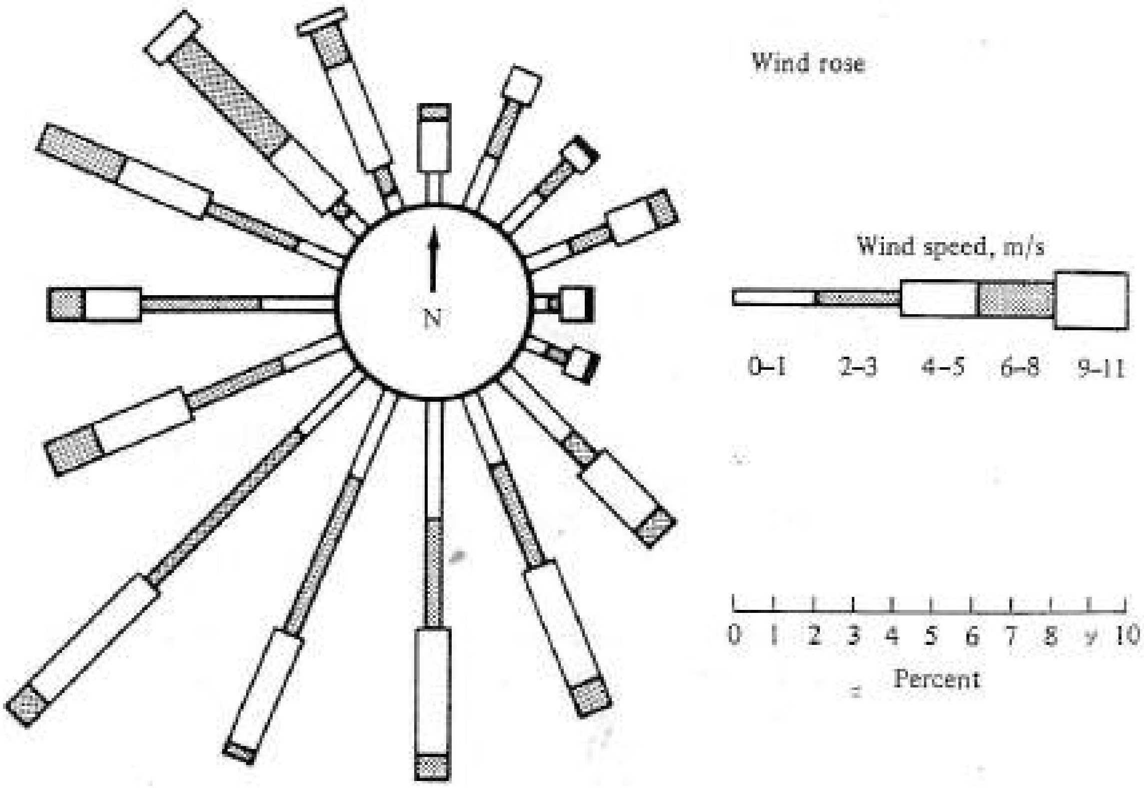


Figure 8-6 Wind rose. (*From Meteorological Aspects . . .* [8-22].)

5 MOISTURE

vaporation to condensation to precipitation is a constantly repeating cycle in ur environment, as discussed in Chap 2. Moisture is first transferred from the arth's surface into the atmosphere. This water vapor then condenses and forms ouds. The cycle completes itself as the condensed vapor is returned to the earth's urface in some form of precipitation—rain, hail, snow, or sleet.

Topography plays an important role in moisture distribution. Mountains end to force the rise of moisture-laden air, resulting in heavier precipitation on he windward side of a range.

8-6 RELATIVE HUMIDITY

The amount of water vapor present in the atmosphere is measured in terms of humidity. The higher the temperature of the air, the more water vapor it can hold before it becomes saturated. At ground level, a temperature increase of 11.1°C roughly doubles the moisture capacity of the atmosphere. Saturated air at 16°C thus contains approximately twice as much water vapor as saturated air at 5°C.

Relative humidity is measured by an instrument called a *psychrometer*. The dry-bulb thermometer of a psychrometer indicates the temperature of the air, while the wet-bulb thermometer measures the amount of cooling that occurs as the moisture on the bulb evaporates. With the difference in the two readings (called the *wet-bulb depression*) and the dry-bulb temperature, one can obtain relative humidity readings from psychrometric tables. [8-2]

Influence of Meteorological Phenomena on Air Quality

The meteorological phenomena which have been briefly discussed to this point exert a critical influence on air quality. As noted earlier, under adverse atmospheric conditions, the presence of air contaminants gives rise to problems of air pollution. Understanding the relationship between atmospheric conditions and air pollution problems can enable the environmental engineer to minimize the adverse effects of the relationship.

As a river or stream is able to absorb a specific contaminant load without undesirable results, so the atmosphere can assimilate a certain amount of air contamination without ill effects. Dilution of air contaminants in the atmosphere is an important process in preventing undesirable levels of pollutants in the ambient air. Atmospheric dispersion of air contaminants is the result of ventilation, atmospheric turbulence, and molecular diffusion. However, gaseous and particulate air contaminants are primarily dispersed into the ambient air through wind action and atmospheric turbulence, much of it on the microscale level.

8-7 LAPSE RATES AND DISPERSION

By comparing the ambient lapse rate to the adiabatic lapse rate, it may be possible to predict what will happen to gases emitted from a stack. In the following examples, the *dry* adiabatic lapse rate is used, but prediction of plume patterns is more likely to be accurate if the moisture content of the stack gas is taken into account when ambient and adiabatic lapse rates are compared.

When the ambient lapse rate is superadiabatic (greater than the adiabatic), the turbulence of the air itself causes the atmosphere to serve as an effective vehicle of dispersion. As indicated in Fig. 8-7*a*, the resultant plume is designated a "looping" plume. In this highly unstable atmosphere, the stream of emitted pollutants undergoes rapid mixing, and any wind causes large eddies which may carry the entire plume down to the ground, causing high concentrations close to the stack before dispersion is complete. [8-26] In areas where conditions make looping plumes likely, higher stacks may be needed to prevent premature contact with the ground.

When the ambient lapse rate is equal to or very near the dry adiabatic lapse rate, the plume issuing from a single chimney or smokestack tends to rise directly into the atmosphere until it reaches air of density similar to that of the plume itself. This type emission, called a *neutral plume*, is seen in Fig. 8-7*b*. [8-11]

However, this neutral plume tends to "cone" (see Fig. 8-7*c*) when wind velocity is greater than 20 mi/h [8-9] and when cloud cover blocks solar radiation by day and terrestrial radiation by night.

When the ambient lapse rate is subadiabatic (less than the dry adiabatic), the atmosphere is slightly stable. Under such conditions, there is limited vertical mixing, and the probability of air pollution problems in the area is increased. The typical plume in such a situation is said to be "coning," since it assumes a conelike shape about the plume line, as shown in Fig. 8-7*c*. While the dispersion rate is faster for a looping plume, the distance at which a coning plume first reaches the ground is greater. [8-26]

When the lapse rate is negative, as in the presence of an inversion, the dispersion of stack gas is minimal, because of lack of turbulence. In the extremely stable air, a plume spreads horizontally, with little vertical mixing, and is said to be "fanning" (Fig. 8-7*d*), and in flat country such a plume may be visible for miles downwind of its source. [8-9] In areas where radiation inversions are common, construction of stacks high enough to allow for discharge of emissions above the inversion layer is recommended. This solution is not practical for subsidence inversions, since they usually extend to much greater heights.

Extenuating circumstances can often alleviate or aggravate the pollution possibilities accompanying negative lapse rate conditions. For instance, when the lapse rate is superadiabatic above the emission source and inversion conditions exist below the source, the plume is said to be "lofting." As shown in Fig. 8-7*e*, a lofting plume has minimal downward mixing, and the pollutants are dispersed downwind without any significant ground-level concentrations. As long as stack height remains above the inversion, lofting will continue, but lofting is usually a

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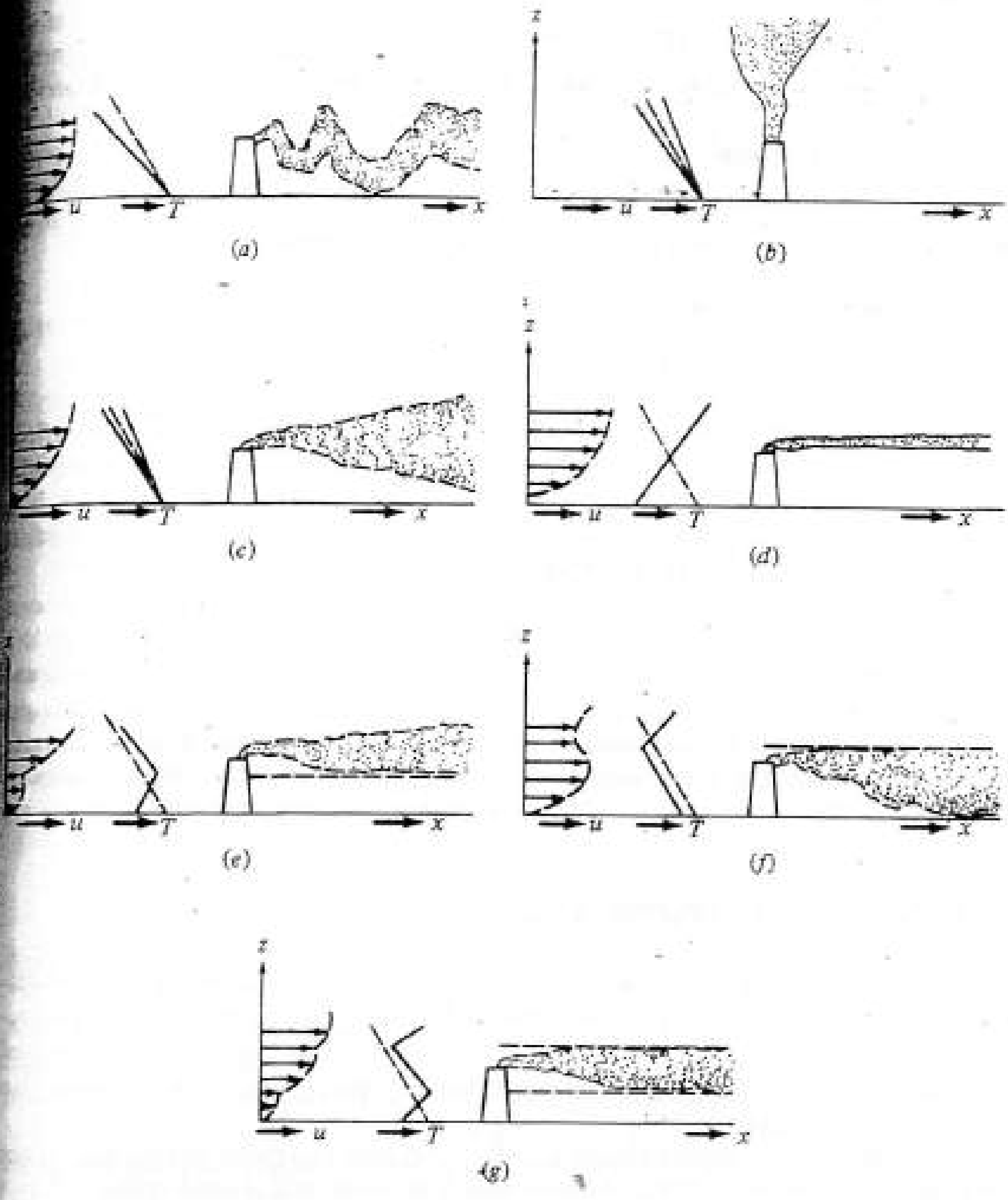


Figure 8-7 Effect of lapse rate on plume behavior (*a*) looping, (*b*) neutral, (*c*) coning, (*d*) fanning, (*e*) lofting, (*f*) fumigating, and (*g*) trapping.

transitional situation. If the inversion grows past the stack height, lofting will change to fanning. [8-26]

When an inversion layer occurs a short distance above the plume source and superadiabatic conditions prevail below the stack, the plume is said to be "fumigating" (Fig. 8-7*f*). Fumigating often begins when a fanning plume breaks up into a looping plume, as when morning sun breaks up a radiation inversion and the superadiabatic conditions below the inversion act to move the plume into a vigorously looping pattern. Fumigating can cause high ground-level concentrations of air contaminants, though these usually last only a relatively short period of time. [8-9]

Similar to the conditions which provoke the "fumigating" plume are the conditions which create a "trapping" effect. Here an inversion layer prevails both above and below the emission source. This results in the "coning" of the plume below the source and above the lower inversion, as seen in Fig. 8-7*g*.

8-8 PRESSURE SYSTEMS AND DISPERSION

The influence of meteorological conditions on air quality is also noted in the effect of pressure systems on dispersion of pollutants. It was previously stated that high-pressure systems are related to clear skies, light winds, and atmospheric stability. When such a system becomes stagnant over an area for several days, air contaminants can build up to cause air pollution problems.

Conversely, low-pressure systems are associated with unstable atmospheric conditions and commonly bring winds and rain; contaminant buildup is less likely to occur in low-pressure cells. [8-6] However, conflicting influences are operant when a warm front dominates a low-pressure cell. Initially, a warm front will reduce air-contaminant concentrations, primarily through the storm activity along its leading edge. As the warm front develops, however, more stable conditions will result, with an accompanying increase in air pollution potential.

8-9 WINDS AND DISPERSION

Wind is one of the most important vehicles in the distribution, transport, and dispersion of air contaminants. As meteorologists make use of a wind rose to graphically portray wind speed and direction, so environmental engineers have devised a pollution rose for plotting the data necessary to determine the source direction of specific air contaminants. [8-38]

The velocity of the wind determines the travel time of a particulate to a receptor and also the dispersion rate of air contaminants. Assuming a wind speed of 1 m/s and a source emitting 5 g of air contaminants per second, it can be determined that contaminant concentration in this plume is 5 g/m^3. If the wind velocity increases to 5 m/s, then the contaminant concentration from the same source is reduced to a single gram per cubic meter. Concentration of air contaminants in a plume is inversely proportional to wind velocity.

Frequently, topographic conditions will have a profound effect on winds and thus on air quality. This is seen in the wind channeling effect of a valley. Here, because of a particular geographic structure, air movement is predominantly up or down the valley, and dispersion of ambient contaminants outside the valley may be limited.

The differing conductive capacity of landmass and water mass gives rise to the alternating flow of sea breezes and land breezes, a pattern which can contribute to air pollution problems. The Los Angeles area frequently experiences this pattern of air movement, which carries the contaminants toward the ocean in the evening, only to return the polluted air to the urban basin when the direction of the wind shifts back toward land with the morning sun.

8-10 MOISTURE AND DISPERSION

Moisture content and form in the atmosphere can have a profound effect upon the air quality of a region. The presence and amount of water vapor in the atmosphere affects the amount of solar radiation received and reflected by earth. Water vapor serves to scatter or absorb radiation energy, and hence humidity has a major influence on air quality.

Precipitation serves as a cleansing agent for the atmosphere, removing particulates and soluble gases in a process called *washout*. Though the beneficial effects of washout are obvious, there are also some detrimental effects. When rainfall removes sulfur dioxide (SO_2) from the air, it may react with the water to form H_2SO_3 (sulfurous acid) or H_2SO_4 (sulfuric acid). The resultant "acid rain" increases the rate of corrosion where air contaminants are present. [8-17] In addition, the unnaturally low pH of such rains may change the pH of rivers and streams and thus influence the species of algae and other plant life which predominate in those bodies of water. [8-37]

8-11 MODELING

A knowledge of meteorological phenomena and an understanding of the variable factors that build weather systems can be used as a basis for forecasting air pollution potential and for devising air-pollution prevention and abatement programs. With information from an emission inventory and with atmospheric dispersion rates, it is possible to estimate air contaminant levels with some degree of reliability.

Maximum Mixing Depth (MMD)

Operations likely to produce significant amounts of air pollution should be limited to those areas in which atmospheric dispersion processes are most favorable. A determination of the maximum mixing depth of an ambient environment could help establish whether an area is a proper site for contaminant-causing human activities.

Maximum mixing depth (MMD) can be estimated by plotting maximum surface temperature and drawing a line parallel to the dry adiabatic lapse rate from the point of maximum surface temperature to the point at which the line

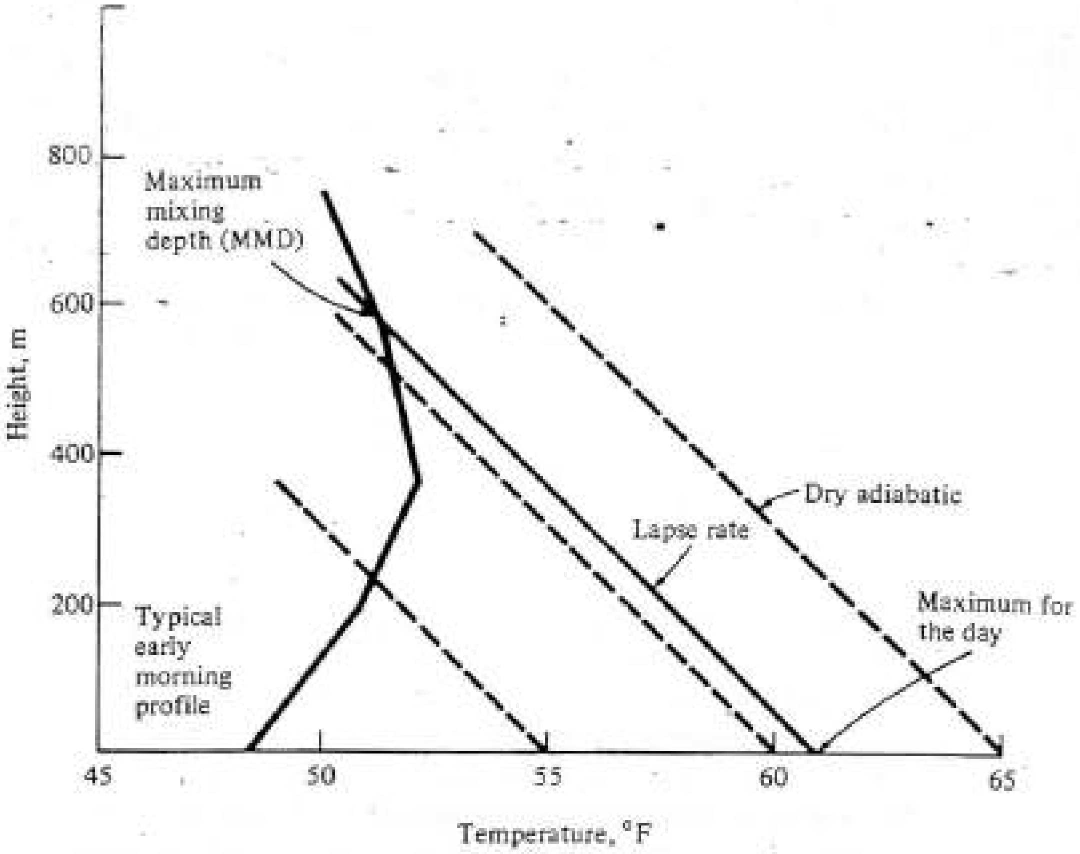


Figure 8-8 Maximum mixing depth. (*From Ledbetter* [*8-15*].)

intersects the ambient lapse rate for early morning. [8-15] In the instance plotted in Fig. 8-8, the MMD for the area was about 600 m.

Dispersion Models

Several empirical dispersion models have been developed. These models, or equations, are mathematical descriptions of the meteorological transport and dispersion of air contaminants in an area [8-5], and permit estimates of contaminant concentrations, either in the plume from an elevated or ground-level source. Among the most useful formula are those developed by Sutton, Bosanquet and Pearson, and Pasquill and Gifford. Most of the equations in use today are based on the following general equation which was suggested by Pasquill and modified by Gifford. [8-3, 8-4, 8-11, 8-13, and 8-25]

$$\frac{dC}{dt} = \frac{\partial x}{\partial x}\left(K_x \frac{\partial x}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial x}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial x}{\partial z}\right) \tag{8-2}$$

Equation (8-2) relates dispersion in the x (downwind) direction as a function of variables in all directions of a three-dimensional space. It assumes that the

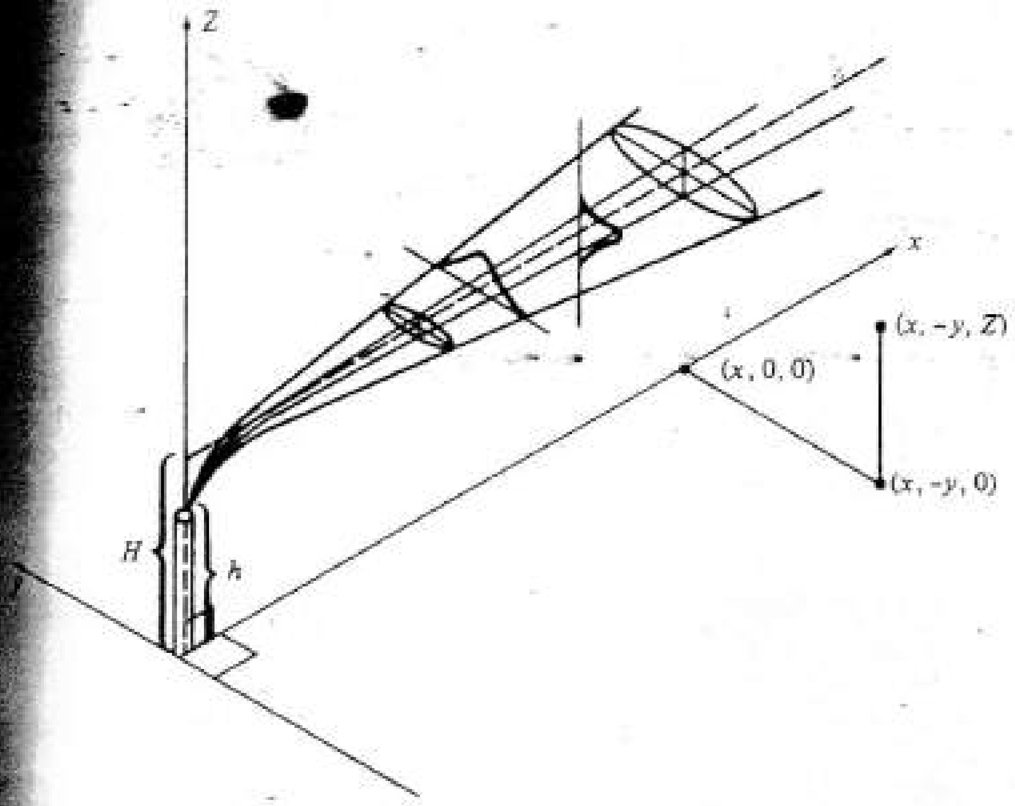


Figure 8-9 Coordinate system showing Gaussian distribution in the horizontal and vertical. (*From Turner* [8-34].)

plume has a Gaussian concentration distribution in both the z (vertical) and y (horizontal) directions, as shown in Fig. 8-9. [8-34]

The concentration (C) of a gas or aerosol ($<20\mu$) calculated at ground level for a distance downwind (x) is given by

$$C_{x,y} = \frac{Q}{\pi u \sigma_z \sigma_y} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \tag{8-3}$$

where C = pollutant concentration, g/m^3
Q = pollutant emission rate, g/s
π = pi, 3.14159
u = mean wind speed, m/s
σ_y = standard deviation of horizontal plume concentration, evaluated in terms of downwind distance x, m, (as shown in Fig. 8-10)
σ_z = standard deviation of vertical plume concentration evaluated in terms of downwind distance x, m, (as shown in Fig. 8-11)
exp = base of natural logs, 2.71828183
H = effective stack height, m
x = downwind distance along plume mean centerline from point source, m
y = crosswind distance from the centerline of the plume, m

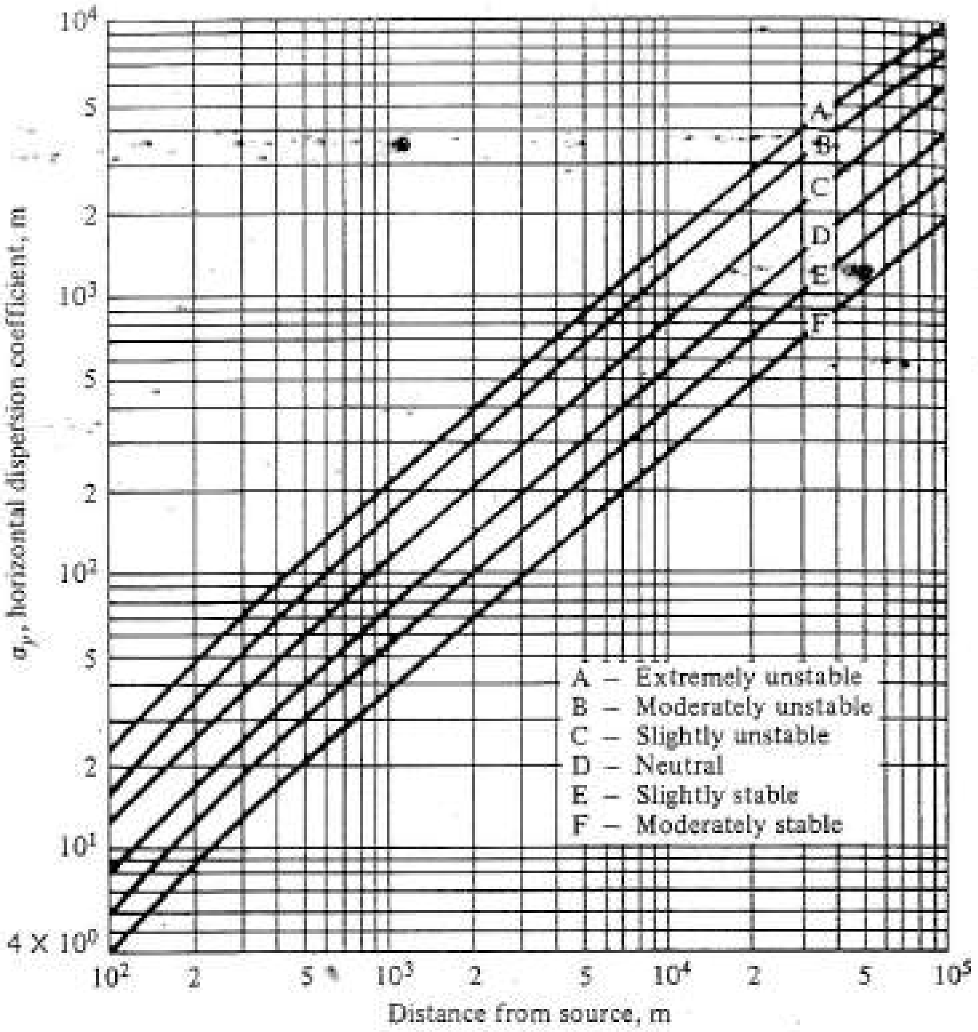


Figure 8-10 Lateral diffusion coefficient σ_y vs. downward distance from source. (*From Davis* [8-7].)

This equation may be simplified if concentrations along only the plume centerline are needed. In this case, $Y = 0$, and the equation is as follows:

$$C_{x,0} = \frac{Q}{\pi u \sigma_z \sigma_y} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right] \tag{8-4}$$

The equation may be further simplified if the effective stack height is zero, such as in a situation of ground-level burning.

$$C_{x,0} = \frac{Q}{\pi u \sigma_y \sigma_z} \tag{8-5}$$

Values for σ_y and σ_z are not only a function of downwind distances but are also a function of atmospheric stability. Values of σ_y and σ_z for various distances downwind (x), with various stability categories, are indicated in Figs. 8-10 and 8-11. Generalized categories are included in Table 8-1. [8-34]

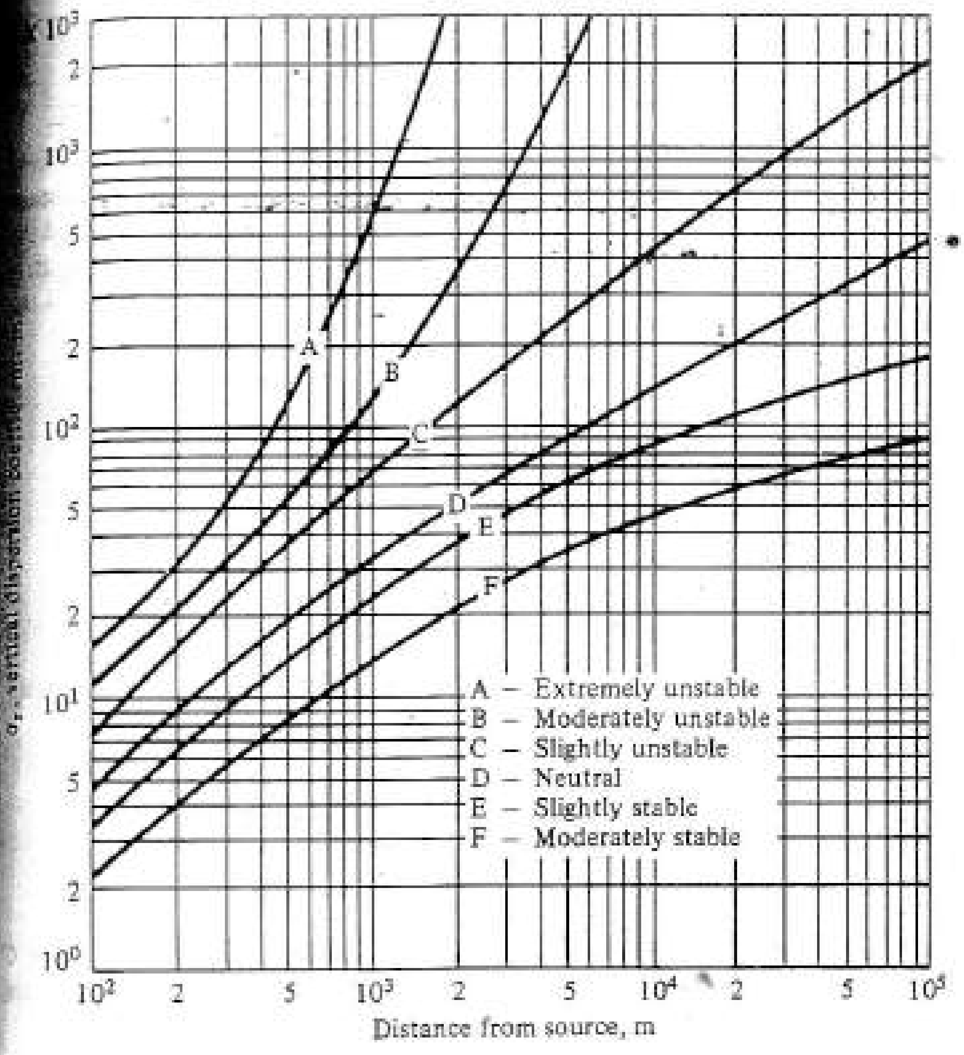


Figure 8-11 Vertical diffusion coefficient σ_z vs. downward distance from source. (*From Davis* [8-7].)

Table 8-1 Pasquill stability types

Surface wind speed, m/s	Day			Night	
	Incoming solar radiation				
	Strong	Moderate	Slight	Mostly overcast	Mostly clear
<2	A	A–B	B		
2	A–B	B	C	E	F
4	B	B–C	C	D	E
6	C	C–D	D	D	D
>6	C	D	D	D	D

A—Extremely unstable
B—Moderately unstable
C—Slightly unstable
D—Neutral
E—Slightly stable
F—Moderately stable

The maximum ground-level concentration occurs where $\sigma_z = 0.707H$, provided σ_z/σ_y are constant with downwind distance x. [8-22]

Example 8-1 Determining maximum ground-level concentration A power plant burns 5.45 tonnes of coal per hour and discharges the combustion products through a stack that has an effective height of 75 m. The coal has a sulfur content of 4.2 percent, and the wind velocity at the top of the stack is 6.0 m/s. The atmospheric conditions are moderately to slightly stable. Determine the maximum ground-level concentration of SO_2 and the distance from the stack at which the maximum occurs.

SOLUTION

1. Determine the emission rate Q for SO_2.

$$5.45 \times 10^3 \text{ kg/h} \times 0.042 = 229 \text{ kg S/h}$$

$$S + O_2 = SO_2$$

the molecular mass of both S and O_2 is 32, they combine on a one-to-one mass basis.

$$229 \text{ kg S} + 229 \text{ kg } O_2 = 458 \text{ kg } SO_2\text{/h}$$

$$Q = 458 \text{ kg } SO_2\text{/h} \times \frac{\text{h}}{3600 \text{ s}} \times \frac{1000 \text{ g}}{\text{kg}} = 127 \text{ g/s}$$

2. Determine location of maximum concentration.

For the given atmospheric conditions, the stability class will be either B or C (see Table 8-1). To be conservative, choose C. For class C, the σ_z/σ_y ratio is a constant for distances up to 1 km from the stack. Therefore,

$$\sigma_z = 0.707H = 0.707 \times 75 = 53 \text{ m}$$

From Fig. 8-11, σ_z reaches a value of 53 m at a distance of about 850 m from the stack with class C atmosphere. Thus,

$$x_{\text{max}} = 850 \text{ m}$$

3. Determine concentration at x_{max}.

From Fig. 8-10, $\sigma_y = 88$ m at $x = 850$ m.

$$C_{\text{max}} = \frac{127}{\pi \times 6 \times 53 \times 88} \exp - \frac{1}{2}\left(\frac{75}{53}\right)^2$$

$$= 5.31 \times 10^{-4} \text{ g/m}^3$$

$$= 531 \ \mu\text{g/m}^3$$

Example 8-2: Determining crosswind concentrations From the data in Example 8-1, determine the ground-level concentrations at a distance of 3.0 km downwind at the centerline of the plume and at a crosswind distance of 0.4 km on either side of the centerline.

SOLUTION

1. At 1.5 km:

$$\sigma_z = 170 \text{ m}$$
$$\sigma_y = 280 \text{ m}$$

2. The centerline concentration is

$$C_{(3,0)} = \frac{Q}{\pi u \sigma_z \sigma_y} \exp - \left[\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right]$$
$$= \frac{127}{\pi \times 6 \times 170 \times 280} \exp\left[-\frac{1}{2}\left(\frac{75}{170}\right)^2\right]$$
$$= 1.28 \times 10^{4} \text{ g/m}^3$$
$$= 128\ \mu\text{g/m}^3$$

3. The concentration 0.4 km away from centerline is:

$$C_{(3,0.4)} = \frac{Q}{\pi u \sigma_z \sigma_y} \exp\left[-\frac{1}{2}\left(\frac{H}{\sigma_3}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{Y}{\sigma_y}\right)^2\right]$$
$$= \frac{127}{\pi \times 6 \times 170 \times 280} \exp\left[-\frac{1}{2}\left(\frac{85}{170}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{400}{280}\right)^2\right]$$
$$= 4.49 \times 10^{-5} \text{ g/m}^3$$
$$= 44.9\ \mu\text{g/m}^3$$

Stack Design

Meteorological data are necessary for the effective design of a stack. All factors must be weighed, including the fact that emissions from a tall stack designed to disperse contaminants into the upper atmosphere and away from the immediate area may result in fallout or washout far downwind. [8-23] Dispersion equations such as those in the foregoing section may be helpful. However, formulas alone are not enough, since many local variables must be considered if optimum stack design is to be achieved.

Location of nearby buildings may cause mechanical turbulence which may bring a plume to ground level, especially when the stack is downwind of the building and wind speeds are high. To avoid this problem, stacks should usually be designed 2 to $2\frac{1}{2}$ times the height of nearby structures. Since dispersion formulas commonly used are for flat, level terrain, irregular terrain must be taken into consideration when dispersion models are being adapted for use in specific cases. Heat islands and mechanical turbulence in metropolitan areas must also be considered. [8-9]

All of the above considerations concern single stacks designed for continuous emissions. When multiple stacks are preferred, still other factors must be taken into account. [8-32]. Different criteria may be used, too, for design of single stacks intended for short-term releases, for explosions, or for instantaneous release of nuclear fission products. [8-9, 8-31]

When the air contaminants are emitted from a stack, they rise above the stack before leveling out. The effective stack height H is not only the physical stack height h but includes the plume rise (Δh). [8-22]

$$H = h + \Delta h \tag{8-6}$$

See Fig. 8-12. Stack heights used in calculations such as those for Example 8-1 must be the effective stack height, and there are numerous equations for the calculation of plume height Δh. Holland's equation [8-22], often used for this determination, is given below.

$$\Delta h = \frac{v_s d}{u}\left[1.5 + \left(2.68 \times 10^{-3}\, p \frac{\Delta T d}{T_s}\right)\right] \tag{8-7}$$

where Δh = rise of plume above the stack, m
v_s = stack gas velocity, m/s
d = inside stack diameter, m
u = wind speed, m/s
p = atmospheric pressure, millibars
ΔT = stack gas temperature minus air temperature, K
T_s = stack gas temperature, K

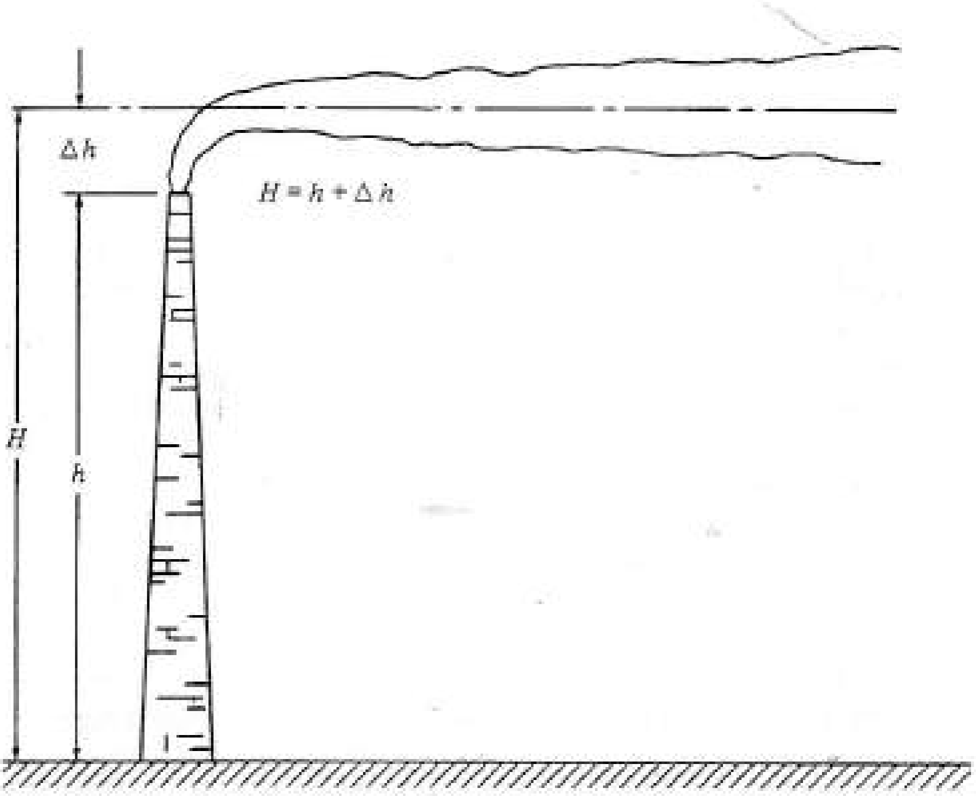


Figure 8-12 Effective stack height. (*From Smith* [8-32].)

The preceding calculations are suitable for neutral conditions. For unstable conditions, Δh should be increased by a factor of 1.1 to 1.2, and for stable conditions, Δh should be decreased by a factor of 0.8 to 0.9.

Davidson and Bryant [8-22] present another equation for plume rise.

$$\Delta h = d\left(\frac{v_s}{u}\right)^{1.4}\left(1 + \frac{\Delta T}{T_s}\right) \tag{8-8}$$

The terms in this equation have the same definition as those used in the Holland equation. Both equations frequently underestimate effective stack heights and provide a conservative estimate when used in the dispersion equation.

Example 8-3: Calculating effective stack height Determine the effective height of a stack given the following data.

(*a*) Physical stack is 203 m tall with 1.07 m inside diameter.
(*b*) Wind velocity is 3.56 m/s.
(*c*) Air temperature is 13°C.
(*d*) Barometric pressure is 1000 millibars.
(*e*) Stack gas velocity is 9.14 m/s.
(*f*) Stack gas temperature is 149°C.

SOLUTION

1. Convert temperatures to K.

$$T_a = 273 + 13 = 286$$

$$T_s = 273 + 149 = 422$$

2. Calculate ΔT.

$$\Delta T = 422 - 286 = 136\ \text{K}$$

3. Calculate ΔH using Eq. (8-7).

$$\begin{aligned}\Delta h &= \frac{v_s d}{u}\left[1.5 + \left(2.68 \times 10^{-3} p \frac{\Delta T_d}{T_s}\right)\right] \\ &= \frac{9.14 \times 1.07}{3.56}\left[1.5 + \left(2.68 \times 10^{-3} \frac{1000 \times 136 \times 1.07}{422}\right)\right] \\ &= 6.6\ \text{m}\end{aligned}$$

4. Calculate effective height.

$$H = h + \Delta h = 203 + 6.6 = 209.6\ \text{m}$$

Effects of Air Pollution on Meteorological Conditions

The interrelatedness of atmospheric conditions and air quality should be evident from the foregoing discussion of the effects that meteorological conditions can have upon the dispersion, concentration, or removal of atmospheric pollutants.

CHAPTER 5

Air Pollution Control Methods and Equipment

5.1 CONTROL METHODS

The most effective means of dealing with the problem of air pollution is to prevent the formation of the pollutants or minimize their 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. These are known as source correction methods. Application of these methods to existing plants is difficult, but still some of these correction methods could be applied without severely upsetting the economy of the operation. Control of the pollutant 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.

When source correction methods can not achieve the desired goal of air pollution control, use is made of effluent gas cleaning techniques. These involve many of the chemical engineering unit operations and at present form the main part of pollution control technology.

5.2 SOURCE CORRECTION METHODS

5.2.1 Raw Material Changes

If a particular raw material is responsible for causing air pollution, use of a purer grade of raw material is often beneficial and may reduce the formation of undesirable impurities and byproducts or may even eliminate the troublesome effluent. A typical example of this approach is the use of low-sulphur fuel in place of high-sulphur ones. Burning of natural gas produces less pollution than that of coal, but a major drawback of such low-sulphur fuels is their limited availability for wholesale use.

Fuel desulphurization is an attractive alternative, but removal of sulphur from fuels such as coal poses formidable technical problems. The most promising way of using coal in combustion processes with minimum air pollution appears to be through coal gasification because sulphur and some other unwanted materials can be removed from the gas much more readily than from solid coal. Coal gasification can be carried out in two possible steps:

1. Gas can be produced by destructive distillation of coal. The greater part of the volatile matter is driven off and coke is left as a by-product.
2. Gasification of the coke residues of the carbonisation process can be done with steam, CO_2, O_2, air, or a mixture of these gases. The main products are H_2, CO, CO_2 and undecomposed steam. Hydrogen can also be used as a gasifying medium. In the case of hydrogasification methane is produced; however, high pressures are required to obtain considerable yields.

In all these processes, the sulphur is recovered by passing the gases through an absorbing medium. Surveys of some industrial desulphurization processes are given by Strauss[1].

Ore handling operations usually result in the emission of large quantities of dust into the atmosphere. In steel industry, replacement of raw ore with pelleted sintered ore has gradually reduced dust emissions and also helped to reduce the blast furnace "slips".

5.2.2 Process Changes

Process changes involving new or modified techniques offer important ways of lowering atmospheric pollutant emissions. Radical changes in chemical and petroleum refining industries have resulted in minimizing of the release of materials to the atmosphere. The volatile substances are recovered by condensation and the non-condensable gases are recycled for additional reactions. Hydrogen sulphide, which was once flared in refineries, is now recycled and used in Claus process to recover elemental sulphur.

Rotary kilns are a major source of dust generation in cement plants. Some degree of dust control may be achieved in the kiln operation by adjusting operating conditions. 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 can lead to dust control.

Smelting and paper industries are notorious for emitting highly objectionable sulphurous materials. These emissions are being curtailed by major process changes such as hydro-metallurgical separations of ores and use of no sulphides 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 iron bath. The combustibles in the fuel are partially oxidised 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, flue gas recirculation and water injection, (2) washing the coal before pulverization to reduce the fly ash emissions, and (3) substitution of bauxite flux for fluorine containing fluorspar in the open hearth method.

5.2.3 Equipment Modification or Replacement

Air pollutant emissions can be minimized by suitable modification or replacement of process equipment. 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 modifications in the carburation and ignition systems.

In petroleum refineries, hydrocarbon vapours 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.

Replacement of the open hearth furnace by oxygen furnace in steel industry and development of an alternative power source for automobiles in place of the internal combustion engine are additional examples of equipment alteration.

In addition to the above mentioned source correction methods, air pollutant emissions from industrial operations can be reduced by proper equipment maintenance, housekeeping 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.

5.3 CLEANING OF GASEOUS EFFLUENTS

The technology for the removal of gaseous pollutant emissions after their formation has probably received the maximum attention. The cleaning techniques are applied to those cases where emissions of pollutants can not be prevented and pollution control equipment is necessary to remove them from the main gas stream. Normally, it is more economical to install the control equipment at the source where the pollutants are present in the smallest possible volume in relatively high concentrations rather than at some point away from the source where the pollutants are diluted by other process gases or air. The size of the equipment is directly related to the volume being treated, and equipment costs can be drastically reduced by decreasing the exhaust volume. At the same time, the equipment is more efficient for the handling of higher concentrations of pollutants. Gas cleaning techniques used alone, or in conjunction with source correction methods form the basis of present-day air resource management concepts. The methods are often integrated into chemical processes, which eliminate pollutant discharges and conserve materials in the same unit operation.

Emission control equipment may be classified into two general types: particulate control type, and gases and odours control type. For gaseous pollutants, essentially two alternative classes or methods are available. The first class comprises the wet absorption and dry adsorption methods, and the second class includes methods depending on the chemical alteration of the pollutant, usually through combustion or catalytic incineration. The basic mechanism in all these is the diffusion of the particular gas either to the surface of an absorbing liquid or adsorbing solid or catalyst, or to the reaction zone of a chemical reaction. On the other hand, the removal of particles relies only partly on their diffusion from the gas stream to a collecting surface or space, and other mechanisms which take special advantage of the nature and properties of particulate matter play a more important role.

5.4 PARTICULATE EMISSION CONTROL

Particulate matter emitted in gaseous streams consists of discrete and minute suspended particles. Particle sizes range generally from 100 µm down to 0.1 µm and even less. The choice of collection devices depends upon a number of factors: the physical and chemical characteristics of particulates, the particulate size and concentration in the gas, volume of particulates to be handled, and the temperature and humidity of gaseous medium. In particular, factors like toxicity and inflammability must be taken into consideration when evaluating operating efficiency.

5.4.1 Collection Efficiency

The operating or collection efficiency measures the system performance. In existing systems, it represents the actual performance. The most common way of expressing the efficiency is in terms of the weight of the material caught in or retained by the collector compared to the total amount entering the collector. This is known as the gravimetric efficiency and is usually expressed as a percentage.

$$\eta_T = 100 \times \frac{\text{Weight of material collected}}{\text{Total amount entering collector}} \qquad \text{...(5.1)}$$

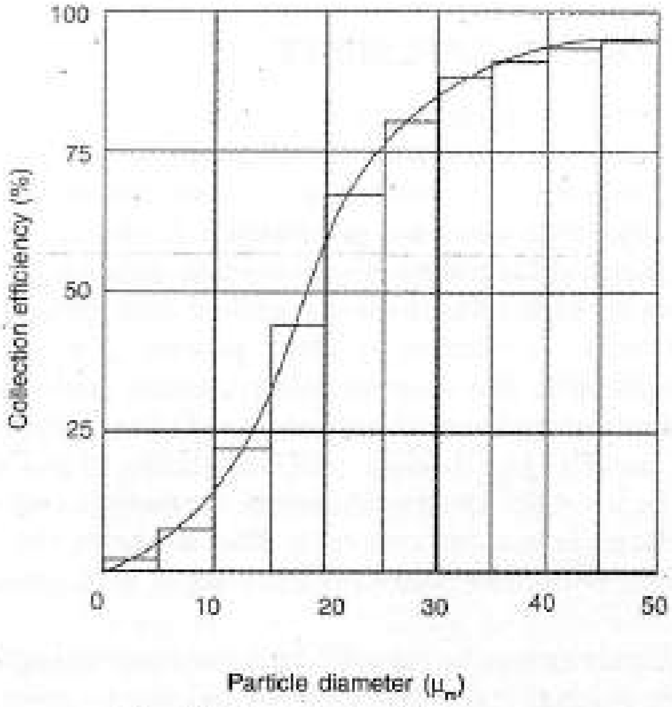


Fig. 5.1 Fractional efficiency curve

In particulate collection systems, the efficiency of collection varies with particle size. This variation of efficiency is often expressed in the form of fractional efficiency. It is the efficiency with which particles of a specified size-range are collected under specific conditions of gas flow rate, temperature, and particle composition. From a knowledge of the particle size distribution, a fractional efficiency curve can be constructed by considering the efficiency in a series of narrow ranges of the particle size spectrum. A typical fractional efficiency curve is shown in Fig. 5.1. From this information, the efficiency in each size range can be computed by the equation

$$\eta_i = \frac{\text{fraction in range "}i\text{" collected}}{m_i} \times 100 \qquad ...(5.2)$$

where m_i = amount in range "i" entering the collector.

The overall efficiency η_T can then be calculated over n number of size fractions as:

$$\eta_T = \frac{\sum_{i=1}^{n} m_i \eta_i}{M} \text{ per cent} \qquad ...(5.3)$$

where M = total amount entering the collector.

Example 1

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

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

Solution

Using Eq. (5.3), we can calculate the overall collection efficiency η_T as

$$\eta_T = \frac{\sum_{i=1}^{n} m_i \eta_i}{M} = \sum_{i=1}^{n} \omega_i \eta_i$$

where ω_i is the weight fraction in each size range.

$$\eta_T = \sum_{i=1}^{n} \omega_i \eta_i = (0.02 \times 1) + (0.02 \times 7) + (0.04 \times 16)$$

$$+ (0.07 \times 44) + (0.1 \times 67) + (0.08 \times 81)$$

$$+ (0.07 \times 88) + (0.1 \times 92) + (0.15 \times 93)$$

$$+ (0.2 \times 95) + (0.1 \times 98) + (0.05 \times 100)$$

$$\eta_T = 80.17\%$$

5.4.2 Particulate Control Equipment

The basic mechanisms of removing particulate matter from gas streams may be classified as: (1) gravitational settling, (2) centrifugal impaction, (3) inertial impaction, (4) direct interception, (5) diffusion, and (6) electrostatic precipitation.

Equipment presently available, which make use of one or more of the above mechanisms, fall into the following five broad categories: (1) gravitational settling chambers, (2) cyclone separators, (3) fabric filters, (4) electrostatic precipitators, and (5) wet collectors (scrubbers).

The gravitational settling chambers and cyclone separators will not generally achieve high efficiencies for removing small-size particles. For most practical applications, only fabric filters, electrostatic precipitators and high energy scrubbers are capable of meeting the rigorous air pollution control regulations.

5.4.3 Gravitational Settling Chambers

Gravitational settling chambers are generally used to remove large, abrasive particles (usually >50 μm) from gas streams. They offer low pressure drop and require simple maintenance, but their efficiencies are quite low for particles smaller than 50 μm. Since most of the troublesome particles have much smaller sizes than 50 μm, these devices are normally used as precleaners prior to passing the gas stream through high efficiency collection devices. The simplest form of horizontal type settling chamber is shown in Fig. 5.2.

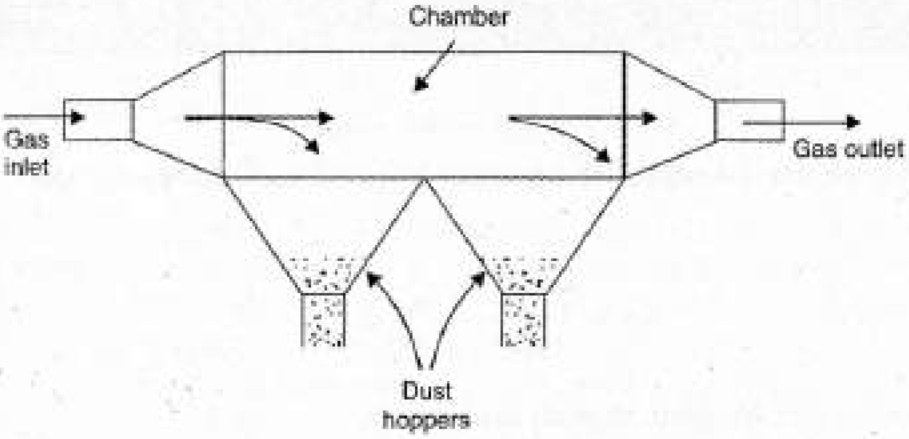


Fig. 5.2 Horizontal flow settling chamber

In the settling chamber the gas stream, with its entrained particles, is allowed to flow at a low velocity, allowing sufficient time for the particles to settle down. A more elaborate settling chamber is the Howard type whose simplified diagram is shown in Fig. 5.3. By inserting several trays, the collection efficiency of the device is improved since the gas flow 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 trays.

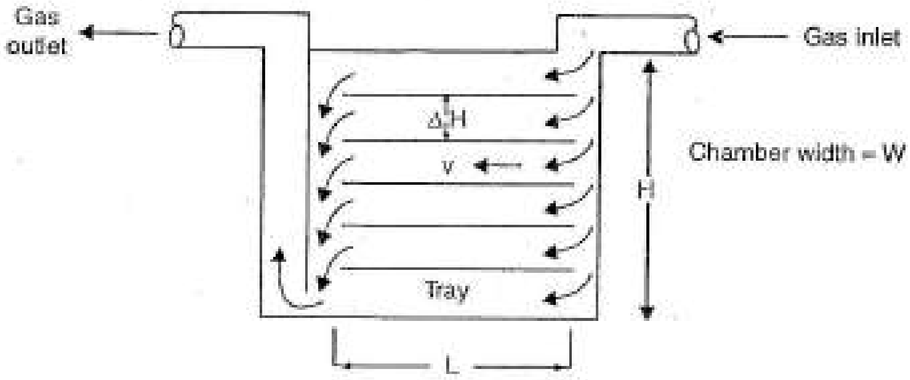


Fig. 5.3 Howard settling chamber

Design Concepts

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

$$D_h = \frac{2W\,\Delta H}{W + \Delta H} \quad \text{...(5.4)}$$

and the Reynolds number,

$$Re = \frac{vD_h\rho_g}{\mu_g} \quad \text{...(5.5)}$$

where v, the velocity inside the chamber, is given by

$$v = \frac{Q}{nW\Delta H}$$

where Q = volumetric flow rate of the gas stream

Substituting for v and D_h in the Eq. (5.5), we get

$$Re = \frac{2Q\rho_g}{n\mu_g(W + \Delta H)} \quad \text{...(5.6)}$$

The spacing between the trays, ΔH, is given by

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

provided there is no dust layer initially present on the tray surface. Substituting for ΔH in Eq. (5.6) we have

$$Re = \frac{2Q\rho_g}{\mu_g (nW + H)} \qquad \text{...(5.7)}$$

If a layer of dust H_d is initially present, then

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

With this modification,

$$Re = \frac{2Q\rho_g}{\mu_g (nW + H - nH_d)} \qquad \text{...(5.8)}$$

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. During this time the particles are transported a distance L with the velocity of the gas stream. Equating these two, we have:

$$\frac{y}{v_t} = \frac{L}{v} \qquad \text{...(5.9)}$$

the value of y can be found from a knowledge of the particle settling velocity.

If the particles are uniformly distributed over the incoming stream, the efficiency of collection $\eta = y/\Delta H$ or

$$\eta = \frac{Lv_t}{v\Delta H} = \frac{nWLv_t}{Q} \qquad \text{...(5.10)}$$

When $y \geq \Delta H$, all particles of that size (or larger) will be collected in the settling chamber.

The terminal settling velocity of the particles is found by equating the drag force on the particle with the weight minus the buoyancy of the particle:

$$F = C_D\left(\frac{\pi}{4}d_p^2\right)\left(\frac{1}{2}\rho_g v_t^2\right) = \frac{\pi}{6}d_p^3(\rho_p - \rho_g)g \qquad \text{...(5.11)}$$

where ρ_p = density of the particle, ρ_g = density of gas, and d_p = particle diameter. Rearranging, we get

$$v_t = \sqrt{\frac{4gd_p(\rho_p - \rho_g)}{3C_D\rho_g}} \qquad \text{...(5.12)}$$

where C_D is the drag coefficient which is related to the particle Reynolds number, $Re_p = d_p \rho_g v_t / \mu_g$. The general drag coefficient curve for spherical particles may be represented by three relationships. In the Stokes' law region,

$$C_D = \frac{24}{Re_p} \quad \text{for } Re_p < 1 \qquad \text{...(5.13)}$$

In the turbulent region ($Re_p > 1000$), the drag coefficient C_D becomes almost constant with a value of 0.45.

$$C_D = 0.45 \quad \text{for} \quad Re_p > 1000 \qquad \text{...(5.14)}$$

Between this region and the Stokes' law region of laminar flow around the particle, there is the transition region. Several empirical equations have been suggested for this region, such as that given by Schiller and Naumann[2]:

$$C_D = \frac{24}{Re_p}\left(1 + 0.15\, Re_p^{0.687}\right) \qquad \text{...(5.15)}$$

Substituting Eq. (5.13) into Eq. (5.12), we can calculate the terminal settling velocity in the Stokes' region.

$$v_t = \frac{g d_p^2 (\rho_p - \rho_g)}{18\, \mu_g} \qquad \text{...(5.16)}$$

In the transition region, where C_D is a function of Re_p, Eq. (5.12) is difficult to solve except by a trial-and-error method. This problem has been overcome by rearranging Eq. (5.12) as

$$C_D\, Re_p^2 = \frac{4 g d_p^3 (\rho_p - \rho_g)\rho_g}{3\mu_g^2} \qquad \text{...(5.17)}$$

Values of $C_D\ Re_p^2$, C_D and Re_p are available in the *Chemical Engineering Handbook*[3] from which v_t can be calculated.

For particulates most often encountered in air pollution control, Stokes' law is a reasonable approximation for calculating the settling velocity. Table 5.1 shows typical values of terminal settling velocity calculated using Stokes' law, together with actual measured values, from which it is apparent that Stokes' law is accurate for particles smaller than 100 µm. The minimum particle size that can be removed with 100% efficiency can be found from the equation,

$$d_{p,\,\text{min}} = \sqrt{\frac{18 Q\, \mu_g}{n W L g (\rho_p - \rho_g)}} \qquad \text{...(5.18)}$$

These 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 re-entrainment of most materials.

Although the efficiency relationship is based on laminar flow conditions within the unit, it is practically impossible to achieve laminar conditions without a very large particle size or an inordinately large number of trays combined with an awkward shape of the chamber. Hence, the flow in the settling chamber will probably be turbulent rather than laminar.

Table 5.1 Settling velocities of spherical particles in air [particle density: 1000 kg/m^3, air temperature: 20 °C, pressure: 760 mm Hg]

Particle size (μm)	*Exp (m/s)*	*Calc from Eq (5.12) (m/s)*
0.1	8.7×10^{-7}	8.71×10^{-7}
0.2	2.3×10^{-6}	2.27×10^{-6}
0.4	6.8×10^{-6}	6.85×10^{-6}
1.0	3.5×10^{-5}	3.49×10^{-5}
2	1.19×10^{-4}	1.19×10^{-4}
4	5.0×10^{-4}	5.0×10^{-4}
10	3.06×10^{-3}	3.06×10^{-3}
20	1.2×10^{-2}	1.2×10^{-2}
40	4.8×10^{-2}	5.0×10^{-2}
100	0.246	0.25
400	1.57	4.83
1000	3.82	30.50

Turbulent Flow

This model is often referred to as the well-mixed settling model. Here we assume that the gas flow is totally mixed in the y-direction and not in the x-direction (Fig. 5.4). We consider a section between the trays with thickness dx and cross section A. The mass balance for the particles may be written as:

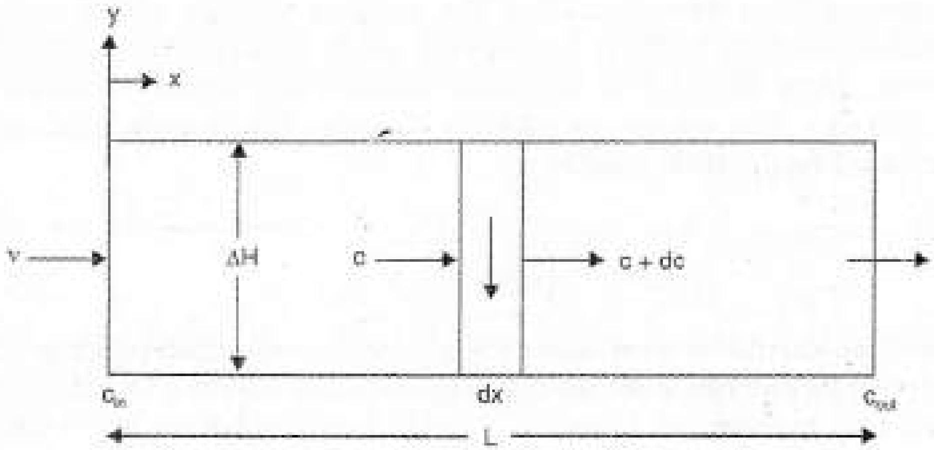


Fig. 5.4 Gravity settling in a horizontal duct: turbulent flow

$$\begin{pmatrix}\text{Mass concentration of}\\ \text{particles entering the}\\ \text{elemental volume }(Adx)\end{pmatrix} = \begin{pmatrix}\text{Mass concentration of}\\ \text{particles leaving the}\\ \text{elemental volume }(Adx)\end{pmatrix} + \begin{pmatrix}\text{Rate at which particles}\\ \text{are deposited within}\\ \text{the volume }(Adx)\end{pmatrix} \quad \text{...(5.19)}$$

Thus

$$cAv = (c + dc)\,Av + cv_t W dx \qquad ...(5.20)$$

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

Rearranging Eq. (5.20) and integrating,

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

or

$$\ln \frac{c_{out}}{c_{in}} = -\frac{v_t WL}{Av} \qquad ...(5.21)$$

The efficiency

$$\eta = 1 - \frac{c_{out}}{c_{in}} \qquad ...(5.22)$$

Substituting Eq. (5.21) into Eq. (5.22), we get in terms of volumetric flow, Q,

The efficiency,

$$\eta = 1 - \exp\left[-\frac{nWLv_t}{Q}\right] \qquad ...(5.23)$$

Noting that the term in the brackets is the negative of the efficiency term for the laminar flow (Eq. 5.10), we can write Eq. (5.23) as:

$$\eta_{\text{turb}} = 1 - \exp(-\eta_{\text{laminar}}) \qquad ...(5.24)$$

Example 2

A multi-tray settling chamber having 8 trays, including the bottom surface, handles 6 m³/s of air at 20 °C. The trays are spaced 0.25 m apart and the chamber is to be 1 m wide and 4 m long. What is the minimum particle size of density 2000 kg/m³ that can be collected with 100% efficiency? What will be the efficiency of the settling chamber if 50 μm particles are to be removed? Laminar flow condition within the chamber and presence of no dust initially on trays may be assumed.

Solution

From Eq. 5.18

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

μ_g at $20°\text{C} = 1.81 \times 10^{-5}$ kg/m-s and $\rho_p = 2000$ kg/m³. Since $\rho_p \gg \rho_g$, ρ_g may be neglected in the above equation. Substituting for $n = 8$, $W = 1$ m, $L = 4$ m, $g = 9.81$ m/s² and $Q = 6$ m³/s, we have

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

$$d_{p,\min} = 56 \mu m$$

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

$$= (50/56)^2 = 80\%$$

Example 3

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

Solution

The Reynolds number may be calculated as,

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

The kinematic viscosity of air at 20°C, is 1.51×10^{-5} m^2/s and $H = 2$ m

$$Re = \frac{2 \times 6}{1.51 \times 10^{-5} (8 \times 1 + 2)} = 79{,}470$$

We see that the flow is turbulent and the laminar flow assumption in example 2 was not justified. Hence, using Eq. (5.23) we get

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

$$\eta_{dp=56} = 1 - \exp\left(-\frac{8 \times 1 \times 4 \times 0.188}{6} \right)$$

$$= 1 - 0.37 = 0.63 \text{ or } 63\%$$

$$\eta_{dp=50} = 1 - \exp\left(-\frac{8 \times 1 \times 4 \times 0.15}{6} \right)$$

$$= 1 - 0.45 = 0.55 \text{ or } 55\%$$

The terminal settling velocity v_t was calculated using the simplified relation for particles settling in air at 20°C;

$$v_t = 30{,}000 \, \rho_p d_p^2$$

where d_p is in metres.

$$v_t(56 \mu m) = 0.188 \text{ m/s and}$$

$$v_t(50 \mu m) = 0.15 \text{ m/s}.$$

5.4.4 Cyclone Separators

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

There is a variety of cyclone designs, differing in the manner in which the rotating motion is imparted to the gas stream. The simple reverse-flow type depicted in Fig. 5.5 consists of a vertical cylinder having a conical bottom and is fitted with a tangential inlet located near the top, and an outlet at the bottom of the cone for discharging separated particles. The gas outlet pipe is extended into the cylinder to prevent short-circuiting of gas from inlet to outlet.

In operation, the particle-laden gas upon entering the cyclone cylinder receives a rotating motion. The vortex so formed develops a centrifugal force, which acts to throw the particles radially towards the wall. The gas spirals downward to the bottom of the cone, and at the bottom the gas flow reverses to form an inner vortex which leaves through the outlet pipe.

Theory

In a cyclone, the inertial separating force is the radial component of the simple centrifugal force and is a function of the tangential velocity. The centrifugal force can be expressed by F_c where

$$F_c = \frac{mv_\theta^2}{r} \qquad \text{...(5.25)}$$

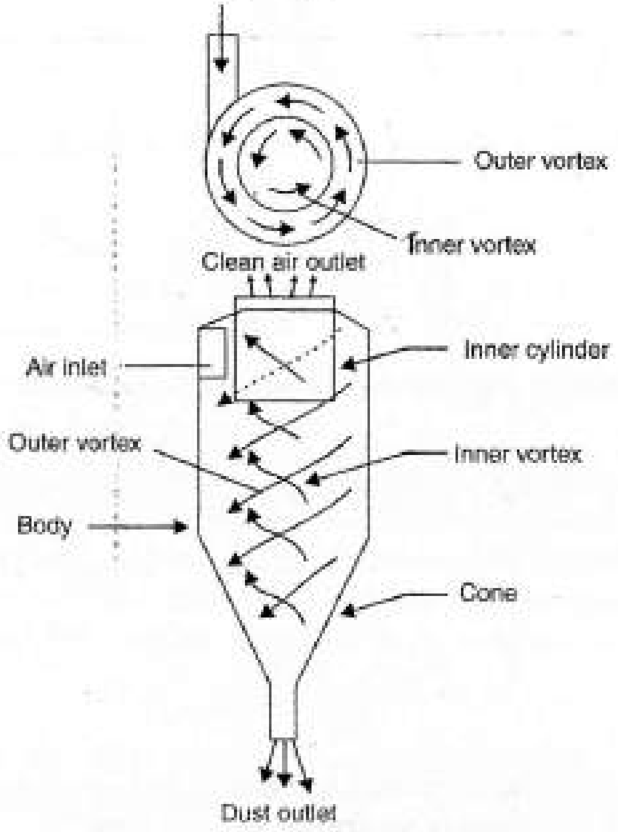


Fig. 5.5 Reverse-flow cyclone separator

where m = mass of the particle, v_θ = tangential velocity of the particle (and gas) at radius r and 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 a gravity. The separation factor S is given by

$$S = \frac{v_\theta^2}{gr} \qquad \text{...(5.26)}$$

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.

In a cyclone, the gas, in addition to moving in a circular path, also moves radially inwards between the inlet on the periphery and the exit on the axis. Since the tangential velocities of the particle and the gas are the same, the relative velocity between the gas and particle is simply equal to the radial velocity of the gas. This results in a drag force on the particle towards the centre, and the equilibrium radius of rotation of the particle can be obtained by balancing the radial drag force and the centrifugal force:

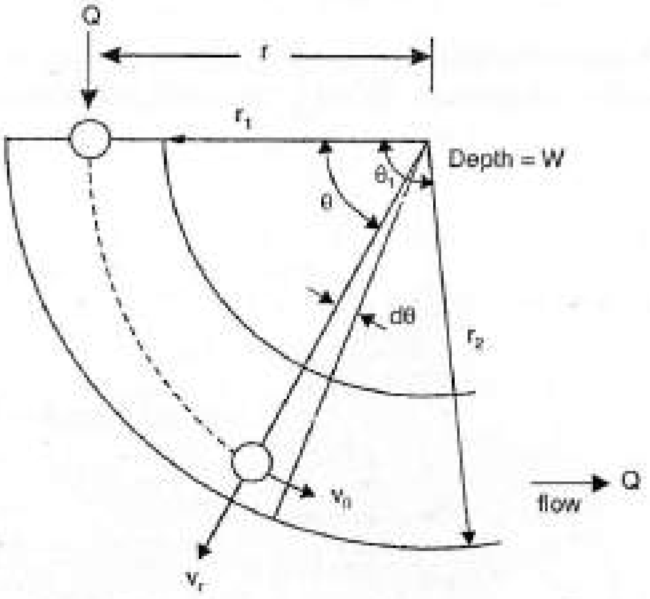


Fig. 5.6 Particle motion in a curved duct of rectangular cross-section: turbulent flow

$$3\pi\mu_g d_p v_r = \frac{\pi}{6} d_p^3 (\rho_p - \rho_g) \frac{v_\theta^2}{r} \qquad \text{...(5.27)}$$

where d_p = particle diameter, and v_r = radial velocity of the gas at radius r. Arranging the above equation for v_r, we have

$$v_r = \frac{d_p^2 (\rho_p - \rho_g)}{18\mu_g} \frac{v_\theta^2}{r} \qquad \text{...(5.28)}$$

The tangential velocity of the particle has been found experimentally to be inversely proportional to the radius of rotation according to equation,

$$v_\theta r^n = \text{Constant} = \alpha \quad \text{...(5.29)}$$

or

$$v_\theta = \frac{\alpha}{r^n} \quad \text{...(5.30)}$$

where n, the exponent, is dimensionless. To evaluate the constant α, we can write the volumetric flow rate through a curved duct of rectangular cross-section as (Fig. 5.6):

$$Q = W \int_{r_1}^{r_2} v_\theta dr \quad \text{...(5.31)}$$

where W = height (depth) of the entrance section of the duct, and r_1 and r_2 are inner and outer radius of the curved duct, respectively. Substituting Eq. 5.30 in Eq. 5.31 and integrating:

$$Q = \alpha W \int_{r_1}^{r_2} \frac{dr}{r^n} = \alpha W \frac{\left(r_2^{1-n} - r_1^{1-n}\right)}{1-n} \quad \text{...(5.32)}$$

or,

$$\alpha = \frac{Q(1-n)}{W\left(r_2^{1-n} - r_1^{1-n}\right)} \quad \text{...(5.33)}$$

Therefore,

$$v_\theta = \frac{Q(1-n)}{W r^n \left(r_2^{1-n} - r_1^{1-n}\right)} \quad \text{...(5.34)}$$

Now, substituting Eq. (5.34) in Eq. (5.28), we have v_r, the radial velocity of the gas at radius r:

$$v_r = \frac{d_p^2(\rho_p - \rho_g)(1-n)^2 Q^2}{18\mu_g W^2 r^{2n+1}\left(r_2^{1-n} - r_1^{1-n}\right)^2} \quad \text{...(5.35)}$$

Collection Efficiency

Due to turbulence, we can assume that the particles are uniformly distributed over the cross-section at any given angle θ. Consider the effect of the laminar sublayer next to the outer edge of the duct (cyclone) where all particles which enter it are captured. If $r_2\, d\theta$ is the distance required for capture, then the fractional decrease of particles over the angle $d\theta$ can be obtained by writing a mass balance for an element of flow.

$$cQ = (c + dc)Q + c v_{r_2} W r_2 d\theta \quad \text{...(5.36)}$$

The second term on the right side of the equation (5.36) is the rate at which the particles are captured within the element.

Equation (5.36) can be rearranged as

$$-\frac{dc}{c} = v_{r_2}\frac{W}{Q}r_2\,d\theta \qquad \text{...(5.37)}$$

Integrating the Eq. (5.37) and noting that at $\theta = 0$, $c = c_0$ (total particle concentration), we have

$$\frac{c}{c_0} = \exp\left[-v_{r_2}\frac{W}{Q}r_2\theta\right]$$

The efficiency at any angle, $\theta = \theta_1$, is then

$$\eta = 1 - \frac{c}{c_0} = 1 - \exp\left[-v_{r_2}\frac{W}{Q}r_2\theta_1\right] \qquad \text{...(5.38)}$$

Now from Eq. (5.34)

$$\frac{W}{Q} = \frac{(1-n)}{v_{\theta_2} r_2^{n}\left(r_2^{1-n} - r_1^{1-n}\right)} \qquad \text{...(5.39)}$$

Substituting Eq. (5.39) in Eq. (5.38), we have

$$\eta = 1 - \exp\left[-\frac{v_{r_2}}{v_{\theta_2}}\,\frac{r_2(1-n)\theta_1}{r_2^{n}\left(r_2^{1-n} - r_1^{1-n}\right)}\right] \qquad \text{...(5.40)}$$

In Eq. (5.40), $\frac{v_{r_2}}{v_{\theta_2}}$ is the ratio of the radial velocity to the tangential velocity of the particle at $r = r_2$. From equations (5.34) and (5.35), we get

$$\frac{v_{r_2}}{v_{\theta_2}} = \frac{(\rho_p - \rho_g)d_p^2(1-n)Q}{18\mu_g W r_2^{n+1}\left(r_2^{1-n} - r_1^{1-n}\right)} \qquad \text{...(5.41)}$$

Substituting Eq. (5.41) into Eq. (5.40) and rearranging:

$$\eta = 1 - \exp\left[-\frac{(\rho_p - \rho_g)d_p^2 Q(1-n)^2\theta_1}{18\mu_g W r_2^{2n}\left(r_2^{1-n} - r_1^{1-n}\right)^2}\right] \qquad \text{...(5.42)}$$

For a reverse flow cyclone. Strauss[30] recommends a value of $n = 0.5$ Substitution of $n = 0.5$ in Eq. (5.42) leads to:

$$\eta = 1 - \exp\left[-\frac{(\rho_p - \rho_g)d_p^2 Q\theta_1}{72\mu_g W\left(r_2^2 + r_1 r_2 - 2r_2\sqrt{r_1 r_2}\right)}\right] \qquad \text{...(5.43)}$$

The angle $\theta_1 = 2\pi N_e$ ...(5.44)

Where N_e = effective number of turns a gas makes in traversing the cyclone (usually 6). It is clear from Eq. (5.43) that as the diameter of the particle increases or as the cross-sectional area of the inlet decreases, the efficiency increases but with a higher pressure drop.

The most satisfactory expression for cyclone performance is still the empirical one. Lapple[5] correlated collection efficiency in terms of the cut size d_{pc}, which is the size of those particles that are collected with 50% efficiency. Particles larger than d_{pc} will have a collection efficiency greater than 50% while the smaller particles will be collected with lesser efficiency.

The cut size is given by

$$d_{pc} = \sqrt{\frac{9\mu_g b}{2\pi N_e v_i \left(\rho_p - \rho_g\right)}} \qquad \text{...(5.45)}$$

where b = inlet width, v_i = gas inlet velocity.

By plotting the ratio of the actual particle size (d_p) to the cut size (d_{pc}), a generalised curve of collection efficiency may be obtained. Such a curve is given in Fig. 5.7

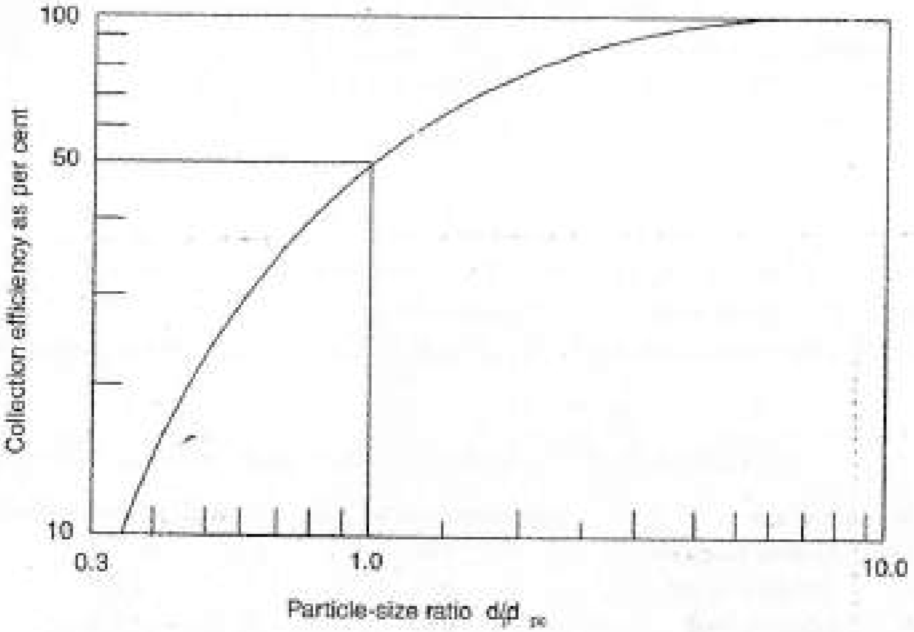


Fig. 5.7 Lapple's correlation for cyclone efficiency

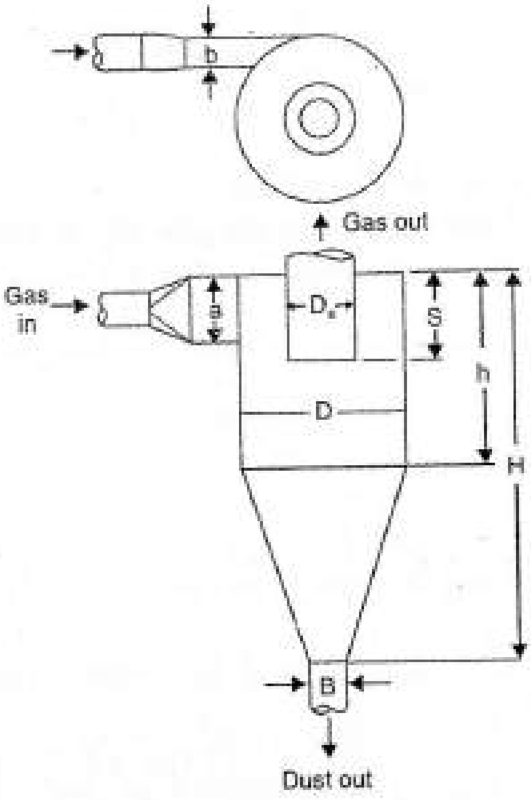
Fig. 5.8 shows a typical cyclone with all the necessary dimensions and gives values of the relative dimensions for conventional and high-efficiency designs. Representative overall efficiencies are presented for conventional as well as for high efficiency type cyclones in Table 5.2.

Pressure Drop

A correct estimate of the pressure drop across a cyclone is necessary, in addition to collection efficiency, so that cost effectiveness may be calculated. A magnitude of 25 cm H_2O, or less,

Table 5.2 Efficiencies of cyclones

Particle size (µm)	*Efficiency of cyclone*	
	Conventional	*High efficiency*
< 5	< 50	50-80
5-20	50-80	80-95
15-40	80-95	95-99
> 40	95-99	95-99



Nomenclature		Conventional (ref. 6)	High efficiency (ref. 7)
D	cyclone diameter	1.0	1.0
a	entrance height	0.5	0.5
b	entrance width	0.25	0.2
S	exit length	0.625	0.5
D_e	exit diameter	0.5	0.5
h	cylinder height	2.0	1.5
H	overall height	4.0	4.0
B	dust exit diameter	0.25	0.375

Fig. 5.8 Generalised cyclone design configurations

is the generally acceptable operating range. The pressure drop may be calculated fro several formulae. The approach of Shepherd and Lapple[8], however, is the simplest and of comparable accuracy to the more complex ones. The pressure drop ΔP may be estimat according to the following equation,

$$\Delta P = \frac{K \rho_g v_i^2 (ab)}{2 D_e^2} \qquad \text{...(5.46)}$$

where K = a constant, which averages 13 and ranges from 7.5 to 18.4, ΔP = pressure drop, a, b and D_e = cyclone dimensions, v_i = inlet gas velocity, and ρ_g = gas density.

Since the pressure drop is proportional to the square of the inlet velocity, it is obvious that high velocities cause not only re-entrainment but also excessive pressure drop.

Other Cyclone Types

Many types of commercial cyclones have been developed and information on their performance for specific applications is generally available. In straight through flow cyclone, the inner vortex of the air leaves at the bottom (rather than reversing direction), with initial centrifugal motion being imparted by vanes at the top. The chief advantages of this unit are low pressure drop and high volumetric 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; its principal drawback is a tendency toward plugging from solid buildup in the unit.

Both these devices are used frequently as pre-cleaners to remove fly ash and large particles. For high efficiency at reasonable capacity, a battery of smaller cyclones operating in parallel is used in preference to a large unit. These multicellular units usually require less space.

Example 4

A conventional cyclone with a diameter of 1.0 m handles 3.0 m^3/s of standard air carrying particles with a density of 2000 kg/m^3. Using $N_e = 6$, determine the collection efficiency as a function of particle diameter using Eq. (5.43) and the empirical correlation of Lapple.

Solution

For conventional cyclone, Eq. (5.43) becomes after substituting,

$$r_2 = \frac{D}{2},\ r_1 = r_2 - b = \frac{D}{2} - \frac{D}{4} = \frac{D}{4}$$

$$a = W = \frac{D}{2},\ \text{and}\ \theta_1 = 12\pi,$$

$$\eta = 1 - \exp\left[\frac{(\rho_p - \rho_g) d_p^2 Q \pi}{6\mu_g \left(\frac{D}{2}\right)\left(\frac{D^2}{4} + \frac{D^2}{8} - D\sqrt{\frac{D^2}{8}}\right)}\right]$$

since $\rho_p >> \rho_g$, ρ_g can be neglected

$$\rho_p = 2000\ \text{kg/m}^3,\ D = 1\text{m},$$

$$Q = 3.0\ m^3/\text{s},\ \mu_g = 1.81\times10^{-5}\ \text{kg/m-s}$$

Substituting of these values and simplification leads to:

$$\eta = 1 - \exp\left(-1.6213\times10^{10} d_p^2\right)$$

From Fig. 5.8, b = 0.25 m, and a = 0.5 m

The gas inlet velocity $v_i = \dfrac{Q}{ab} = \dfrac{3.0}{(0.5)(0.25)} = 24$ m/s

For the cut size d_{pc}, Eq. (5.45) gives

$$d_{pc} = \sqrt{\frac{9\left(1.81\times10^{-5}\right)(0.25)}{2\pi(6)(24)(2000)}} = 4.7\mu\text{m}$$

The empirical efficiency is then obtained from Fig. 5.7 and the values obtained by these two methods are plotted for various particle sizes in Fig. 5.9.

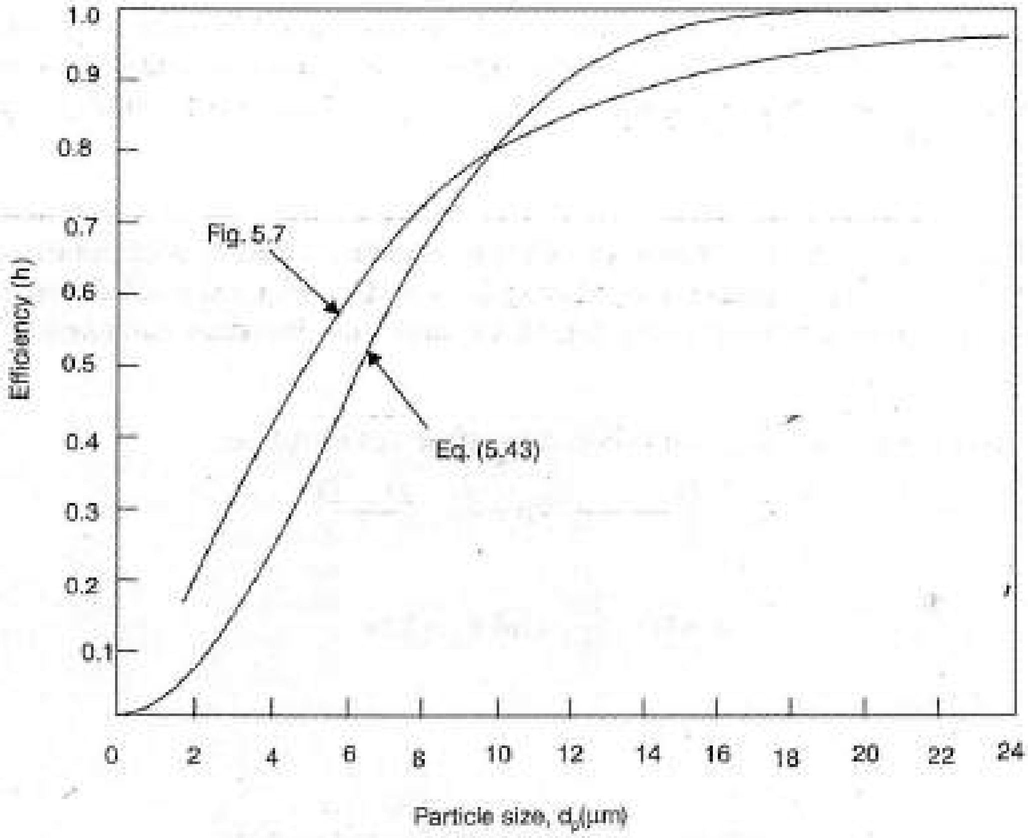


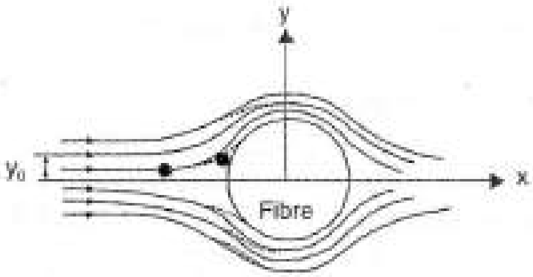
Fig. 5.9 Efficiency curve for example 4

5.4.5 Filters

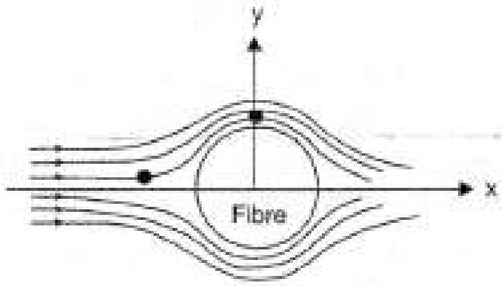
Filtration is the oldest and generally one of the most versatile and efficient methods for removing particulate matter from industrial gases. Filters can be classified as either a packed filter or a fabric filter, depending on the way in which the fibres are held in place. In a packed filter the fibers are loosely packed inside an enclosure where the dust-laden gas takes a long path on its way through the filter. In a fabric filter, fibres are woven into a thin layer of fabric (bag filters) usually made from natural, synthetic, metal or glass fibres. Fabric filters are the most commonly used particle collectors in industry where as packed filters find wide use in air-conditioning and other applications where the dust loading is relatively small.

Packed Filters

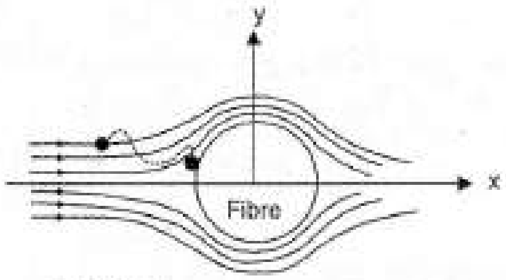
In principle, the dust-laden gas passes through the filter in which the particulates are trapped on to the fibres by the mechanisms of inertial impaction, direct interception and diffusion. These three mechanisms are illustrated in Fig. 5.10.



(a) Inertial impaction



(b) Direct interception



(c) Diffusion

——— Fluid streamline
-------- Particle path

Fig. 5.10 Particle capture mechanisms

Inertial Impaction

Inertial impaction occurs when the particle with high inertia follows a fluid streamline, but as it approaches the fibre its trajectory departs from the fluid streamline around the fibre. The departure of the particle from the streamline may be sufficient to allow the particle to deposit on the curved surface. Fig. 5.10 (*a*) shows that the particles approaching a fibre within a distance of y_0 from the plane of symmetry collide with the fibre. The ratio $2y_0/d_f$ is called the *collision factor* ϕ_c:

$$\phi_c = \frac{2y_0}{d_f} \qquad \text{...(5.47)}$$

where d_f is the diameter of the fibre. Since all the particles that collide will not adhere to the fibre, an adherence factor ϕ_a is defined such that the collection efficiency of a single fibre due to inertial forces, η_{impact}, is the product of ϕ_c and ϕ_a:

$$\eta_{\text{impact}} = \phi_c \phi_a \qquad \text{...(5.48)}$$

Theoretical investigations based on potential flow theory and experimental results reveal that the collection efficiency η_{impact} is a function of the factor ψ and the Reynolds number Re_f, based on the fibre diameter:

$$\eta_{\text{impact}} = f(\psi, \text{Re}_f) \qquad \text{...(5.49)}$$

where ψ is Stokes or inertial impaction parameter defined by

$$\psi = \frac{C(\rho_p - \rho_g) d_p^2 v_{p_0}}{18\mu_g d_f} \qquad \text{...(5.50)}$$

In Eq. (5.50) d_p is the particle diameter. v_{po} is the approach velocity of the particle, d_f is the diameter of the fibre, μ_g is the gas viscosity and C is the Cunningham correction factor. The Cunningham correction factor is included in the above equation to take into account any molecular slip for very small particles. The magnitude of C, as given by Davies[9], is

$$C = 1 + \frac{2\lambda}{d_p}\left(1.257 + 0.4e^{-0.55d_p/\lambda}\right) \qquad \text{...(5.51)}$$

in which λ is the mean free path of the gas molecules. For standard air, $\lambda = 0.066$ µm.

The Reynolds number Re_f in Eq. (5.49) is given by:

$$Re_f = \frac{v_0 d_f \rho_g}{\mu_g} \qquad \text{...(5.52)}$$

where v_0 = free stream velocity of the gas.

In Eq. (5.50), the particle approach velocity is generally assumed to be equal to the free stream gas velocity.

Extensive measurements of collection efficiencies have shown that the particle diameter d_p should be larger than about 1 µm, for inertial effects to play an important role in particle collection. Also, to achieve the greatest possible collection efficiency, the filter medium should be composed of smallest possible fibres consistent with the allowable pressure.

When $\frac{d_p}{d_f} < 0.4$, the collection efficiency due to inertial impaction is given by Hinds[31]:

$$\eta_{\text{impact}} = \left[\left(29.6 - 28 f_f^{0.62}\right)\left(d_p/d_f\right)^2 - 27.5\left(d_p/d_f\right)^{2.8}\right]\frac{\psi}{2(Ku)^2} \qquad ...(5.53)$$

where f_f = fibre solids fraction or packing density defined as the ratio of the volume of the solids (fibres) in a filter per unit volume of the filter. Ku = Kuwabara hydrodynamic factor, which accounts for alteration of the flow field as air flows around fibres in close proximity to one another.

$$Ku = f_f - \frac{3}{4} - \frac{f_f^2}{4} - \frac{1}{2}\ln f_f \qquad ...(5.54)$$

Direct Interception

In the particle collection mechanism of interception, the particles have less inertia and almost follow the streamlines around the obstruction. The particles clear the obstacle but their outer peripheries come in contact with the fibre. Thus, if particle's centre is travelling on a streamline which is closer than the radius of the particle ($d_p/2$), the particle will touch the fibre and will be intercepted (Fig. 5.10b).

The collection efficiency by interception of a cylindrical target may be calculated by the following expression if potential flow is assumed:

$$\eta_{\text{inter}} = \left(1 + \frac{d_p}{d_f}\right) - \frac{1}{\left(1 + \frac{d_p}{d_f}\right)} \qquad ...(5.55)$$

For a viscous flow situation, Strauss[10] recommends Eq. (5.56)

$$\eta_{\text{inter}} = \frac{1}{2.002 - \ln R_{ef}}\left[\left(1 + \frac{d_p}{d_f}\right)\ln\left(1 + \frac{d_p}{d_f}\right) - \frac{2\left(d_p/d_f\right) + \left(d_p/d_f\right)^2}{2 + 2\left(d_p/d_f\right)}\right] \qquad ...(5.56)$$

The combined mechanisms of impaction and interception usually account for more than 99.9% of the collection of the particles larger than 1 μm.

Diffusion

Diffusion mechanism is important for particles that are in the submicron range — particularly for the particles in the range of (0.001–0.05 μm). These particles usually do not follow the gas streamlines surrounding the fibre because the individual motion of the particles can be affected by their collisions with gas molecules. This zigzag random Brownian motion causes the particles to impinge and adhere to the surface of the fibre (Fig. 5.10c).

The collection efficiency by diffusion (η_D) can be obtained from the expression given by Torgeson[11]:

$$\eta_D = 0.775\left(C_{Df} Re_f/2\right)^{0.4} Pe^{-0.6} \qquad ...(5.57)$$

where C_{Df} = drag coefficient of the fibre and Pe = Peclet number, defined by Eq. (5.58)

$$Pe = Re_f \cdot Sc = \frac{v_0 \rho_g d_f}{\mu_g} \cdot \frac{\mu_g}{\rho_g D} = \frac{v_0 d_f}{D} \qquad \text{...(5.58)}$$

In Eq. (5.58), Sc is the Schmidt number and $\mathcal{D}$ is particle diffusivity given by:

$$D = \frac{kTC}{3\pi\mu_g d_p} \qquad \text{...(5.59)}$$

where k = Boltzmann constant (= 1.38×10^{-23} J/K) and T = absolute temperature.

In practice the collection mechanisms of impaction, interception and diffusion are not independent and, hence, all three mechanisms must be combined for calculating the fibre efficiency. A reasonable estimate for the combined efficiency of collection η_f is

$$\eta_f = 1 - (1 - \eta_{\text{impact}})(1 - \eta_{\text{inter}})(1 - \eta_D) \qquad \text{...(5.60)}$$

In addition to the above mentioned three collection mechanisms, electrostatic forces between particles and fibres increase the collection efficiency. The generation of electrostatic charges in filter fabrics may be due to friction between gas and fabrics as well as that between particles and fabric at high gas velocities (1.5 to 2.0 m/s). The increase in collection efficiency on account of electrostatic forces becomes greater with increase in the strength of the electric charge.

Overall Collection Efficiency of a Packed Filter

Consider a packed filter with dimensions of W by H in the plane normal to the gas-flow direction and length L in the gas-flow direction as shown in Fig. 5.11. The approach velocity of the gas is v_0 and its velocity inside the filter is v_∞ where $v_\infty > v_0$. The packing density

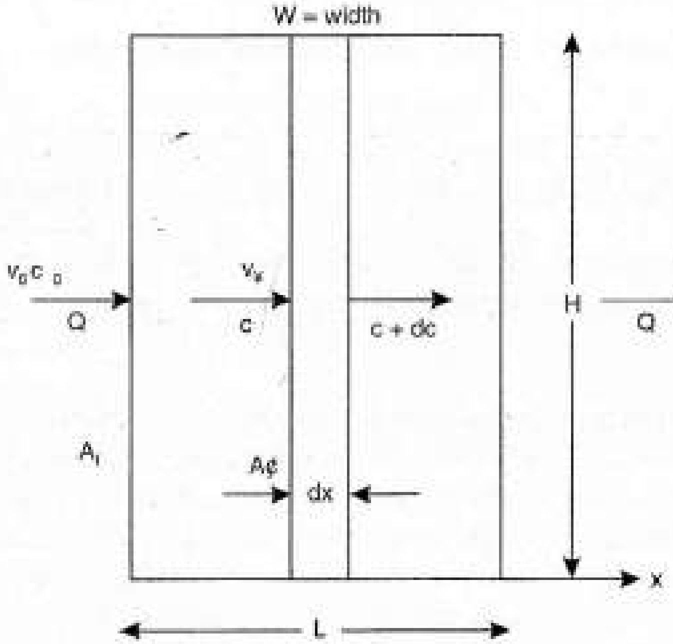


Fig. 5.11 Flow through a packed filter

or fibre solids fraction f_f is related to the porosity (ϵ) of the filter as:

$$1-f_f=\epsilon=\frac{A'}{A_f} \quad \text{...(5.61)}$$

where A^1 is the cross-sectional area for gas moving inside the filter and A_f is the face area of the filter.

The velocity of the gas (v_∞) inside the filter is given by:

$$v_\infty=\frac{Q}{A_f(1-f_f)}=\frac{v_0}{1-f_f} \quad \text{...(5.62)}$$

where Q = volumetric flow rate of the gas.

Writing a mass balance for the particles in the elemental volume as shown in Fig. 5.11, we have:

$$cv_\infty A'=(c+dc)v_\infty A'+v_\infty d_f L_f c\eta_f A_f dx \quad \text{...(5.63)}$$

In Eq. (5.63), L_f is the total length of the fibre per unit volume of filter. This is related to the fibre solids fraction (f_f) as:

$$L_f=\frac{4}{\pi d_f^2}f_f \quad \text{...(5.64)}$$

The last term in Eq. (5.63) gives the rate at which particles are removed from the gas stream in the section of thickness dx. Simplifying Eq. (5.63) and noting

$$\frac{A_f}{A'}=\frac{1}{1-f_f}$$

we have

$$\frac{dc}{c}=-\eta_f\frac{4}{\pi d_f}\left(\frac{f_f}{1-f_f}\right)dx$$

upon integration

$$\frac{c_L}{c_0}=\exp\left[-\eta_f\frac{4}{\pi d_f}\left(\frac{f_f}{1-f_f}\right)L\right]$$

The overall collection efficiency of the filter is:

$$\eta=1-\frac{c_L}{c_0}=1-\exp\left[-\eta_f\frac{4}{\pi d_f}\left(\frac{f_f}{1-f_f}\right)L\right] \quad \text{...(5.65)}$$

where η_f is the individual fibre efficiency as given by Eq. (5.60).

Example 5

A packed filter handling 1.0 m^3/s of standard air is packed with fibres of size 100 μm in diameter. Dust-laden air passes through the filter with a velocity of 1.5 m/s and the

Woven fabrics have a definite long range repeating pattern and have considerable porosity in the direction of gas flow. These open spaces must be bridged by impaction and interception to form a true filtering surface. Felted cloth consists of randomly oriented fibres, compressed into a mat and needled to some loosely woven backing material to improve mechanical strength. Each one of the randomly oriented fibres acts as a target for impaction and interception. This type of filter usually requires substantially lesser cloth area for a given loading than a woven type fabric filter. Felted filters are more expensive than the woven type filters and they can not be used in high humidity service, especially if the particles are hygroscopic because of the high tendency for clogging.

The choice of fabric fibre is based primarily on operating temperature and the corrosiveness or abrasiveness of the particles. Some properties of common fibres are shown in Table 5.3. Cotton is the least expensive fibre, and is preferably used in low temperature dust collection service where no special problems are anticipated. Silicon coated glass fibre cloth is commonly employed in high-temperature applications. The glass fibres must be lubricated to prevent abrasion. All fibres may be applied to the manufacture of woven and felt type fabrics.

Fabric Filter Systems

Fabric filter systems typically consist of a tubular bag or an envelope, suspended or mounted in such a manner that the collected particles fall into a hopper when dislodged from the fabric. The structure in which the bags hang is known as a baghouse. Generally, particle-laden gas enters the bag at the bottom and passes through the fabric while the particles are deposited on the inside of the bag. Fig. 5.12 shows a typical baghouse design in which the cleaning is accomplished by shaking at fixed intervals of time.

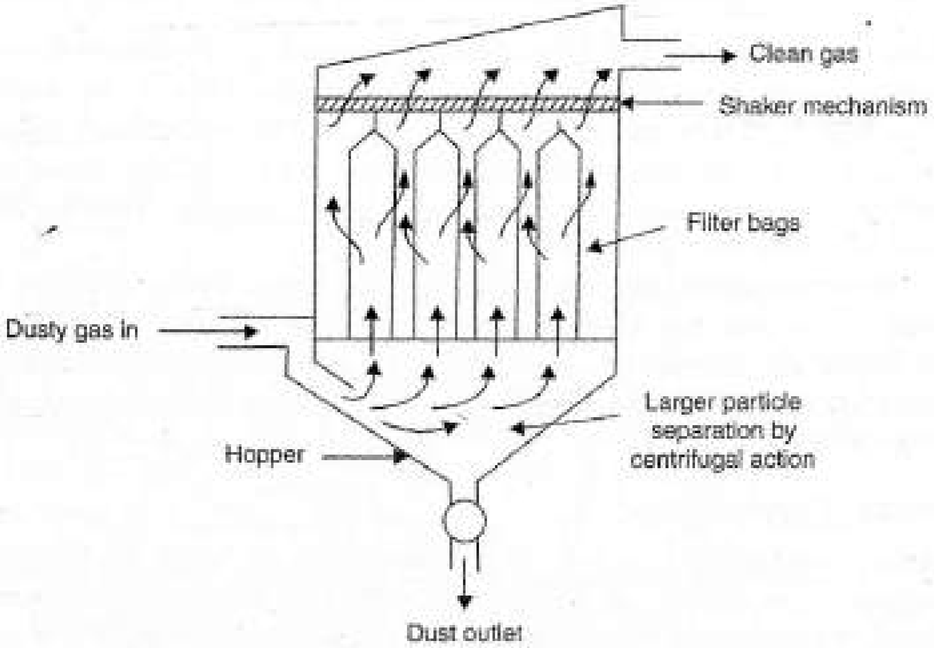


Fig. 5.12 Typical baghouse

Large baghouses are constructed with several compartments, so that one compartment may be isolated for cleaning as needed while the other compartments are operating.

The bags should be arranged in each compartment in such a manner that the available space is utilised effectively and proper access to each bag is provided for its replacement.

Hoppers are provided for dust collection and the dust is removed usually by rotary or screw valves.

Table 5.3 Properties of some fibre materials (ref. 12)

Fibre	*Relative strength*	*Maximum usable temp. (°C)*	*Relative resistance to attack by*			*Other properties*
			Acid	*Base*	*Organic solvent*	
Cotton	Strong	80	Poor	Medium	Good	Low cost
Wool	Medium	95	Medium	Poor	Good	Fair resistance to abrasion
Polyamide (nylon)	Strong	100	Medium	Good	Good	Easy to clean, excellent resistance to abrasion
Polyester (dacron)	Strong	135	Good	Medium	Good	Easy to clean
Tetrafluoro-ethylene (Teflon)	Medium	260	Good	Good	Good	Expensive
Glass	Strong	280	Medium	Medium	Good	Poor resistance to abrasion
"Nomex" nylon	Strong	230	Good	Medium	Good	Poor resistance to moisture

The method of cleaning fabric filters varies according to manufacturer and type of filter. The cleaning may be accomplished by shaking the bags or by increasing the air pressure on the bag in a manner that causes the bag to collapse or otherwise deform sufficiently to dislodge the accumulated dust. Cleaning generally takes less than one minute with the bulk of the dust being removed in a few seconds. A good cleaning schedule ensures longer bag life and efficient filtration.

The following advantages make fabric filters the best choice in many cases: (i) very high efficiencies, (ii) retention of finest particles, (iii) collection of particulates in dry form, and (iv) relatively low pressure drop. The main disadvantages are: (i) their large size, (ii) high construction costs, and (iii) their application only to process temperatures generally below 285°C.

5.4.6 Electrostatic Precipitators

The electrostatic precipitator is one of the most widely used devices for controlling particulate emissions at industrial installations ranging from power plants, cement and paper mills to 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.

Electrostatic precipitation is a physical process by which particles suspended in gas stream are charged electrically and, under the influence of the electrical field, separated from the gas stream. A typical wire and pipe precipitator is illustrated in Fig. 5.13.

The precipitation system consists of a positively charged (grounded) collecting surface and a high-voltage discharge electrode wire suspended from an insulator at the top and held in position by a weight at the bottom. At a very high DC voltage, of the order of 50 kV, a corona discharge occurs close to the negative electrode, setting up an electric field between the emitter and the grounded surface. The particle-laden gas enters near the bottom and flows upward. The gas close to the negative electrode is, thus, ionised upon passing through the corona. As the negative ions and electrons migrate towards the grounded surface, they in turn charge the passing particles. The electrostatic field then draws the particles to the collector surface where they are deposited.

Periodically, the collected particles must be removed from the collecting surface. This is done by rapping or vibrating the collector to dislodge the particles. The dislodged particles drop below the electrical treatment zone and are collected for ultimate disposal. Usually, a large number of these collectors are placed in parallel in a single housing forming a multiple cylindrical unit. Although the multiple unit is not as widely used as the parallel-plate precipitator described in the next paragraph, it finds frequent use in collecting liquid particles.

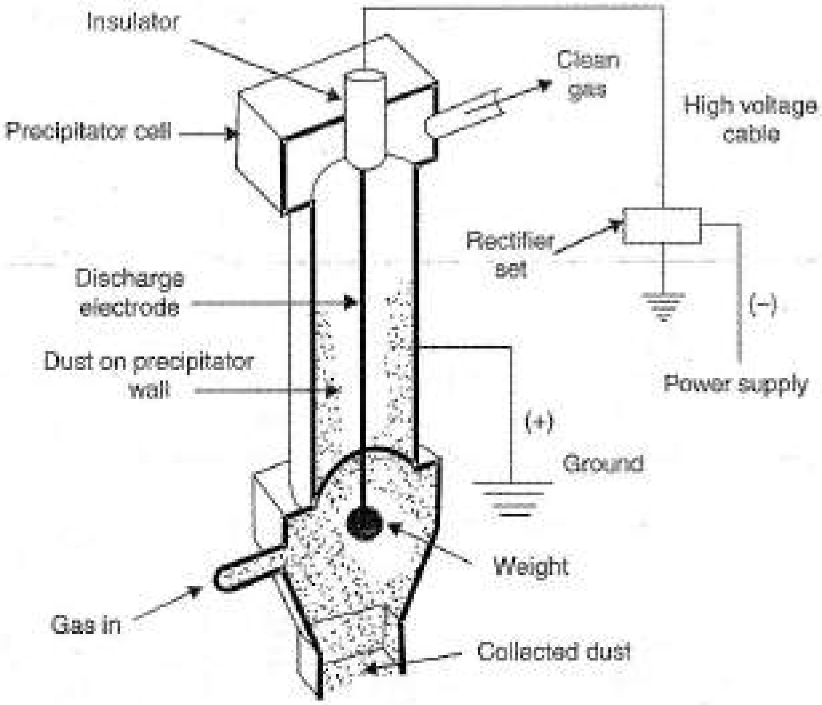


Fig. 5.13 Schematic diagram of a wire and pipe precipitator

For industrial applications, vertical plates exposed to horizontal gas flow are normally used. In this type of collector, the gas flows between two vertical parallel plates between which are suspended a number of vertical wires held in place by weights attached at the bottom. These wires form the discharge electrode, while the vertical plates form the collection electrode. Fig. 5.14 shows the schematic diagram of a typical parallel-plate arrangement.

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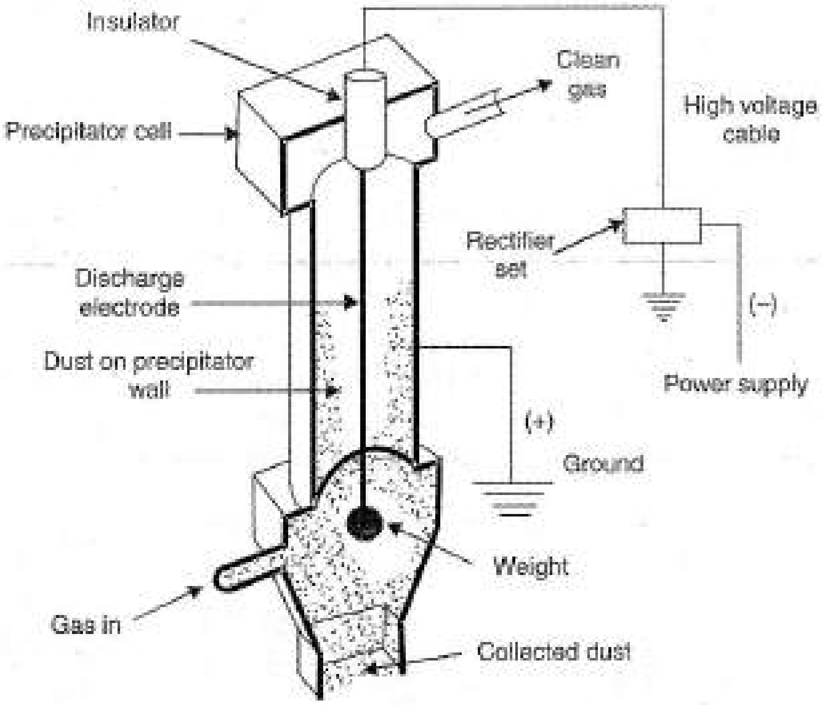

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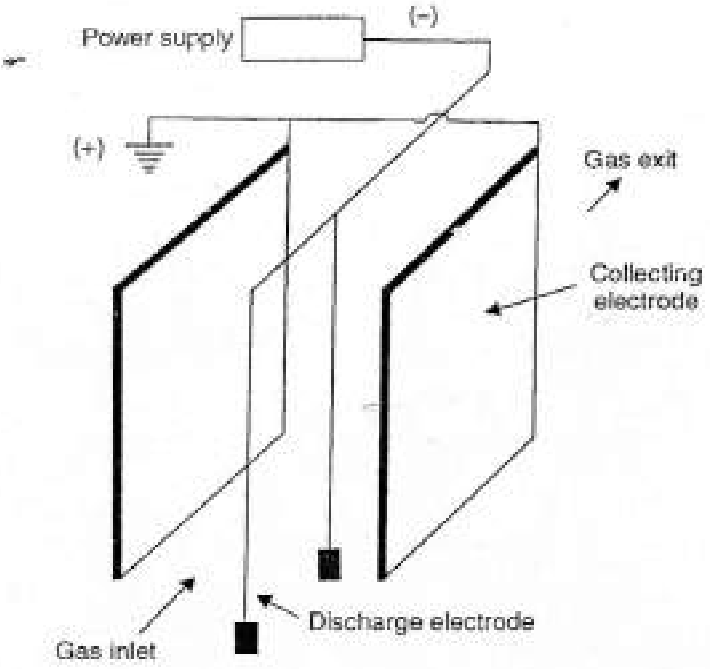

Fig. 5.14 Schematic diagram of a parallel-plate precipitator

Collection Efficiency

The collection efficiency of an electrostatic precipitator as a function of gas flow rate and precipitator size is given by the Deutsch equation (Eq. 5.76) which is applicable to both cylindrical and parallel plate type precipitators. Consider a precipitator of an arbitrary geometry with a cross section A and length L, as shown in Fig. 5.15. It is assumed that the particle distribution over the cross-sectional area is constant.

A particle that has entered the precipitator and received an electric charge moves along a trajectory towards the collection electrode as shown in Fig. 5.15. This trajectory can be resolved into the axial z-component with a velocity v_{pz}, and a y-component with a velocity v_{pm}. The particle velocity v_{pz} is equal to the gas velocity v in the axial direction.

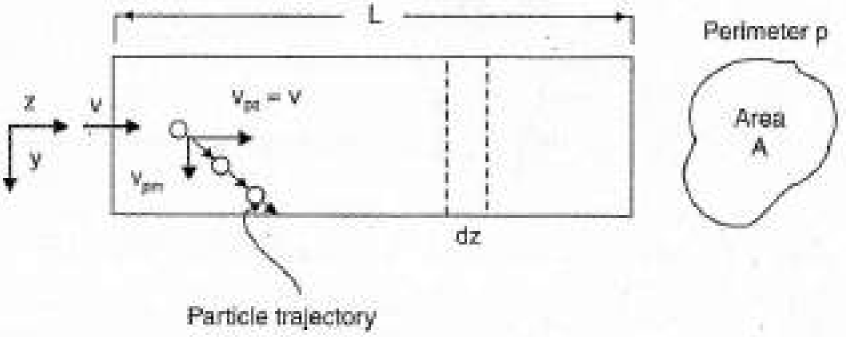

Fig. 5.15 Collection efficiency derivation

When the charged particle possessing a charge q_p is in a region where an electric field strength of E_c is present, a force F_{el} will act on the particle.

$$F_{el} = q_p E_c \tag{5.66}$$

The migration of particles towards the collector is resisted by a drag force and the net force on the particle is zero when it moves with a constant drift velocity, v_{pm}.

$$F_{el} = F_{drag} \qquad \text{...(5.67)}$$

or,

$$q_p E_c = C_D \frac{\pi d_p^2}{4C} \frac{\rho_g v_{pm}^2}{2} \qquad \text{...(5.68)}$$

where C = Cunningham correction factor as given in Eq. (5.51). For small particles, the Stokes law is applicable. Hence

$$C_D = \frac{24\mu_g}{\rho_g d_p v_{pm}} \qquad \text{...(5.69)}$$

Substituting for C_D into Eq. (5.68) and solving for v_{pm}, we find

$$v_{pm} = \frac{q_p E_c C}{3\pi\mu_g d_p} \qquad \text{...(5.70)}$$

The collection efficiency is evaluated by writing a mass balance across the differential element dz (Fig. 5.15). For steady operation with no net accumulation of particles in the gas space, we get

$$Qc = Q(c + dc) + cv_{pm} P\,dz \qquad \text{...(5.71)}$$

where P = perimeter of the geometry, c = particle concentration, mass per unit volume of gas stream, and Q = the volumetric flow rate of the gas.

Simplifying Eq. (5.71), we get

$$\frac{dc}{c} = -\frac{v_{pm} P dz}{Q} \qquad \text{...(5.72)}$$

Integrating Eq. (5.72) over the length L for concentration from c_0 to c_L, we get

$$\frac{c_L}{c_0} = \exp\left(-\frac{v_{pm} PL}{Q}\right) \qquad \text{...(5.73)}$$

The collection efficiency η is defined as

$$\eta = 1 - \frac{c_L}{c_0} \qquad \text{...(5.74)}$$

Substitution of Eq. (5.73) into Eq. (5.74) gives:

$$\eta = 1 - \exp\left(-\frac{v_{pm} PL}{Q}\right) \qquad \text{...(5.75)}$$

Noting that the product PL is equal to the collector surface area A_c, we may write Eq. (5.75) as

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$$\eta = 1 - \exp\left(-\frac{v_{pm} A_c}{Q}\right) \qquad \text{...(5.76)}$$

This is the well known equation for the collection efficiency of a precipitator obtained by Deutsch and it can be used for both tubular and plate type precipitators. Equation (5.76) may also be written in the following form:

$$\eta = 1 - \exp\left(-\frac{v_{pm}}{v}\frac{A_c L}{V}\right) \qquad \text{...(5.77)}$$

where v = gas velocity; V = volume of the precipitator.

For a cylindrical type collector $\frac{A_c}{V} = \frac{4}{D_c}$, where D_c = diameter of the collector, and for a parallel-plate type collector $\frac{A_c}{V} = \frac{2}{S}$, S being the distance between the two parallel plates.

The particle migration velocity is probably the most important parameter in Eq. (5.76). As seen from Eq. (5.70), it is a function of a large number of operational quantities such as the electric field strength (E_c), particle size (d_p), gas viscosity (μ_g) and the particle charge (q_p) which is a function of the dielectric and resistivity properties of the particle. Substituting Eq. (5.70) into Eq. (5.76), we find

$$\eta = 1 - \exp\left(-\frac{q_p E_c C}{3\pi\mu_g d_p}\frac{A_c}{Q}\right) \qquad \text{...(5.78)}$$

Typical values of the migration velocity encountered in practice for use in Eq. (5.76) are given in Table 5.4.

Example 6

An electrostatic precipitator for use with standard air containing dust particles of 1.0 μm diameter is in the form of a cylinder 0.3 m diameter and 2.0 m long. The volumetric flow rate of air is 0.075 m^3/s. If the electric field strength is 1,00,000 V/m and if the particle charge is 0.3×10^{-15} coulomb, compute the collection efficiency.

Solution

The particle migration velocity is calculated from Eq. (5.70)

$$v_{pm} = \frac{q_p E C}{3\pi\mu_g d_p}$$

Substituting the viscosity for standard air, the above equation can be written as:

$$v_{pm} = 5766\,\frac{q_p E_c C}{d_p}$$

The Cunningham correction factor C is evaluated from Eq. (5.51)

$$\bar{C} = 1 + \frac{2\lambda}{d_p}\left(1.257 + 0.4e^{-0.55d_p/\lambda}\right)$$

For standard air, $\lambda = 0.066$ µm and the particle size $d_p = 1.0$ µm. Substituting these values, the value of $C = 1.168$. Therefore,

$$v_{pm} = \frac{5766\left(0.3\times10^{-15}\right)10^{5}\,(1.168)}{\left(1.0\times10^{-6}\right)} = 0.202 \text{ m/s}$$

Table 5.4 Effective migration velocities (ref. 13)

Application	v_{pm} *(m/s)*
Pulverised coal fly ash	0.10–0.13
Paper mills	0.08
Open-hearth furnaces	0.06
Secondary blast furnace	0.12
Gypsum	0.16–0.20
Hot phosphorus	0.03
Sulphuric acid mist	0.06–0.08
Cement	
Wet process	0.10–0.11
Dry process	0.06–0.07
Catalyst dust	0.08

From Eq. (5.76)

$$\eta = 1 - \exp\left(-\frac{v_{pm}A_c}{Q}\right)$$

$$A_c = \pi D_c L = \pi(0.3)(2.0) = 1.88 \text{ m}^2 \text{ and } Q = 0.075 \text{ m}^3/\text{s}$$

Substituting for A_c and Q, we find

$$\eta = 1 - \exp\left(-\frac{(0.202)(1.88)}{(0.075)}\right) = 0.9937$$

Example 7

A plate-type electrostatic precipitator for use in a cement plant for removing dust particles consists of 10 equal channels. The spacing between the plates is 0.15 m, and the plates are 2 m high and 2 m long. The unit handles 10,000 m³/hr of gas. What is the efficiency of collection? What should be the length of the plates for achieving 99% collection efficiency if other condition are the same?

Solution

From Eq. 5.76

$$\eta = 1 - \exp\left(-\frac{v_{pm} A_c}{Q}\right)$$

$$A_c = 2(2 \times 2) = 8 \text{ m}^2,\ v_{pm} = 0.10 \text{ from Table 5.4, and}$$

$$Q = (10{,}000)/(10)(3600) = 0.278 \text{ m}^3/\text{s per channel.}$$

Therefore, $$\eta = 1 - \exp\left(-\frac{(0.10)(8)}{0.278}\right) = 94.4\%$$

$A_c/V = 2/S$. The spacing between the plates, S, is equal to 0.15 m.

Therefore, $$A_c/V = \frac{2}{0.15} = 13.33 \text{ m}^{-1}$$

The velocity of the gas in each channel,

$$v = \frac{Q}{A} = \frac{0.278}{(0.15)(2)} = 0.927 \text{ m/s}$$

From Eq. (5.77), for $\eta = 0.99$,

$$\frac{v_{pm}}{v}\left(\frac{A_c}{V}\right)L = 4.6$$

$$L = \frac{4.6(0.927)}{13.33(0.1)} = 3.2 \text{ m}$$

A unique feature of electrostatic precipitators is that the separating force is applied directly to the particles without the necessity of accelerating the gas as is done for all other particulate collection devices. This unique feature leads to an extremely low pressure loss for the collection of fine particles compared with that in any other type of collector.

The most economical design and operation of dry electrostatic precipitators is obtained when the resistivity of particles falls within certain desired limits. If the resistivity is low, particles give up their charge too easily and become re-entrained in the gases flowing past the collecting electrode. On the other hand, high-resistivity particles can not lose their charge upon reaching the collector electrode because of the low conductivity of the material deposited earlier. As a result, the effective field strength is reduced and the efficiency falls. Particle resistivity can be controlled in many cases by selecting the proper operating temperature or by injecting water to reduce the resistivity. Such irrigated precipitators are used for the collection of fumes from electric arc furnaces.

Table 5.5 summarizes the advantages and disadvantages of the electrostatic precipitator as a particulate control device. These devices are often used in series with cyclones; the coarse particles are first removed in cyclones before the gas enters the precipitator.

Table 5.5 Advantages and disadvantages of electrostatic precipitator

Advantages	*Disadvantages*
1. Pressure drop and hence power requirement is small compared to that in other devices; economical and simple to operate	1. Relatively high initial cost and large space requirement
2. 99+ per cent efficiency obtainable; very small particles can be collected wet or dry	2. Sensitive to variable particulate loadings or flow rates
3. Can handle both gases and mists for high volume flow	3. Safeguard of operating personnel from high voltage is necessary
4. Few moving parts; can be operated at high temperatures and pressures	4. Collection efficiency can deteriorate gradually

5.4.7 Wet Scrubbers

In Chapter 2, it was pointed out that wet precipitation is the principal mechanism by which atmospheric particles are removed by nature. This idea has been exploited by industry to develop a variety of liquid scrubbing equipment. Wet collectors have a number of advantages over dry collectors, such as simultaneous removal of particles and gaseous pollutants but suffer from the problems of corrosion and liquid waste disposal. These are summarised in Table 5.6.

The basic function of wet scrubbers is to provide contact between the scrubbing liquid, usually water, and the particulate to be collected. This contact can be achieved in a variety of ways as the particles are confronted with so-called impaction targets — which can be wetted surfaces or individual droplets. Whether the particles encounter wetted surfaces as in packed scrubbers or individual droplets as in spray scrubbers, the basic collection mechanisms are the same as in filters: inertial impaction, interception and diffusion, which were discussed in an earlier section. Generally, impaction and interception are the predominant mechanisms for particles of diameter above 0.3 μm, and for particles of diameter below 0.3 μm, diffusion begins to prevail. In addition, diffusiophoretic deposition and electrostatic precipitation also effect particle collection.

Diffusiophoretic deposition can be significant when mass transfer within the scrubber, caused by condensation of water vapour from the gas onto a cold liquid surface, exerts a force upon the particles and causes them to get deposited on the surface. The electrostatic charge produced on droplets during atomization is too small to have any influence on particle collection except when a charge is deliberately induced on the droplets[14]. In addition, agglomeration, another phenomenon that occurs in all particle collectors, also enhances particle removal.

There are many scrubber designs presently available where the contact between the scrubbing liquid and the particles is achieved in a variety of ways. The major types are: (i) spray towers, (ii) centrifugal scrubbers, (iii) packed beds and plate columns, and (iv) venturi scrubbers.

Each type of design has a certain range of applicability. Thus, low-energy scrubbers such as spray towers are most often used to handle particles largely about 5-10 μm in diameter, while the high-energy units such as the venturi scrubbers are very effective with fine particles (smaller than 3 μm).

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Table 5.6 Advantages and disadvantages of wet collectors

Advantages	*Disadvantages*
1. Simultaneous removal of gases and particulates	1. Relatively high energy costs
2. Effective performance over a wide loading range	2. Problem of wet sludge disposal
3. Equipment occupies only a moderate amount of space compared to dry collectors such as bag houses	3. Corrosion problems
4. Hazards of explosive dust-air mixtures are reduced	4. Visible wet plume, reduction in buoyancy
5. Indifference to the temperature and moisture content of gas	5. Very small particles (sub-micron sizes) may not be captured
6. Corrosive gases may be neutralised by proper choice of scrubbing liquid	

Spray Towers

The simplest type of wet scrubber is a spray tower into which water is introduced by means of spray nozzles (Fig. 5.16). The polluted gas flows upward and the particle collection results because of inertial impaction and interception on the droplets. The maximum

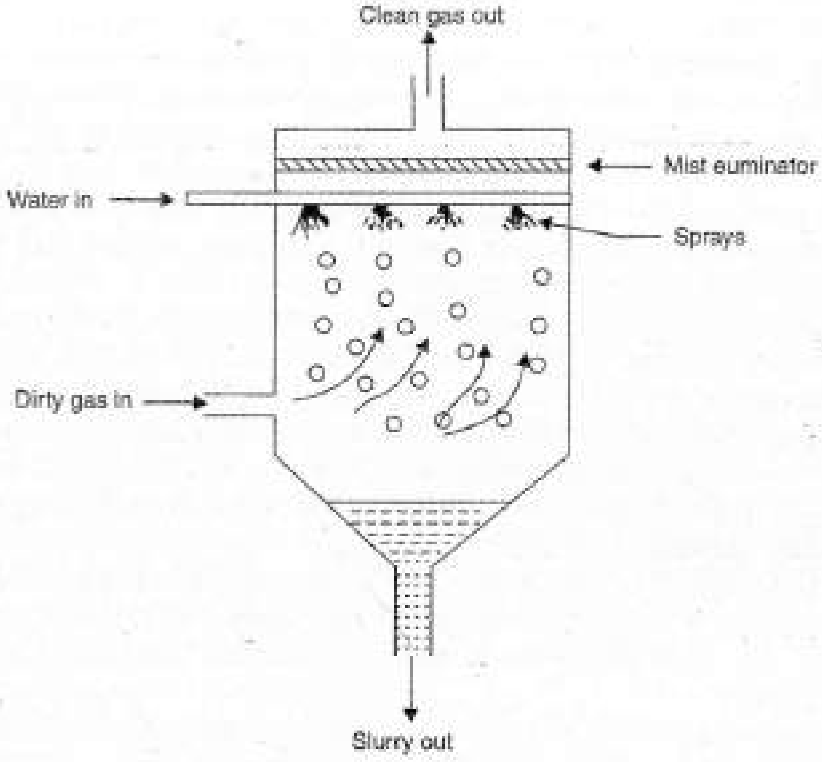

Fig. 5.16 Spray tower

Centrifugal Scrubbers

The collection efficiency for particles smaller than those recovered in spray towers can be increased through the use of centrifugal scrubbers. The simplest type of centrifugal scrubber can be constructed by inserting banks of nozzles inside a conventional dry cyclone. The spray acts on the particles in the outer vortex, and the droplets loaded with particles are thrown outward against the wet inner wall of the cyclone. In the absence of spray, the efficiency will be the same as that for a dry collector.

Another version of a centrifugal scrubber, shown in Fig. 5.18, has the polluted gas introduced tangentially into the lower portion of the vertical cylinder. Water drops are injected into the flow stream from sprays directed outward from a central manifold. These droplets are caught in the spinning gas stream and are thrown upward towards the wall by centrifugal force. During their motion, the droplets collide with the particles and capture them. The scrubbing liquid along with the particles flows down the wall to the bottom of the scrubber. The cleaned gas exits through a demister and is processed for the removal of any entrained water droplets.

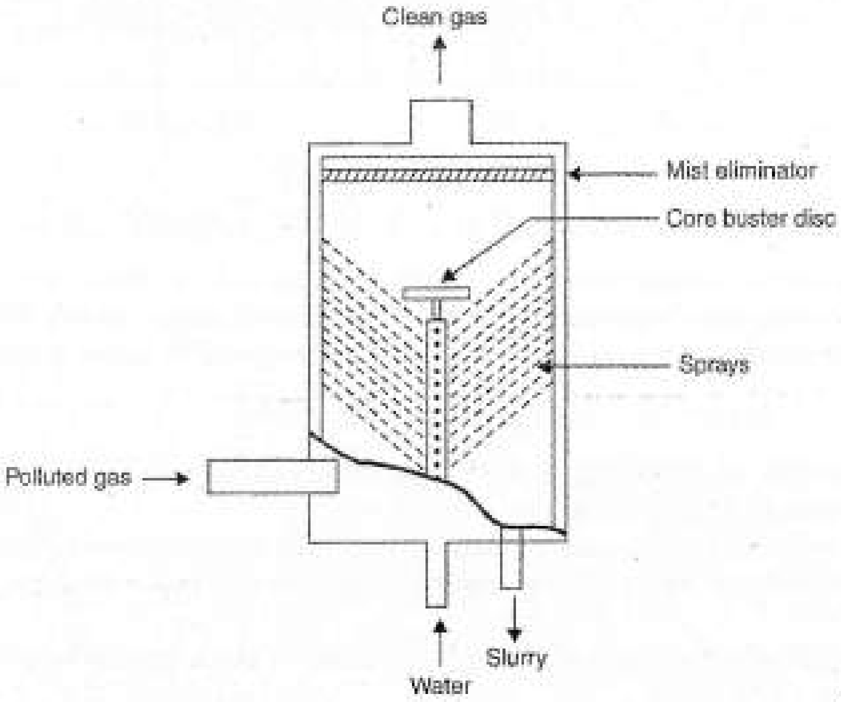

Fig. 5.18 Centrifugal scrubber, tangential entry

The particle cut diameter (d_{pc}) for centrifugal spray scrubbers is between 2 and 3 μm. Commercial scrubbers have operating efficiencies of 97 per cent or better for particles larger than 1 μm. The centrifugal acceleration involved may range from 25 to 300g. In a centrifugal field of 100 g, for example, the most effective droplet size is 100 μm (ref. 16). Smaller droplets can be entrained in the gas stream whereas the bigger droplets are found to have smaller inertial impaction parameters.

Packed Beds and Plate Columns

Packed beds and plate columns, well known to chemical engineers as absorbers or fractionators, can also be used to scrub particulate matter from polluted gases. In a typical countercurrent-flow packed scrubber (Fig. 5.19) the polluted gas stream moves upward and comes in contact with the scrubbing liquid stream which is moving downward over the packing in a film.

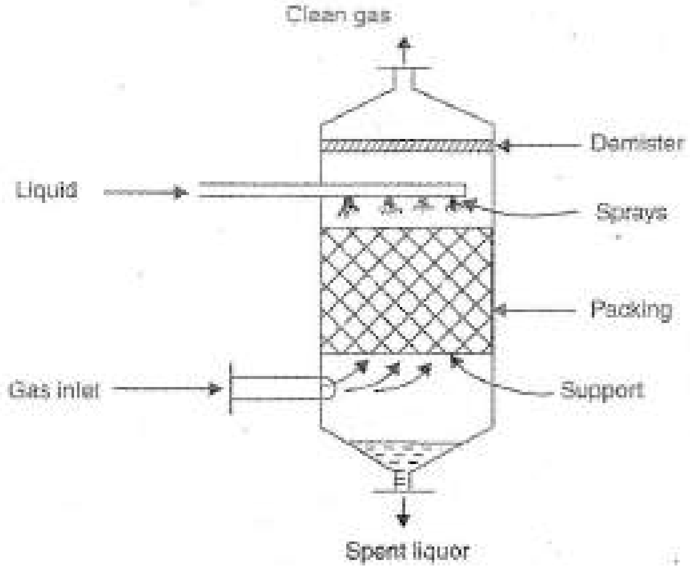

Fig. 5.19 Packed bed tower

The packing provides a target, which allows the gas stream to take a curved path through the pore spaces while the particles carried by the gas stream are captured by inertial impaction. Because of the good mass transfer characteristics of the packing, efficient collection of fine particles by diffusion is also possible. The scrubber can be packed with a variety of materials such as Raschig rings, saddles, coke or broken stone. Smaller packing increases the efficiency of collection but its shape does not appear to affect the collection efficiency.

Packed towers can be chosen for scrubbing particles that are soluble in the scrubbing liquid; otherwise, the packings will encounter plugging problems. The plugging problems can be reduced by employing sprays to wash the packing or by using low density spheres, agitated by the gas flow. More recently, a moist chemical foam packing has been employed, which drains slowly from the scrubber with captured particles and is replaced with fresh material.

In the impingement baffle plate scrubber, the gas stream is passed through a flooded, perforated plate for scrubbing (Fig. 5.20). The impingement baffles are situated directly above each perforation on to which the gas jet is impinged. The particles are collected by inertial impaction. Particle collection may be aided by atomization of liquid flowing past the perforations in the plate.

In impingement type scrubbers the superficial gas velocities are 5 times the velocities generally used for mass transfer operations such as distillation. The main disadvantage of impingement plate systems is their tendency towards scaling, resulting in plugging of the perforations.

Venturi Scrubbers

Venturi scrubbers offer high performance collection of fine particles, usually smaller than

2 to 3 μm in diameter. They are particularly suitable when the particulate matter is sticky, flammable or highly corrosive. The high performance of the venturi scrubbers is achieved by accelerating the gas stream to very high velocities, of the order of 60-120 m/s. The high-speed action atomizes the feed liquid, generally introduced in a uniform fashion across the throat through several low-pressure spray nozzles directed radially inward as shown in Fig. 5.21.

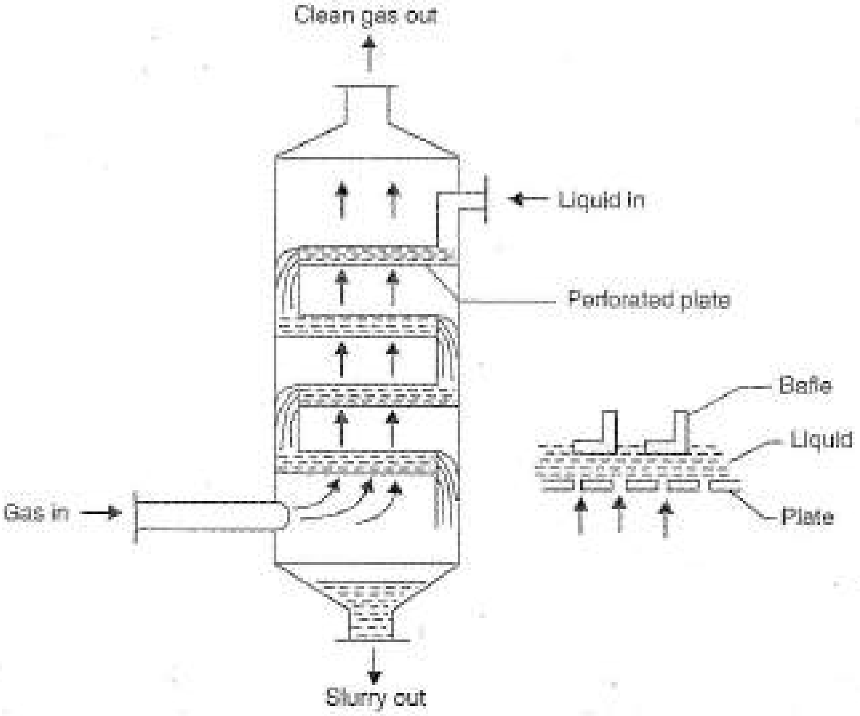

Fig. 5.20 Impingement baffle-plate scrubber

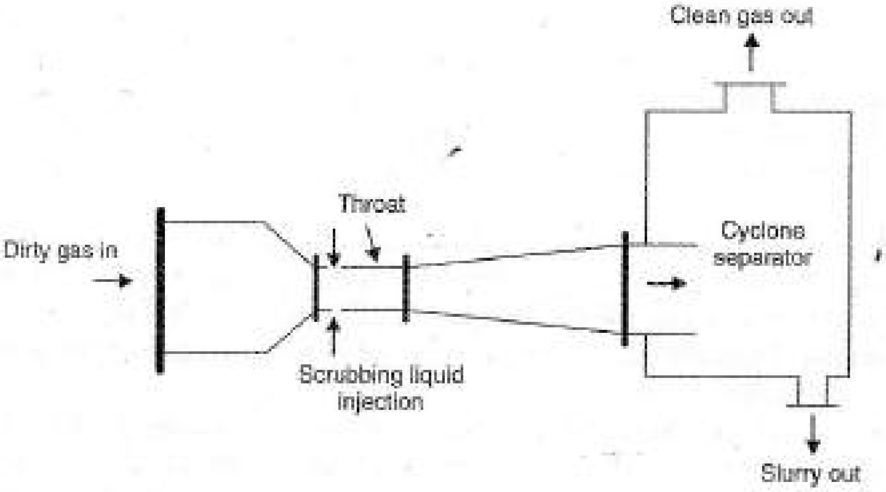

Fig. 5.21 Venturi scrubber followed to cyclone separator

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. This acceleration of the droplets is not likely to be completed at the end of the throat, so that particle collection 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 the droplets carrying the particulate matter are separated from the gas stream.

The mechanisms affecting the collection of particulates in the venturi scrubber are inertial impaction, diffusion, electrostatic-phenomenon, and condensation and agglomeration. Although condensation plays a part in the effectiveness of the scrubber by helping the particles to agglomerate, the predominant mechanism is inertial impaction. Johnstone *et al.*[17] correlated the collection efficiency of the venturi scrubber with the impaction parameter (ψ) as:

$$\eta_{sc} = 1 - \exp\left(-KL\sqrt{\psi}\right) \qquad \text{...(5.81)}$$

where K is an empirical factor determined by throat geometry and other parameters. The value of K may be of the order of 0.1 to 0.2. The inertial impaction parameter can be evaluated from Eq. (5.50) by replacing d_f, the fibre diameter with the droplet diameter d_0 and v_{p0}, the particle velocity with the relative velocity of gas to liquid, v_r.

The diameter of the droplet obtained from gas atomisation in the venturi throat can be evaluated from the following equation:

$$d_0 = 16{,}400/v_r + 1.45\,L^{1.5} \qquad \text{...(5.82)}$$

where d_0 is in μm, L is the liquid flow rate (gal/1000 ft^3 of gas), and v_r is the relative velocity of gas to liquid at venturi throat in ft/sec.

Example 8

A venturi scrubber is to be used to collect particulate matter from an industrial operation. The liquid flow rate through the scrubber is 10 gpm per 1000 ft^3 per min. of the gas and the relative velocity of the gas to liquid is 300 ft/sec. The gas is air at standard temperature of 298 K and pressure of 1 atm carrying particles of density 1000 kg/m^3. Determine the efficiency of the scrubber as a function of particle diameter.

Solution

The droplet diameter from gas atomisation (d_0) is obtained from Eq. (5.82).

$$d_0 = \frac{16{,}400}{v_r} + 1.45L^{1.5}$$

where L = 10 gpm/1,000 ft^3 per min, and v_r = 300 ft/sec = 91.5 m/s.

Substituting the values, we get

$$d_0 = \frac{16{,}400}{300} + 1.45(10)^{1.5} = 100\,\mu m = 100 \times 10^{-6}\ \text{m}$$

The inertial impaction parameter ψ is given by the equation,

$$\psi = \frac{C\rho_p d_p^2 v_r}{18\mu_g d_0}$$

where $C = 1 + 2\dfrac{\lambda}{d_p}\left(1.257 + 0.4e^{-0.55d_p/\lambda}\right)$

$\lambda = 0.066$ μm for standard air at 298 K and 1 atm.

$$\rho_p = 1000 \text{ kg/m}^3, \text{ and } \mu_g = 1.8 \times 10^{-5} \text{ kg/m-s},$$

Substituting, we get

$$\psi = \frac{C(1000)d_p^2\,(91.5)}{18\left(1.8\times10^{-5}\right)\left(100\times10^{-6}\right)} = 2.824\ Cd_p^2$$

The collection efficiency η_{sc} of the scrubber can be obtained from Eq. (5.81):

$$\eta_{sc} = 1 - \exp\left(-KL\sqrt{\psi}\right)$$

Assuming $K = 0.2$, we get

$$\eta_{sc} = 1 - \exp\left(-0.2(10)\sqrt{\psi}\right)$$

$$= 1 - \exp\left(-2\sqrt{2.824\,Cd_p^2}\right)$$

$$= 1 - \exp\left(-3.361\sqrt{C}\,d_p\right)$$

The values of η_{sc} calculated from the above equation for various particle sizes are tabulated below:

d_p (μm)	C	η_{sc} (%)
0.1	2.911	43.64
0.2	1.890	60.32
0.3	1.574	71.78
0.5	1.337	85.68
0.7	1.240	92.72
1.0	1.168	97.36
2.0	1.084	99.91
5.0	1.034	100

The results are plotted in Fig. 5.22.

The pressure drop through the venturi scrubber can be predicted on the basis of the equation suggested by Calvert[18]

$$\Delta P = 5 \times 10^{-5} v_r^2 L \qquad \text{...(5.83)}$$

where Δp is the pressure drop in inches of water. For the problem of example 8, the pressure drop, ΔP, becomes equal to 45″ H_2O. Fig. 5.22 shows typical collection efficiency curves at two other pressure drops for particulate matter having a specific gravity of 1.0 in a well-designed scrubber[19]. As is shown in Fig. 5.22, for particles of a particular size higher efficiencies require greater pressure drop and consequently greater power

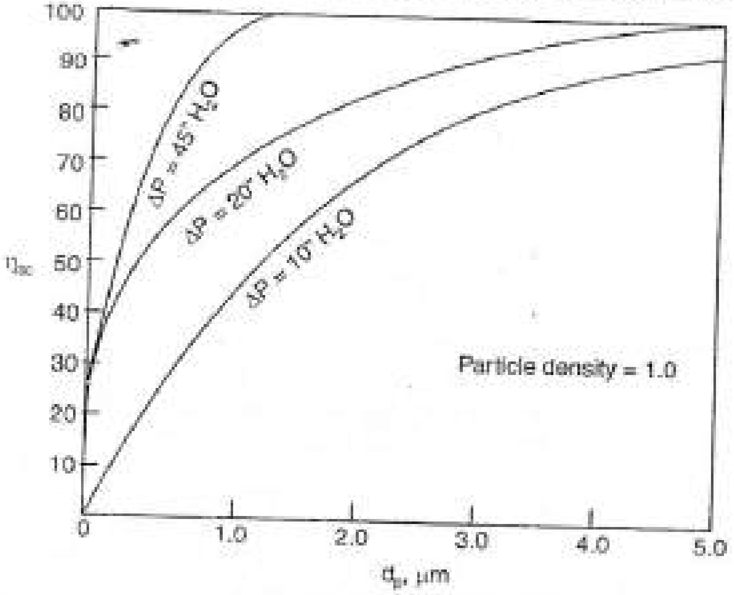

Fig. 5.22 Venturi scrubber efficiency curves

consumption. Similarly, for smaller particles, the same efficiency requires a higher pressure drop or greater power consumption.

Scrubber Performance and Efficiency Correlation

The above ideas have led Semrau[20] to correlate the scrubber efficiency in terms of "contacting power". It is a concept used to describe the power expended in a wet scrubber to force contact between the liquid and solid phases and is usually defined in terms of the power per unit of volumetric gas flow rate that is dissipated in contacting and is ultimately converted into heat. The total contacting power P_T, is the sum of the gas-phase contacting power, P_G, the liquid-phase contacting power, P_L, and mechanical contacting power, P_M (for those devices which are mechanically aided).

$$P_T = P_G + P_L + P_M \qquad \text{...(5.84)}$$

These terms may be determined from Eqs. (5.85-87)

$$P_G = 0.02724\ \Delta P_g \qquad \text{kWh/1000 m}^3 \qquad \text{...(5.85)}$$

where ΔP_g = gas pressure loss in cm H_2O.

$$P_L = 0.02815\ \Delta P_l \left(\frac{Q_L}{Q_G}\right) \qquad \text{kWh/1000 m}^3 \qquad \text{...(5.86)}$$

where ΔP_l = pressure drop for liquid input in atm; Q_L = liquid rate in litre/min; and Q_G = gas rate in m³/min.

$$P_M = 16.67\left(\frac{W_S}{Q_G}\right) \qquad \text{kWh/1000 m}^3 \qquad \text{...(5.87)}$$

where W_S = net mechanical power input in kW.

The collection efficiency of a scrubber can be described in terms of the number of transfer units, N_t, defined as

$$N_t = -\int_{C_1}^{C_2} \frac{dc}{c} = -\ln\left(\frac{c_2}{c_1}\right) \qquad \text{...(5.88)}$$

$$\eta = 1 - \frac{c_2}{c_1} = 1 - e^{-N_t} \qquad \text{...(5.89)}$$

where c_1 = inlet particle concentration and c_2 = outlet particle concentration.

The number of transfer units was plotted against total power consumption (P_T) for series of scrubbers and particulates when the following expression was obtained:

$$N_t = \alpha P_T^{\beta} \qquad \text{...(5.90)}$$

where α and β are empirical constants that depend on the particulate size an characteristics, and are little affected by the scrubber size or geometry, or the manner o applying the contacting power. Some representative values of α and β are given in Tabl 5.7.

Table 5.7 Scrubber efficiency parameters (ref. 21)

Scrubber	*Aerosol*	*Correlation parameter*	
		α	β
Venturi	Talc dust	2.97	0.362
	Phosphoric acid mist	1.33	0.647
	Foundry cupola dust	1.35	0.621
	Open hearth steel furnace fume	1.26	0.569
Venturi and cyclonic spray	Raw gas (lime dust and soda fume)	1.47	1.05
	Black liquor recovery furnace fume	1.75	0.620
	Ferrosilicon furnace fume	0.870	0.459
Venturi pipeline and cyclonic spray	Pre-washed gas (soda fume)	0.915	1.05
	Hot fume solution for scrubbing	0.740	0.861
Venturi condensation scrubber with:			
(*i*) mechanical spray generator	Copper sulphate	0.390	1.14
(*ii*) hydraulic nozzles	Copper sulphate	0.562	1.06
Cyclone	Talc dust	1.16	0.655

In Table 5.7, α, the coefficient of P_T in Eq. (5.90), has units of $hp/(1000\ \text{ft}^3/\text{min})^{-\beta}$ an the exponent β is dimensionless. Since the contacting power P_T is given in the units kWh/1000 m^3, it has to be converted into units of hp/(1000 ft^3/min) when using in Eq. (5.90) along with α and β.

(Note: 1.0 kWh/1000 m^3 = 2.278 hp/1000 ft^3/min).

5.5 SELECTION OF A PARTICULATE COLLECTOR

The selection of a suitable control device for a specific application requires consideration of particle size, its concentration, desired efficiency of collection, costs, space available, and maintenance factors. Fig. 5.23 gives the efficiencies of various gas cleaning devices for three broad particulate size categories: coarse, fine and superfine dusts[22]. This can be used conveniently for a preliminary selection of devices. For example, for 99% removal of fine dust (50% < 25 μm), preliminary selection of an irrigated target type scrubber, an electrostatic precipitator, and an irrigated electrostatic precipitator may be made. After the preliminary selection, a comparative cost analysis must be conducted including the operating and the maintenance costs. After a general selection of equipment is made to meet specific emission limitations, the exact costs are determined, and the actual operating efficiency and pressure drop are obtained on the installed system.

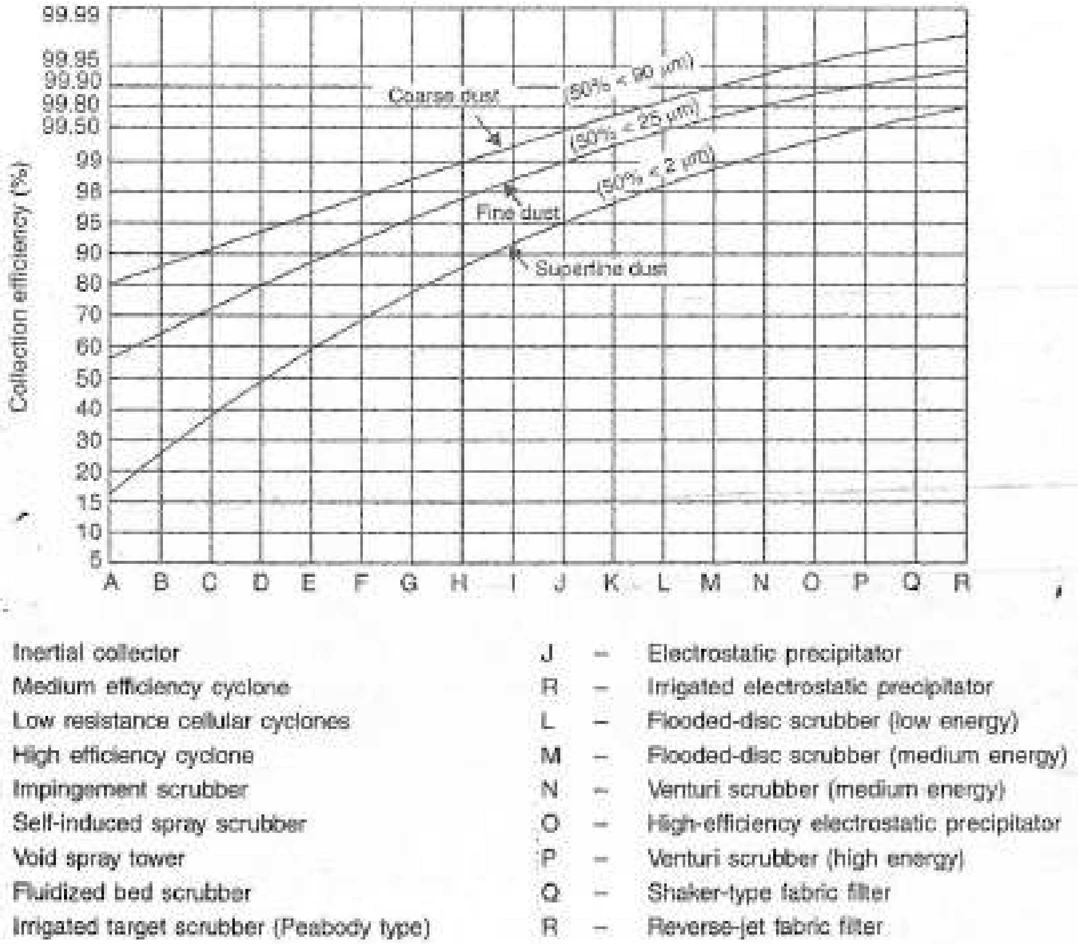

Fig. 5.23 Efficiency of various types of gas cleaning devices (ref. 22, copyright (c) 1974 by Litton Educational Publications Inc., copyright (c) 1979 renewed by Van Nostrand Reinhold, all rights reserved, reproduced with permission)

It is important that the inter-related process and environmental factors must be weighed carefully before taking the final decision. Often the collection equipment eventually selected represents the most desirable compromise. Alternatively, two collectors may be combined to achieve the desired results. Table 5.8 provides a summary of some successful applications of particulate control devices in various industries.

5.6 CONTROL OF GASEOUS EMISSIONS

As noted earlier, there are essentially two classes of techniques by which gaseous pollutants may be removed from an effluent stream: (1) sorption of pollutant, for example through absorption in a liquid or adsorption on a solid surface, and (2) chemical alteration of the pollutant, usually, through combustion or catalytic treatment.

5.6.1 Absorption by Liquids

Absorption is one of the most frequently used techniques for controlling the concentrations of gaseous pollutants before they are discharged into the atmosphere.

It involves the transfer of the pollutant from the gas phase to the liquid phase across the interface in response to a concentration gradient, with the concentration decreasing in the direction of mass transfer.

Table 5.8 Use of particulate collectors in industry

Industry or process	*Particulate matter*	*Collection devices*
Steel	Iron oxide, dust, smoke	Cyclones, fabric filters, electrostatic precipitators, wet scrubbers
Metallurgical (non-ferrous)	Smoke, metal fumes, oil, grease	Electrostatic precipitators, fabric filters, wet scrubbers
Cement, phosphate, gypsum, alumina processing	Process dusts	Electrostatic precipitators, mechanical collectors, fabric filters, wet scrubbers
Kraft paper mills	Chemical dusts	Electrostatic precipitators, venturi scrubbers
Sulphuric, phosphoric, nitric acid manufacture	Acid mist, dust	Electrostatic precipitators, mesh mist eliminators
Petroleum refineries	Catalyst dust, ash from sludge	High efficiency cyclones, electrostatic precipitators, scrubbing towers
Power generation	Coal dust, fly ash	Mechanical collectors, electrostatic precipitators

A two-resistance theory, initially suggested by Whitman[23], is often used to explain this process. According to the theory, the interface offers no resistance to mass transfer, and the mass transfer rate between the two phases is controlled by the rates of diffusion through the phases on each side of the interface. The transfer of component A from the gas phase to the liquid phase is illustrated in Fig. 5.24, with a concentration gradient in the gas phase from the bulk gas concentration of component A, p_{AG}, to the interfacial concentration, p_{Ai}, and a concentration gradient in the liquid phase from, c_{Ai} at the interface to the bulk liquid concentration, c_{AL}. The bulk concentrations p_{AG} and c_{AL} are not equilibrium values; because if they were, diffusion of component A will not take place. If no resistance to mass transfer exists at the interface, p_{Ai} and c_{Ai} are equilibrium concentrations; these are the values which would be obtained if the two phases had been in contact for an infinite period of time. p_{Ai} and c_{Ai} are directly related through the equilibrium data.

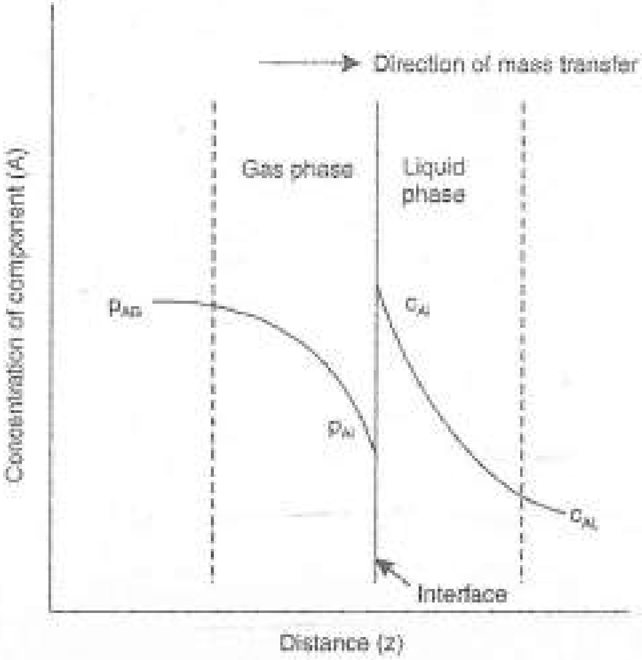

Fig. 5.24 Concentration profiles

For dilute solutions the equilibrium relation between p_A and c_A can be expressed in terms of Henry's law:

$$p_A = Hc_A \qquad ...(5.91)$$

where H is the Henry's constant, which depends on the definition of concentration units. For example, if the Henry's law is expressed in terms of the mole fraction units, Eq. (5.91) becomes

$$p_A = H'x_A \qquad ...(5.92)$$

where x_A is the mole fraction of component A in the liquid. Table 5.9 shows values of Henry's constant for several gases in water. Smaller values of H' represent higher solubilities of the gas. That is, for a given partial pressure of the gas, a higher liquid concentration will be reached at equilibrium.

Table 5.9 Values of Henry's constant (H') for several gases in water (ref. 3)

Gas	$H' \times 10^{-3}$ (atm / mole fraction) at		
	10 °C	*20 °C*	*30 °C*
CO	44.2	53.6	62.0
H_2S	0.367	0.483	0.609
NO	21.8	26.4	31.0
N_2	66.8	80.4	92.4
O_2	32.7	40.1	47.5
SO_2	0.007	0.014	0.016
CO_2	1.04	1.42	1.86

Selection of the Scrubbing Medium

The effectiveness of an absorption process for air pollution control mostly depends on the selection of a suitable scrubbing medium. Some of the properties of solvents, which are important in industrial applications, are the following: high gas solubility and high selectivity between solute species, low vapour pressure, non-corrosiveness, easy regeneration and recovery, low costs, low viscosity at absorption temperature, nontoxicity, nonflammability and chemical stability.

In addition, the chosen scrubbing medium should not cause water pollution or waste disposal problems. Table 5.10 summarises the more commonly used solvents in industry for the removal of various gaseous pollutants.

Table 5.10 Suitable solvents for various gaseous pollutants

Gaseous pollutants	*Suitable solvents*
Sulphur dioxide	Sodium hydroxide, sodium sulphite, magnesium oxide, calcium carbonate, calcium oxide and calcium hydroxide solutions
Nitrogen oxides	Ammonium bicarbonate, ammonium bi-sulphite, calcium hydroxide, magnesium hydroxide and sodium hydroxide solutions
Hydrogen sulphide	Sodium hydroxide, potassium hydroxide solutions
Hydrogen chloride	Water, ammonia, calcium and magnesium hydroxide solutions
Chlorine	Solutions of sodium hydroxide, sodium sulphite, sodium thiosulphite and water
Phosgene	Sodium hydroxide and water
Ammonia	Sulphuric acid, nitric acid
Mercaptans	Sodium hypochlorite solution

Gas Absorption Equipment

Gas absorption is commonly conducted in equipment which are designed to provide intimate contact between the two phases. The contact between gas and liquid can be accomplished by dispersing the liquid in the gas or vice versa. Some of the commonly used absorbers in air pollution control are packed towers, plate and spray towers and venturi scrubbers.

Packed towers are very efficient absorption devices involving a continuous contact of two phases. These use a variety of packing materials ranging from specially designed ceramic packing to crushed rock. The liquid is distributed over the packing, which provides high interfacial surface area, and flows down the packing surface in the form of thin films or subdivided streams. Normally, the liquid and gas flow countercurrent to each other, the gas flowing upward and the liquid flowing downward. The use of packed towers is limited to clean gases, as any precipitate or slurry will cause plugging of packing.

In *tray or plate towers*, stepwise contact between the liquid and gas occurs. Liquid introduced at the top cascades from one stage to another and eventually is withdrawn from the bottom of the tower. The gas flows in a countercurrent direction to the dropping liquid. At each tray, gas passes through small holes drilled in the tray or under slotted caps immersed in the liquid, forming bubbles. Absorption takes place during the bubble formation and their ascent through the liquid. In the *spray towers*, the flow arrangements are normally countercurrent and cross-flow. The liquid is introduced by spray nozzles or other atomising devices which form droplets. These droplets provide the mass transfer surface. Spray towers are used for absorption of highly soluble gases and solid particles when these are present in the gas.

In *venturi scrubbers* the gas and liquid flow in the same direction. The absorbing liquid is introduced at the throat of the venturi and the dispersion of the liquid is accomplished by the high velocity gas stream. The resulting large interfacial area makes the venturi scrubber an extremely efficient absorber. However, the energy required for achieving high efficiencies is considerable.

In air pollution control, the most popular means of gas cleaning is the packed tower; however, tray columns, spray and venturi scrubber are used in nearly 10% of the cases. Absorption is treated extensively in most chemical engineering texts (ref. 24-27), to which reference can be made for detailed information regarding the equipment design and construction. Here the discussion will be limited to the basic concepts related to the design of packed columns.

Basic Design Considerations

Consider a steady-state operation involving a countercurrent absorber as shown in Fig. 5.25.

A solute material balance gives,

$$G_1 y_1 + L_2 x_2 = G_2 y_2 + L_1 x_1 \qquad \text{...(5.93)}$$

where G = total molal flow rate of the gas phase per cross-sectional area of tower, L = total molal flow rate of the liquid phase per cross-sectional area of tower, y = mole fraction of solute in the gas phase and x = mole fraction of solute in the liquid phase.

Since G and L vary along the height of the tower, it is much simpler to express material balance equations in terms of solute-free concentration units. The material balance then becomes:

can be calculated from the relation,

$$H_G = \frac{\alpha(G')^{\beta}}{(L')^{\gamma}}\sqrt{Sc_G}$$

In the above equation G' and L' are the average values for the entire tower which in this case are 1.254 and 1.007 kg/m^2 -s, respectively. From Table 5.11, for 1 in. Rachig rings, α = 0.557, β = 0.32 and γ = 0.51. These data are used with some reservation since G' exceeds the limit shown in the table. The Schmidt number Sc_G = 0.705.

$$H_G = \frac{0.557(1.254)^{0.32}}{(1.007)^{0.51}}\sqrt{0.705} = 0.503 \text{ m}$$

Similarly, H_L is given by

$$H_L = \phi\left(\frac{L'}{\mu_L}\right)^{\eta}\sqrt{Sc_L}$$

where, from Table 5.12, ϕ = 0.00235, and η = 0.22. The Schmidt number Sc_L = 462. Substituting these values, we get

$$H_L = 0.00235\left(\frac{1.007}{9.82\times10^{-4}}\right)^{0.22}\sqrt{462}$$

or

$$H_L = 0.232 \text{ m}$$

Employing, Eq. (5.116), we can get the height of the overall transfer unit (H_{OG}). The slope (m) of the equilibrium line can be evaluated to be equal to 0.78. The average values of G and L are 0.0103 and 0.0134 kg moles/sec, respectively. Substituting, these values in Eq. (5.116), we get

$$H_{OG} = 0.503 + 0.78\left(\frac{0.0103}{0.0134}\right)0.232$$

or

$$H_{OG} = 0.503 + 0.139 = 0.642 \text{ m}$$

The height of the packing,

$$Z = 3.58(0.642) = 2.3 \text{ m}$$

The total height of the tower should be somewhat greater than this value to allow for the distribution space at the top and at the bottom.

5.6.2 Adsorption by Solids

An alternative to absorption by liquids is the adsorption of pollutants on solids. Adsorption is a surface phenomenon by which gas or liquid molecules are captured by and adhere to the surface of a solid adsorbent. The attractive forces holding the molecules at the surface may be either physical (physical adsorption) or chemical (chemisorption) in nature. In physical adsorption, the gaseous material condenses upon the surface of the solid, accompanied by an evolution of heat. The adsorbed material can be removed or desorb by reducing the pressure or by increasing the temperature. Thus, the process is reversib Chemisorption, which is the result of a chemical interaction between the solid and t adsorbed material, is usually irreversible with the heat of adsorption being much high than that for physical adsorption. The molecules are held to the solid surface by chemic bonds and the original material undergoes a chemical change. Chemisorption is of particul importance in catalysis but is not a primary mechanism in air pollution control metho

Adsorption techniques are widely used in the field of odour control for removing sm quantities of pollutants present in a large volume of air. Adsorption techniques are al used for collecting valuable organic substances that cannot be picked up by scrubbi methods. The rate of adsorption of a substance depends on the concentration of the materi around the adsorbent, the surface area of the adsorbent, the pore volume of the adsorbe and some other properties such as temperature, molecular polarity and the chemical natu of the adsorbent surface. Several solids possess adsorptive ability with extremely lar specific surface areas. Some of the adsorbents commonly used in air pollution control a activated carbon, activated alumina, silica gel and molecular sieves. Typical data for ads bent materials and their uses are given in Table 5.14.

Adsorption of a gas on a solid occurs in several stages. The first stage is the diffusi of the pollutant from the bulk gas phase to the external surface of the solid, and this similar to the diffusion of the gas to the gas-liquid interface in absorption. The seco stage is the diffusion of the gas molecules into the pores of the solid, and the third sta is the actual adsorption on the active sites in the pores. The third stage is relatively fa compared to the first two stages, and it is these earlier states that determine the rate adsorption. It is usually not possible to determine which of the first two stages controls t adsorption rate. In some cases they are of equal significance. For that reason, adsorbe are most often designed using empirical methods based on scale-up from pilot scale dat

Table 5.14 Properties of adsorbents and their uses

Adsorbent	*Specific surface area (m^2/g)*	*Bulk density (g/cm^3)*	*Pore volume (cm^3/g)*	*Average pore size (Å)*	*Uses*
Activated carbon	1000–1500	0.3–0.5	0.6–0.8	20–35	Removal of odours, and trace impurities from gases, purification of industrial gases and hydrocarbons, solvent recovery
Activated alumina	175–250	0.7–0.8	0.4	34	Dehydration of gases and liquids
Silica gel	250–850	0.4–0.8	0.3–0.45	21	Dehydration and purification of gases
Molecular sieves	500–1000	0.6–0.9	0.25–0.3	~4	Selective adsorption of CO_2, NH_3, C_2H_2, H_2S and SO_2

Removal of pollutants by adsorption may be carried out in a batchwise or continuous manner of operation. A typical fixed bed operating on a batch cycle is shown in Fig. 5.30. The polluted gas stream enters the bed at the top, travels downward through the bed and leaves at the bottom.

When the gas first enters the solid bed, the front portion of the bed adsorbs the pollutant gas very rapidly and the little amount of solute left is taken up by the deeper layers of the bed. Thus, the gas initially leaving the bed is almost completely free of the pollutant.

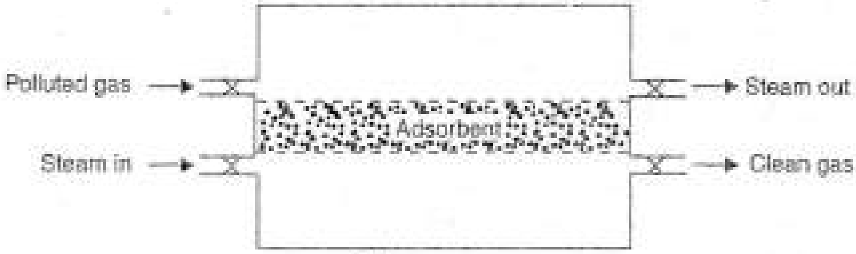

Fig. 5.30 Fixed bed adsorber

After a period of time, the layers of the solid at the entrance become saturated with the adsorbed gas and the zone of active adsorption moves deeper into the bed. Finally, when the front of the active zone reaches the bottom of the bed, the bed starts becoming inactive and the pollutant level in the exit gas stream starts to rise and continues to rise until it approaches the influent concentration. The curve of pollutant concentration as a function of time thus has an *S*-shaped appearance and is commonly called the break-through curve. Fig. 5.31 shows a typical break-through curve. The time at which the break-through curve first begins to rise appreciably is called the break-through point, and the time at which the outlet effluent concentration essentially reaches that of the inlet pollutant concentration is called the exhaustion point.

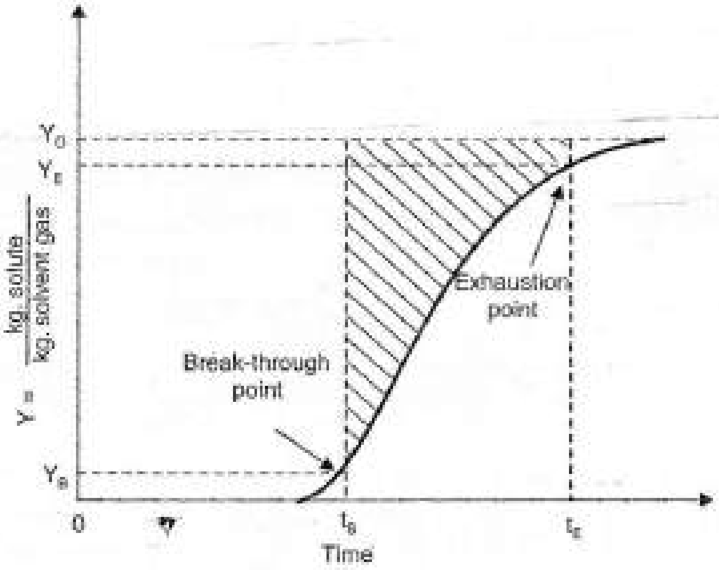

Fig. 5.31 Typical adsorption break-through curve

The adsorber is normally regenerated when the break-through point is reached. Regeneration means removing the pollutant from the adsorbent thereby renewing it for further use. For the single-bed adsorber, as shown in Fig. 5.30, the regeneration is accomplished by stopping the gas stream and then allowing steam or an inert gas to flow through the adsorbent bed. Regeneration is often facilitated by using parallel beds, one of which removes pollutant while the other is being regenerated.

Adsorption Process Design

Adsorption processes are most easily designed through the use of break-through curves obtained in pilot-plant studies. When break-through occurs, the adsorbent in the adsorption zone is practically spent. A major part of the break-through curve analysis is concerned with the determination of the fractional ability of the adsorbent in the adsorption zone and the depth of the adsorption zone.

The mass velocity of the solvent gas stream is G_m kg/(hr) (m^2). The initial concentration of the pollutant (solute) in the inlet gas is Y_0 kg. solute/kg. solvent gas and the concentration at the break-through point is Y_B. The adsorbent has essentially exhausted at some arbitrarily chosen value Y_E close to Y_0. The adsorption zone Z_A in the bed, of constant depth is that part of the bed in which the concentration is in the process of being changed from Y_B to Y_E. If t_F is the adsorption zone formation time and Z is the height of the adsorbent bed,

$$Z_A = Z\frac{t_E - t_B}{t_E - t_F} \qquad \text{...(5.119)}$$

where t_E = time to exhaustion, t_B = time to break-through point.

The difference $t_E - t_B$ gives the time required for the adsorption zone to move its own depth down the adsorbent bed after the zone has been established.

The amount of solute S, removed from the gas in the adsorption zone from t_B to t_E is given by the shaded area in Fig. 5.31 times G_m. This is given by

$$S = G_m \int_{t_B}^{t_E} (Y_0 - Y)\,dt \qquad \text{...(5.120)}$$

If, however, all adsorbent in the zone were saturated with solute, it would contain $Y_0\, G_m\, (t_E - t_B)$ kg solute/m^2 of bed cross-section. Therefore, the fractional ability of the adsorbent in the adsorption zone still to adsorb solute is,

$$f = \frac{S}{Y_0 G_m (t_E - t_B)} = \frac{\int_{t_B}^{t_E} (Y_0 - Y)\,dt}{Y_0 (t_E - t_B)} \qquad \text{...(5.121)}$$

or

$$f = \int_0^{1.0} \left(1 - \frac{Y}{Y_0}\right) d\left(\frac{t - t_B}{t_E - t_B}\right) \qquad \text{...(5.122)}$$

and

$$t_F = (1 - f)(t_E - t_B) \qquad \text{...(5.123)}$$

From Eq. (5.132) $\quad H_{OG} = \dfrac{G_m}{K_Y a} = \dfrac{100}{7150} = 0.014$ m

The depth of adsorption, $\quad Z_A = (9.314)(0.014) = 0.13$ m

The height of the bed, Z = 1 m.

Degree of bed saturation at break-through point,

$$\eta = \frac{Z-(1-f)Z_A}{Z} = \frac{1.0-(1-0.556)0.13}{1.0} = 0.942.$$

$$= 94.2\ \%$$

At break-through point the amount of adsorbate

$$= \eta Z \rho_b X_T = (0.942)(1.0)(440)(0.042) = 17.4\ \text{kg/m}^2 \text{ cross-section}$$

The pollutant enters with the air at a rate of

$$(100)\ (0.024) = 2.4\ \text{kg/(hr)(m}^2)$$

The time required to reach the break-through point,

$$t_B = 17.4/2.4 = 7.25\ \text{hr}$$

5.6.3 Combustion

Many industrial processes produce gas streams that have no recovery value, so absorption or adsorption methods may not be economically feasible. If the waste gas contains sufficient combustible material then incineration may be the simplest route to air pollution control. Combustion applications include the destruction of odours, toxic substances, and reactive materials, the prevention of explosion hazards, and the reduction of pollutants in the oxidised forms. The products of combustion of organic materials are normally odourless, colourless, and harmless giving off carbon dioxide and water vapour. However, high molecular weight hydrocarbons could cause smoke problems. Similarly, certain inorganic materials upon combustion give oxidation products like sulphur dioxide and oxides of nitrogen, and these remain a pollution problem unless they are easily separated from the gas stream.

When a pollutant is to be destroyed, the combustion must be complete; otherwise, intermediate products of combustion will form which may be more noxious than the original contaminant. For complete combustion, the oxygen must come into intimate contact with the combustible material through adequate turbulence at sufficiently high temperature and have a sufficiently long residence time. In fact, time, temperature, and turbulence have so predominant role in combustion reactions that they are often called the “three T's” of combustion.

The normal ranges are: temperature: 375–825 °C, residence time; 0.2–0.5 sec and gas velocity: 4.5–7.5 m/sec.

There are three methods of combustion in common use today: direct combustion (or flaring), thermal incineration (also called after-burning or flame combustion), and catalytic oxidation. Highly combustible streams with high heating values can be eliminated by direct flaring. However, flaring is not a satisfactory solution when the gas streams contain excessive amounts of inorganic pollutants like sulphur, chlorine and fluorine. In suc cases the gas streams are pretreated before flaring. Often unsaturated hydrocarbons suc as olefins and aromatics with their low hydrogen-to-carbon ratios produce smoke unless th design is such that it allows them to burn smokelessly. One such design incorporate steam injection through jets surrounding the flare tip (Fig. 5.35). The steam jets induc turbulence in the periphery of the flame and add heat to the combustion process. I addition, this sets up a water gas reaction giving carbon monoxide and hydrogen whic helps to generate smokeless flame. The steam requirements vary from 0.05 to 0.3 k steam/kg gas, depending on the olefinic and aromatic content of the gas stream. A pil flame is also provided to re-ignite the gas stream if flameout occurs.

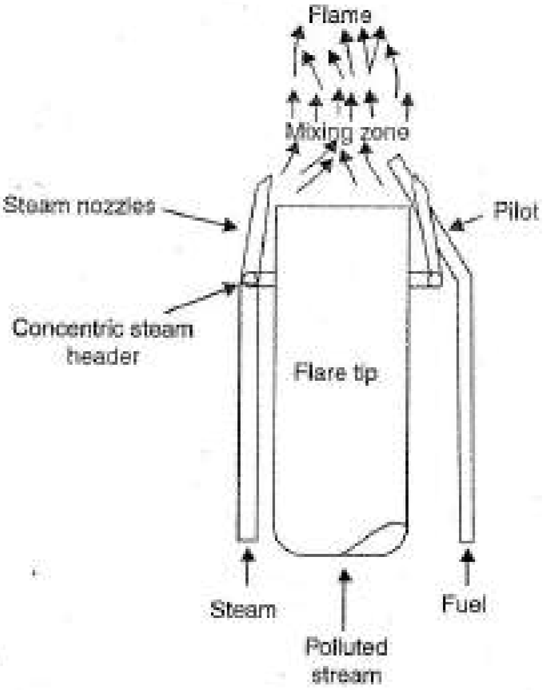

Fig. 5.35 Steam injection type flare

Preheating of the gas stream is often required if the combustible gases are diluted wit inert gases to ensure that the minimum fume energy concentration is not reached. This i done by using a ring burner in addition to the pilot flame burners. *Thermal incineratio* is perhaps the most efficient as well as the most flexible technique for destroying such diluted gas streams. In the thermal incinerator (Fig. 5.36) the waste gas is preheated ofte over an auxiliary fuel-fired burner and passed into a combustion chamber where temperature of 500 to 800°C is maintained. The gas stream is kept at this elevate temperature long enough (0.3 to 0.7 sec residence time) to allow complete oxidation. Th gas stream is introduced in such a geometry and at a velocity that promote turbulence an thorough mixing with the burning fuel. Thermal incinerators require little maintenance properly engineered. The major operating cost is in the form of fuel required to sustai appropriate temperature levels. The fuel requirements may be reduced by recovering th waste heat either by returning the heat to the process or to preheat the gases.

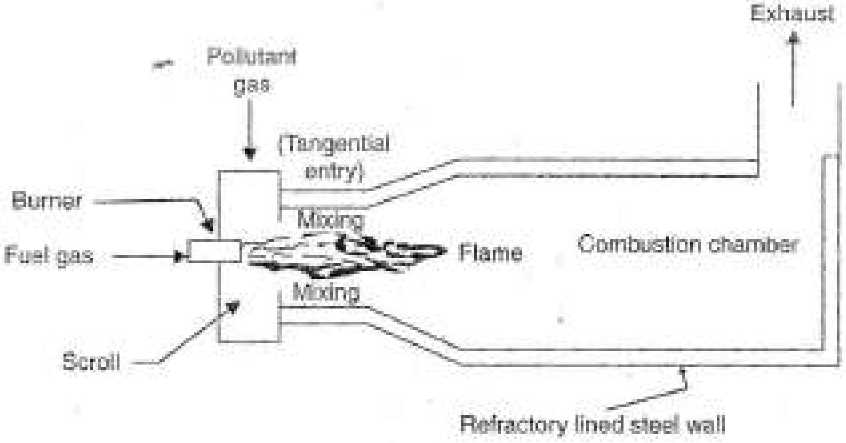

Fig. 5.36 Thermal incinerator

Regenerative Heat Recovery

In the regenerative heat recovery arrangement, a heat exchanger is usually placed in the exhaust stream following the oxidiser where the hot exhaust gases are used to heat the incoming air stream containing the pollutant. The preheated air stream then enters the oxidiser where the pollutant is destroyed. The products of combustion then pass through the heat exchanger and are discharged into the atmosphere. A schematic of the regenerative heat recovery arrangement for the oxidiser is shown in Fig. 5.37.

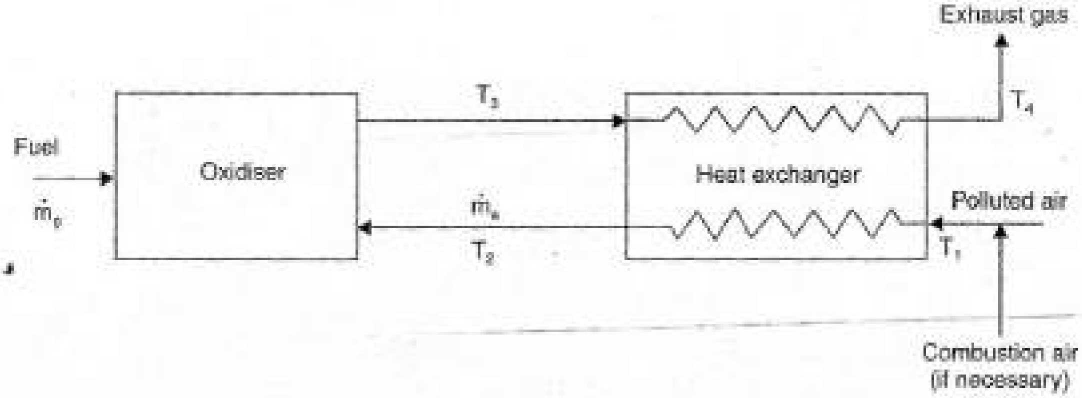

Fig. 5.37 Regenerative arrangement for an oxidiser

The effectiveness of the heat exchanger is given as:

$$\varepsilon = \frac{h_2 - h_1}{h_3 - h_1} \qquad \text{...(5.135)}$$

Where, h_1 and h_2 are the specific enthalpies of the polluted air stream entering and leaving the heat exchanger respectively, and h_3 is the specific enthalpy of the process gas stream leaving the oxidiser and entering the heat exchanger. Now, writing a heat balance around the heat exchanger, we have

$$\dot{m}_a (h_2 - h_1) = (\dot{m}_a + \dot{m}_g)(h_3 - h_4) \qquad \text{...(5.136)}$$

where $\dot{m}_a$ = mass flow rate of polluted air stream, $\dot{m}_g$ = mass flow rate of the fuel and h_4 = specific enthalpy of the exhaust gas leaving the heat exchanger.

Solving Eq. (5.136) for h_4 gives

$$h_4 = h_3 - \frac{\dot{m}_a}{\dot{m}_a + \dot{m}_g}(h_2 - h_1) \qquad ...(5.137)$$

The air-fuel ratio

$$\frac{A}{F} = \frac{\dot{m}_a}{\dot{m}_g} \qquad ...(5.138)$$

Substituting Eq. (5.138) into Eq. (5.137), gives

$$h_4 = h_3 - \frac{(A/F)}{(1 + A/F)}(h_2 - h_1) \qquad ...(5.139)$$

We assume that the oxidation of the pollutant takes place under adiabatic conditions. The enthalpy h_3 of the product air stream leaving the oxidiser from which the temperature T_3, called the *adiabatic combustion temperature* can be obtained, is given by

$$h_3 = h_2 + \frac{\left(\frac{-\Delta H_R}{m_g}\right)}{\left(1 + \frac{A}{F}\right)} \qquad ...(5.140)$$

where $\frac{-\Delta H_R}{m_g}$ is the heat of combustion of the fuel used, per unit mass. Table 5.15 lists heat of combustion values for several common fuels. Solving Eq. (5.140) for h_2 and substituting into Eq. (5.135) gives

$$\varepsilon = \frac{h_3 - \frac{\left(\frac{-\Delta H_R}{m_g}\right)}{\left(1 + \frac{A}{F}\right)} - h_1}{h_3 - h_1}$$

or

$$\varepsilon = 1 - \frac{\left(\frac{-\Delta H_R}{m_g}\right)}{(h_3 - h_1)\left(1 + \frac{A}{F}\right)} \qquad ...(5.141)$$

Solving Eq. (5.141) for the air-fuel ratio, $\frac{A}{F}$, we have

$$\frac{A}{F}=\frac{\dfrac{-\Delta H_R}{m_g}}{(h_3-h_1)(1-\varepsilon)}-1 \qquad \text{...(5.142)}$$

Substituting Eq. (5.142) into Eq. (5.139) and noting that $h_2 - h_1 = \varepsilon\,(h_3 - h_1)$, we get

$$h_4 = h_3 - \left[1-\frac{(h_3-h_1)(1-\varepsilon)}{\left(-\dfrac{\Delta H_R}{m_g}\right)}\right]\varepsilon(h_3-h_1) \qquad \text{...(5.143)}$$

Table 5.15 Heats of combustion of some common fuels

Fuel	*Molecular weight*	*Heat of combustion gas-gas* $\frac{-\Delta H_R}{m_g}\left(\frac{MJ}{kg}\right)$
Acetylene	26.0	48.23
Benzene	78.1	40.58
n-Butane	58.1	45.72
Carbon monoxide	28.0	10.11
Ethane	30.1	47.48
n-Hexane	86.2	45.10
Hydrogen	2.0	119.95
Methane	16.0	50.01
Methyl alcohol	32.0	19.97
n-Octane	114.2	44.79
Propane	44.1	46.35
Toluene	92.1	40.94

The enthalpy values for air as a function of temperature are shown in Fig. 5.38.

Example 11

A heat exchanger is to be used with an oxidiser in a regenerative set up. Air containing a volatile organic compound (VOC) enters the heat exchanger under standard conditions at a rate of 10 kg/s and is preheated to a temperature of 550 °C. The effectiveness of the heat exchanger is 0.6 and the oxidiser is fueled with propane gas. Calculate the following:

(*a*) The adiabatic combustion temperature of the air stream leaving the oxidiser.
(*b*) The mass flow rate of propane entering the oxidiser.
(*c*) The temperature of the exhaust gas leaving the heat exchanger.

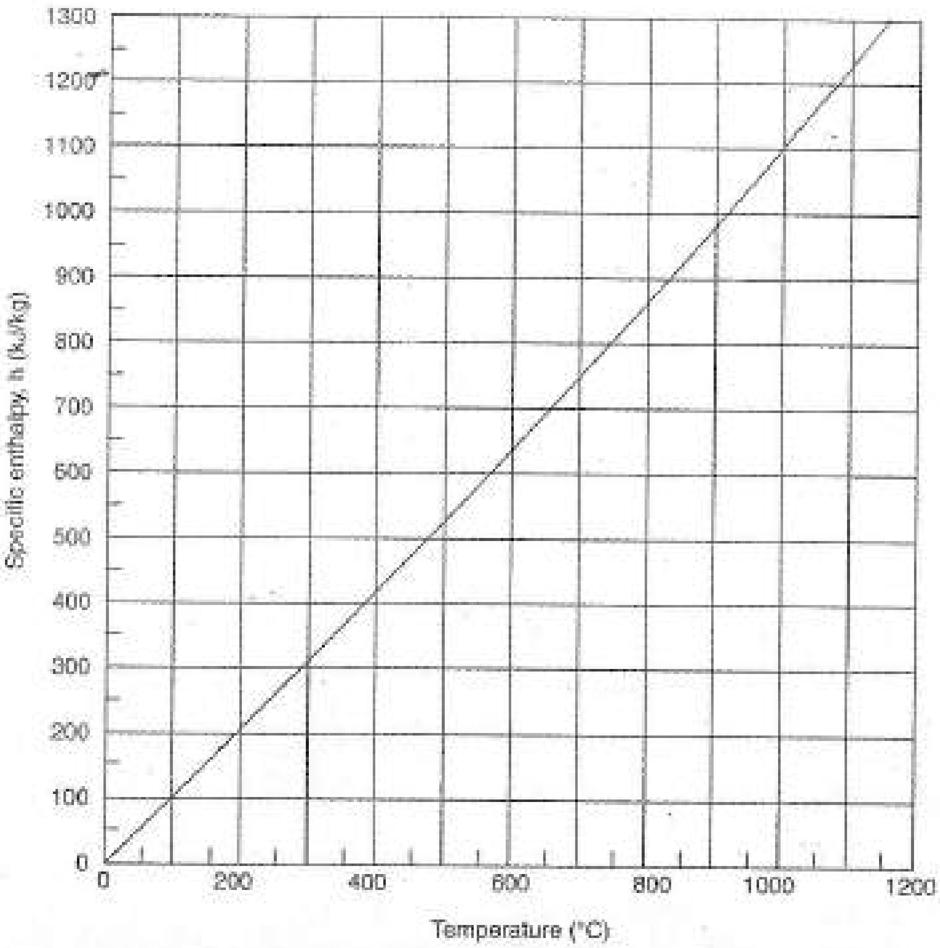

Fig. 5.38 Air specific enthalpy *vs* temperature

Solution

(*a*) From Eq. (5.135), the specific enthalpy, h_3, of the gas leaving the oxidiser is given by

$$h_3 = h_1 + \frac{(h_2 - h_1)}{\varepsilon}$$

From Fig. 5.38 we have

$$h_1 = 25 \text{ kJ/kg}$$

$$h_2 = 570 \text{ kJ/kg and } \varepsilon = 0.6$$

substituting the above values:

$$h_3 = 25 + \frac{(570 - 25)}{0.6} = 933 \text{ kJ/kg}$$

From Fig. 5.38, the temperature T_3 = 880 °C

(*b*) The air-fuel ratio $\frac{A}{F}$ can be calculated using Eq. (5.142)

$$\frac{A}{F} = \frac{\dfrac{-\Delta H_R}{mg}}{(h_3 - h_1)(1-\varepsilon)} - 1$$

From Table 5.15, for propane

$$\frac{-\Delta H_R}{mg} = 46{,}350 \text{ kJ/kg}$$

$$\frac{A}{F} = \frac{46350}{(933-25)(1-0.6)} = 127.6$$

The mass flow rate of propane entering the oxidiser is given by

$$\dot{m}_g = \frac{\dot{m}_a}{\left(\dfrac{A}{F}\right)} = \frac{10}{127.6} = 0.0784 \text{ kg/s}$$

(e) The temperature, T_4, of the exhaust gas leaving the heat exchanger can be obtained from Eq. (5.137) and Fig. 5.38.

$$h_4 = h_3 - \frac{(\dot{m}_a)}{(\dot{m}_a) + (\dot{m}_g)}(h_2 - h_1)$$

or

$$h_4 = 933 - \frac{10}{10 + 0.0784}(570 - 25)$$

$$= 933 - 540 = 393 \text{ kJ/kg}$$

From Fig. 5.38, $T_4 = 390$ °C.

Catalytic oxidation is an attractive proposition when thermal incineration of very diluted pollutants is not economically feasible due to additional fuel cost or when heat recovery would result in only marginal savings. The combustion takes place on a catalyst usually at temperatures several degrees below those required for thermal incineration. The temperature that is necessary to initiate the reaction depends on the type of pollutant present in the gas stream. Table 5.16 summarizes the catalyst entry temperatures for various industrial systems.

The catalysts used for effective pollution control are the precious metals, primarily platinum and palladium or their alloys. These are arranged in such a way as to provide the maximum possible surface area for contact with the gas. The catalyst is coated onto suitable elements such as metal ribbons, ceramic rods, or alumina pellets. These elements are then packed into the catalyst bed. A typical catalytic combustion unit is shown in Fig. 5.39. It consists of a reaction vessel or converter in which the catalyst is arranged in single or multiple fixed beds preceded by a preheat section, if necessary.

In the preheat section, only the gas stream is heated to the temperature required to support catalytic combustion. The preheated gas is then passed through the catalyst bed where the combustion occurs. To maintain the catalyst in an active state and to achieve complete combustion, about 1% excess oxygen is required.

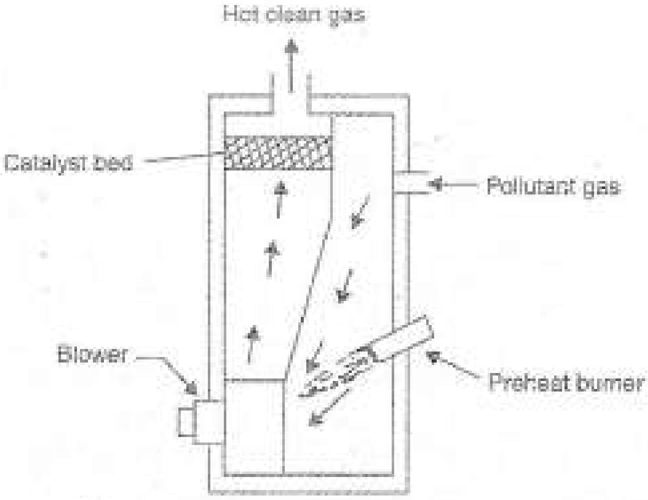

Fig. 5.39 Catalytic combustion unit

Table 5.16 Inlet temperatures for catalyst combustion (ref. 29)

Process	*Contaminants in waste gas*	*Catalytic oxidation temp. (°C)*
Asphalt oxidising	Aldehydes, anthracenes, oil vapours, hydrocarbons	315-371
Carbon black mfg	Hydrogen, carbon monoxide, methane, carbon	649-982*
Catalytic cracking units	Carbon monoxide, hydrocarbons	343-427
Coke ovens	Wax, oil vapours	315-371
Formaldehyde mfg	Hydrogen, methane, carbon monoxide, formaldehyde	343
Nitric acid mfg	Nitric oxide, nitrogen dioxide	260-649**
Lithography ovens	Solvents, resins	260-399
Octyl-phenol mfg	Phenol	315-427
Phthalic anhydride mfg	Maleic acid, phthalic acid, naptha-quinones, carbon monoxide, formaldehyde	315-343
Polyethylene mfg	Hydrocarbons	260-649
Printing presses	Solvents	315
Varnish cooking	Hydrocarbons	315-371
Wire coating and enameling ovens	Solvents, varnish	315-371

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* Temperatures > 649 °C required to oxidise carbon.

** Reduction reaction, all others are oxidation reactions.

The catalytic combustion technique is recommended for gases that are free of particulate matter and certainly free of metallic substances which could poison the catalyst. The catalyst bed is cleaned periodically (quarterly or annually) by scrubbing with water or sometimes with acid and by heating to high temperatures.