

Air Pollution Control Technologies

14.1 INTRODUCTION

The atmosphere is understood by its composition, temperature structure, and pressure. Air is a fluid mixture, which is constantly changing in its motion (wind), pressure distribution, temperature, and composition or cloud cover. The composition of the air is primarily of permanent gases of clean, dry air, variable gases, green house gases, ozone, and suspended particles (aerosol droplets). The concentration of these gases vary widely: nitrogen (N_2 , 78%) and oxygen (O_2 , 21%), which are most plentiful and have little or no importance in affecting weather, argon (Ar, 1%), a noble gas with no effect, and green house gases which have a major role in determining the weather. Table 14.1 shows the permanent gases in the atmosphere.

The composition of the atmosphere varies with the vertical increases in height. Typically two layers are identified: homosphere and heterosphere. Homosphere is 0–80 km and the permanent components are generally uniform. Heterosphere is >80 km and the heavier gases deplete with height and the lighter gas components occur as we go higher. These include molecular N_2 , atomic oxygen (O), helium atoms (He), and hydrogen atoms (H). The vertical structure of the atmosphere is also identified by the variations in temperatures. The features of the layers in the temperature structure are identified and given as follows:

Troposphere (greek: "overturning"):

- 0–10 km
- Temperature decrease with height:
 $\sim 6.5^\circ\text{C}/\text{km}$ (due to adiabatic cooling)
- Strong vertical mixing (cumulonimbus clouds)
- Contains 80% of the atmospheric mass
- Contains almost all atmospheric H_2O
- Called the "weather layer"

Tropopause: Very cold (first cold trap), boundary between troposphere and stratosphere; start of temperature inversion.

Table 14.1 Permanent Gases of the Atmosphere

Constituent	Formula	Percent by Volume	Molecular Weight
Nitrogen	N_2	78.08	28.01
Oxygen	O_2	20.95	32.00
Argon	Ar	0.93	39.95
Neon	Ne	0.002	20.18
Helium	He	0.0005	4.00
Krypton	Kr	0.0001	83.8
Xenon	Xe	0.00009	131.3
Hydrogen	H_2	0.00005	2.02

Stratosphere (greek: "lying flat"):

- 10–50 km
- Temperature increase with height: temperature inversion, due to absorption of UV-radiation by Ozone: the "ozone layer"
- Temperature inversion: stable layering, reduced vertical mixing

Stratopause: Boundary between stratosphere and mesosphere; upper end of temperature inversion.

Mesosphere (greek: "middle layer"):

- 50–90 km
- Temperature decrease with height (almost adiabatically)
- Upper part: coldest part of the atmosphere.

Mesopause: extremely cold (second cold trap); boundary between mesosphere and thermosphere; start of temperature inversion.

Thermosphere (greek: "hot layer"):

- Above ~90 km
- Strong temperature increase with height (temperature inversion), due to absorption of UV-radiation by O_2 and N_2
- Extremely "thin" atmosphere (temperature high, but almost no mass: energy content is low)
- No defined upper end

14.2 CLASSIFICATION OF AIR POLLUTANTS, THEIR SOURCES OF EMISSION, AND AIR QUALITY STANDARDS

14.2.1 Classification

As clean air in the troposphere moves across the Earth's surface, it collects the products of both natural events, dust storms, and volcanic eruption, and human activities (emissions from sources like transportation,

fuel combustion, industrial operations, solid waste disposal, and various other activities). These potential pollutants, called, **primary pollutants**, which are emitted directly from the source, mix with the churning air in the troposphere. Some primary pollutants may react with one another or with the basic components of the atmosphere in chemical and photochemical reactions to form new pollutants, which are called **secondary pollutants**.

14.2.2 Sources of Emission of Air Pollutants

Natural sources produce considerable pollutants but most of them are essential components of a balanced ecosystem. None of these natural pollutants normally accumulate to a level that is dangerous for life. However, many industrial activities produce air pollutants in levels that exceed the normal natural assimilation processes. Some of the typical sources of air pollutants are given in Table 14.2.

Table 14.2 Typical Sources of Air Pollutants

Sulfur dioxide	Colorless gas produced by combustion of oil and coal and certain industrial sources
Nitrogen dioxide	Brownish orange gas produced by combustion and major industrial locations and motor vehicles
Hydrogen sulfide	Refineries, chemical industries, and bituminous fuels
Carbon monoxide	Burning of coal, gasoline, and automobile exhausts
Hydrogen cyanide	Blast furnace, fumigation, chemical manufacturing, metal plating, etc
Ammonia	Explosives, dye making, fertilizer plants, and lacquers
Lead	Very small particles emitted by motor vehicles and smelters
Ozone	A colorless gas formed from the reaction of emissions from motor vehicles and sunlight. It forms a major portion in smog
Phosgene or carbonyl chloride	Chemical and dye making
Aldehydes	Thermal decomposition of oils, fats, and glycerols
Arsines	Process involving metal or acids containing arsenic soldering
Suspended particles (ash, soot, smoke, etc)	Solid or liquid particles produced by combustion and other processes at major industrial sources (steel mills, power plants, chemical plants, incinerators, etc)

14.3 AIR POLLUTANTS AND THEIR HARMFUL EFFECTS

1. Particulate pollutants: Airborne, small, solid particles and liquid droplets are commonly known as particulates. When present in air in excess, they pose a serious pollution threat. The life period of particulates varies from a few seconds to several months; it depends on the settling rate, size, and density of particles and turbulence. Particulates can be inert or extremely reactive materials ranging in size from $100\text{ }\mu\text{m}$ down to $0.1\text{ }\mu\text{m}$ 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 reaction materials could be further oxidized or may react chemically with the environment. Particulates can be further classified as:

Dust: Particles of size $1\text{--}200\text{ }\mu\text{m}$ belong to this category and are formed by the natural disintegration of rocks and soil or by mechanical processes like grinding and spraying. They are removed from the air by gravity and other inertial processes by large settling velocities and also act as centers of catalysis for many of the chemical reactions taking place in the atmosphere.

Smoke: Particles of size $0.01\text{--}1\text{ }\mu\text{m}$ constitute smoke which can be either in the liquid or solid form, and is formed by combustion or other chemical processes. Smoke may have different colors depending on the nature of materials burnt.

Fumes: Solid particles of size $0.1\text{--}1\text{ }\mu\text{m}$ which are normally released from chemical or metallurgical processes belong to this category.

Mists: Liquid droplets generally smaller than $10\text{ }\mu\text{m}$, which are formed by condensation in the atmosphere or released from industrial operations represent mist.

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

Aerosols: All airborne suspensions, either solid or liquid, belong to this category and these are generally smaller than $1\text{ }\mu\text{m}$.

Particles of size $1\text{--}10\text{ }\mu\text{m}$ have measurable settling velocities but are readily stirred by air movements, whereas particles of size $0.1\text{--}1\text{ }\mu\text{m}$ have small settling velocities. Those below $0.1\text{ }\mu\text{m}$, a sub-microscopic size found in urban air, undergo random Brownian motion resulting from collision among individual molecules.

2. Sulfur oxides: Sulfur dioxide (SO_2) is one of the major air pollutants discharged by various pollutant sources. Further, it reacts photo-chemically or catalytically with other pollutants or normal atmospheric constituents to form sulfur trioxide (SO_3), sulfuric acid, and salts of sulfuric acid. It is estimated that SO_2 remains in the air for an average of 2–4 days; during this time it may be transported a distance of 1000 km before it is deposited on the ground. Thus, the harmful effects of SO_2 and its deposition as sulfuric acid may be felt far away from the source, the pollution problem becomes an international one affecting countries which may not have pollutant sources discharging SO_2 .

Many industries, especially those dealing with petroleum, metallurgy, paper, and pulp contributes substantially to SO_2 pollution. It is perhaps the most damaging among the various gaseous air pollutants. Along with SO_2 , SO_3 is discharged at about 1–5% of the SO_2 concentration, and it combines rapidly with moisture in the atmosphere to form sulfuric acid, which has a low dew point. Both of these oxides are rapidly removed from the atmosphere by rain, or settle out as aerosol due to their concentration being less compared to their emissions from human activities. More than 90% of the anthropogenic emissions of SO_2 are over Europe, North America, India, and the Far East. Emissions of SO_2 were highest (77 Mt Sa^{-1}) during the late 1970s, but have fallen over the last two decades as a result of emission controls, changes in the patterns of fuel consumption, and economic recession. The taste threshold limit is 0.3 ppm, and SO_2 produces an unpleasant smell at 0.5 ppm concentration. In fact, sulfur oxides in general have been considered as prime candidates for an air pollution index.

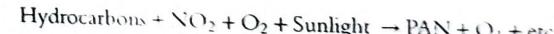
3. Oxides of nitrogen: Natural stratospheric oxides of N_2 are produced by the action of cosmic rays in the upper atmosphere. Emissions of oxides of N_2 from man-made sources vary in different areas. Nitrogen oxides are 10–100 times greater in the urban atmosphere as compared to rural areas. Oxides of N_2 , which include N_2O , NO , NO_2 , N_2O_3 , and N_2O_5 are usually represented by the symbol NO_x . The two major pollutants among them are nitric oxide, NO , and nitrogen dioxide, NO_2 . Any excess artificial fertilizer remaining after application, which has not drained away, is usually removed by denitrification. Increasing global use of artificial fertilizers therefore contributes to higher NO_x levels. Emissions from stationary sources are estimated to be 16 million tons of NO_x per year (computed as NO_2). Stationary sources include power plants, industrial boilers, certain internal combustion engines

used in gas transmission, and small combustion sources. Mobile sources of NO_x pollution are automobiles emitting an "estimated" average of 10.7 million tons per year.

Major man-made activities like combustion of coal, oil, natural gas, and gasoline produce up to 50 ppm of oxides of N_2 . Atmospheric nuclear explosions can be another potential serious source of man-made stratospheric oxides of N_2 . Anthropogenic impacts upon the global exchange of N are considerable, but the bulk of the global N cycling remains microbial. Soil conditions where O_2 levels are low favor denitrification. Consequently, stagnant, waterlogged, or compacted soils are major sources of N_2O , and one of the main purposes of plowing and draining is to discourage this anaerobic process.

- 4. Carbon monoxide:** Carbon monoxide is the most abundant gaseous pollutant emitted through anthropogenic sources into the troposphere; 0.075 Gt per annum which is a very high rate when compared to other gaseous pollutants, and this rate is still rising. Carbon monoxide, a product of combustion processes, is produced from cigarette smoking, household heating, and, more seriously, from the internal combustion engines of automobiles. Incomplete combustion, yielding CO instead of CO_2 , results when any of the following four variables are not kept sufficiently high.
- Oxygen supply.
 - Flame temperature.
 - Gas residence time at high temperature, and
 - Combustion chamber turbulence.

- 5. Hydrocarbons:** As their name indicates, the components of hydrocarbons are hydrogen and carbon. Hydrocarbons constitute the major chemicals in petrol, gasoline, and other petroleum products. In the presence of sunlight, NO_2 reacts with hydrocarbons to give a series of extremely complex reactions; chief among the products of these reactions are peroxyacetyl nitrate (PAN), and ozone.



Natural sources, particularly trees, emit huge quantities of hydrocarbons into the air. Plants mostly emitting terpenes belong to the family *Coniferae* and *Mycetaceae* and the genus *Urtica*. Automobile exhausts emit the maximum amount of hydrocarbons into the atmosphere. Some industrial sources, especially refineries, emit hydrocarbons, but the major source of this type of pollution is automotive emissions.

The emissions from incomplete combustion in car engines, along with evaporative emissions from fuel tanks, carburetors, and crank cases, amount to approximately 12 million tons per year. Human activities contribute nearly 20% of the hydrocarbons emitted to the atmosphere every year; animals contribute about 80–85 million tons of methane to the atmosphere every year.

6. **Ammonia:** Ammonia (NH_3), which is a pungent gas, is used as a raw material in large quantities by industries for the synthesis of ammonium nitrate, plastics, explosives, dyes, and drugs. Emission of NH_3 from the biological degradation of proteins on soil surfaces into the atmosphere occurs on a very large scale. This is known as " NH_3 volatilization," and compared to this, the industrial contribution is negligible. Atmospheric concentrations of NH_3 in temperate rural regions range from 5 to 10 ppm, but are much higher near the equator. In urban regions, higher levels of NH_3 up to 280 ppm are recorded and it may be found in increasing levels close to industrial and intensive agricultural sources.
7. **Organic lead:** Lead is discharged into the atmosphere in the organic form as tetraethyl lead ($(\text{CH}_3\text{CH}_2)_4\text{Pb}$) or trimethyl lead ($(\text{CH}_3)_3\text{Pb}$) in un-burnt or partially combusted fuel vapors. The amounts involved in developed countries were huge. In the late 1960s, for example, the amounts were 181 kt of lead in the whole of the United States, and 5 kt of lead in Los Angeles alone. In most developed countries, legislation to limit the amounts of tetraethyl and trimethyl lead, used as anti-knocking agents in vehicle fuels, has been progressively introduced and newer vehicles have been redesigned to use low lead or unleaded fuels. This has significantly reduced that fraction of lead entering the environment by airborne emissions in developed countries to less than one-tenth of the highest overall total in the past.
8. **Hydrogen sulfide:** Hydrogen sulfide is emitted into the atmosphere by the degradation of industrial wastes in stagnant waters, swamps, and other areas where bacterial action reduces sulfur compounds to hydrogen sulfide, which is highly insoluble in water. It is estimated that decaying organic matter in the world emits 70 million tons of H_2S . However, industrially, this gas comes from sewage treatment plants and the petroleum industry.
9. **Fluorides:** Hydrogen fluoride, HF, is a highly corrosive and irritant gas. A typical fluoride concentration in the atmosphere is 0.05 mg/m^3 . Because of its extreme toxicity, HF is a problem wherever processes involving fluorides take place, such as in the production of phosphate

fertilizers, smelting of certain iron ores, and manufacturing of aluminum. Many fluoride containing minerals such as fluorspar, cryolite, and certain appertites are used by industry. Some industries also produce HF either as a by-product or to form various useful fluoro-derivatives. Industrial emissions are superimposed upon significant natural background sources. Consequently, levels in both air and water supplies vary widely. The majority of rural and urban air monitoring sites record very low levels of atmospheric fluoride measured as total dissolved fluoride. Near phosphate fertilizer plants, aluminum smelters, or volcanoes, however, levels may rise above 200 ppm.

10. **Radon:** Radon, which occurs naturally, is the heaviest known gas. Radon gas comes from a decay process of underground uranium ore. It is by far the most important source of ionizing radiation to affect humans. In most developed countries, radon accounts for 40–50% of the total ionizing radiation received by the population. There are 27 isotopes of radon (^{200}Rn – ^{226}Rn), but only three have half-lives longer than an hour (^{210}Rn , 2.4 h; ^{211}Rn , 14.6 h and ^{222}Rn , 3.82 days). Of these, ^{222}Rn is the most important, and arises from the decay of ^{238}U . ^{222}Rn also decays into a series of radionuclides known as radon daughters or progeny. Principal among these are ^{211}Po (half-life 26.8 min), ^{210}Pb (22.3 years), ^{210}Bi (5 days), and ^{210}Pb (13–4 days). The final product is ^{206}Pb , which is non-radioactive. Radon merges into the atmosphere by a variety of routes, including from the ground below and around the water supplies, and from natural gas or building materials; being denser than other gases, it tends to concentrate at low points. Consequently, lower stories of buildings in radon-prone areas have higher levels of radon than upper floors.

14.3.1 Acid Rain

"Acid rain" is a broad term used to describe several ways that acids fall out of the atmosphere. A more precise term is acid deposition, which has two parts: wet and dry. Wet deposition refers to acidic rain, fog, and snow. As this acidic water flows over and through the ground, it affects a variety of plants and animals. The strength of the effects depend on many factors, including how acidic the water is, the chemistry and buffering capacity of the soils involved, and the types of fish, trees, and other living things that rely on the water. Dry deposition refers to acidic gases and particles. About half of the acidity in the atmosphere falls back to earth through dry deposition. The wind blows these acidic particles and gases

onto buildings, cars, homes, and trees. Dry deposited gases and particles can also be washed from trees and other surfaces by rainstorms. When that happens, the runoff water adds those acids to the acid rain, making the combination more acidic than the falling rain alone. Prevailing winds blow the compounds that cause both wet and dry acid deposition across state and national borders, and sometimes over hundreds of miles. Scientists discovered, and have confirmed, that SO_2 and NO_x are the primary causes of acid rain. In the United States, about two-thirds of all SO_2 and one quarter of all NO_x comes from electric power generation that relies on burning fossil fuels like coal.

Acid rain occurs when these gases react in the atmosphere with water, oxygen, and other chemicals to form various acidic compounds. Sunlight increases the rate of most of these reactions. Rain is slightly acidic because it contains dissolved carbon dioxide (CO_2), SO_2 , and NO_x , which are normally present in the air. Acid rain contains more acidity than the normal value because of presence of acid ions due to the dissolution of these gases in higher concentration. Acid rain, therefore, is the direct consequence of air pollution caused by gaseous emissions from industrial sources, burning of fuels (thermal plants, chimneys of brick-kilns, or sugar mills) and vehicular emissions. Acid rain will not necessarily occur locally near the sources of air pollution. Due to the movement of air, acid rain may occur far away from the source. For instance, the United Kingdom contributes 26% of the acidic sulfur deposited in the Netherlands, 23% in Norway, and 12% in Sweden. Smokestacks of power plants and a number of industries around the world spew out the basic ingredients of acid rain, namely, SO_2 and NO_x . With time, these oxides combine with water vapor in the atmosphere and return to the Earth's surface in the form of acid rain.

Acid emissions arise naturally from volcanoes, forest fires and biological decomposition, especially in the oceans. But their contribution to acid rain are SO_2 , NO_x , and to a lesser extent, CO_2 and hydrocarbon (HC) gas. SO_2 pollution is mostly contributed by thermal power plants, refineries, and industry, and NO_x from road transport, power stations, and industry. The acid gas concentrations in the air will vary according to location, time, and weather conditions. Acid rain is measured using a scale "pH". The lower a substance's pH, the more acidic it is. Pure water has a pH of 7.0. Normal rain is slightly acidic because carbon dioxide dissolves into it, so it has a pH of about 5.5. When the pH is below 5.0, it is expected to lead to acid rain.

Like China, in India to the main threat of an acid rain disaster springs from our heavy dependence on coal as a major energy source. Even though Indian coal is relatively low in sulfur content compared to the nature of coal reserves of other countries like China, what threatens to cause acid rain in India is the concentrated quantity of consumption that is expected to reach very high levels in some parts of the country by 2020. As energy requirements in India are growing rapidly in tune with the growing economy, coal dependence in the country is expected to grow threefold over the current level of consumption, making the clouds of acid rain heavier over many highly sensitive areas in the country like the northeast region, parts of Bihar, Orissa, West Bengal, and coastal areas in the south. Already the soils of these areas have a low pH value, which acid rain will aggravate further, making them infertile and unsuitable for agriculture. As experience stands in Europe and North America, the threat of acid rain was severely dealt with in these regions through heavy spending on SO_2 abatement technologies and cutting down the dependence on coal by shifting to natural gas and nuclear energy. But, action in these regions came only after a considerable amount of ecological damage. In the 1960s, fish populations in the Scandinavian countries were showing a rapid decline as a result of acid rain. The infamous forest dieback in some parts of central Europe was also from acid rain. Thus, experience from elsewhere bears out clearly enough that the whole problem as it confronts India needs proactive handling.

The issue of rapidly growing SO_2 emissions, the resultant sulfur deposition and the threat of acid rain in many areas of Asia is a transboundary problem involving many countries, and therefore, its solution calls for regional initiatives. In Europe, the situation of acid deposition from many countries in the 1970s and the related concerns about the pollution being carried over long distances, led to the signing of an international agreement in 1979 called "The Convention on Long-Range Transboundary Air Pollution." The signing of subsequent protocols led to binding commitments from European countries to limit and reduce their transboundary emissions of air pollutants.

14.3.1.1 Effects of Acid Rain

Acid rain causes acidification of lakes and streams, and contributes to damage of trees at high elevations (for example, red spruce trees above 2000 ft), and many sensitive forest soils. In addition, acid rain accelerates the decay of building materials and paints, including irreplaceable buildings, statues, and sculptures that are part of our nation's cultural heritage. Prior to falling to the

3. The particulate size and concentration in the gas
4. Volume of particulates to be handled
5. Temperature and humidity of gaseous medium
6. Factors like toxicity and inflammability must be taken into consideration when evaluating column efficiency
7. Quality of the treated effluent, i.e., efficiency of the removal of particulate matter

14.9.1.2 Gravitational Setting Chambers

A gravity settler is simply a long chamber through which the contaminated gas passes slowly, allowing time for the particles to settle by gravity to the bottom. Solid or liquid particles suspended in the gas reach a terminal free falling velocity which is given by Stokes' Law for small particles, and is proportional to the product of the square of the particle diameter and the density difference between the particle and the carrier gas, and inversely proportional to the viscosity of the carrier gas as discussed in detail earlier. In practice, this implies that the method can only be applied for removing particles greater than 100 μm in diameter. As most of the troublesome particles have sizes smaller than 50 μm , these devices are normally used as precleaners prior to passing the gas stream through high efficiency collection devices. The cross-sectional area of (WH) of the settling chamber is much larger than that of the duct through which the pollutant gas stream enters this settling chamber. The gas stream, containing the particulate matter is allowed to flow at a low velocity in the settling chamber allowing sufficient time for the particles to settle down.

The gravity settling chamber is one of the simplest and oldest methods of dust collection. The large cross-sectional area of the chamber (A_c) relative to the cross-sectional area of the entrance duct (A_d) serves to reduce the gas and particle velocity within the chamber:

$$\text{Velocity of gas, in chamber} = \left[\frac{\text{Cross-section area, duct}}{\text{Cross-sectional area, chamber}} \right]$$

[Velocity of gas, induct]

$$D_{psc} = \left[\frac{A_d}{A_c} \right]^{0.25}$$

For best results, the gas flow through the chamber should be uniform and less than 60 fpm.



Figure 14.13 Horizontal fl w settling chamber.

A simple horizontal flow gravity settler (Fig. 14.13), which has a cross-sectional area much larger than that of the duct, brings the dust laden gas stream into the settling chamber. The gravitational settling chambers usually operate with velocity between 0.5 and 2.5 m/s, although for best operating results, the gas flow should be uniformly maintained at less than 0.3 m/s. Some settling chambers have simply enlarged conduits and some have horizontal shelves and baffles, about 2.5 cm apart. The collection efficiency of the chamber depends upon the type of flow also.

In Howard type of settling chamber (Fig. 14.14), horizontal trays will be fixed in the chamber at about 1-3 in height intervals. The increase in the efficiency of the Howard type gravitational chambers is dependent on the number of trays added. A maximum of five to seven trays can be added to increase efficiency.

14.9.1.3 Cyclone Separators

In a cyclone, the particulate laden gas is accelerated through a spiral motion which imparts centrifugal force to the particles. The centrifugal force forces the particles out from the spinning gas, and makes them fall on the wall

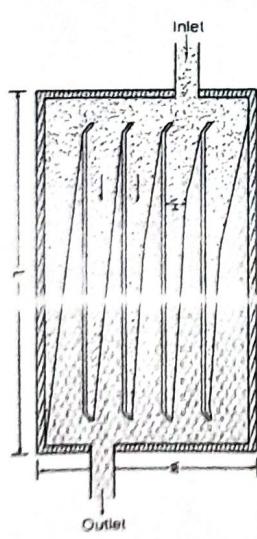


Figure 14.14 Howard settling chamber with five trays.

The centrifugal force (F_c), which separates a particle of mass (m_p) from the gas stream, is given by the equation:

$$\text{Centrifugal force} = \frac{[\text{particle mass}] [\text{particle tangential velocity}]^2}{\text{Cyclone radius}}$$

$$F_c = \frac{(m_p)(v_p)^2}{r}$$

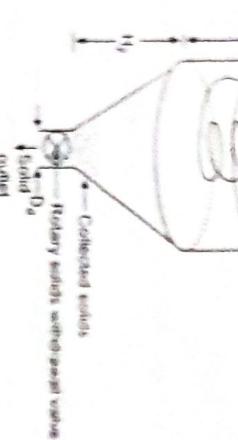


Figure 14.15 Cyclone separation

of the cyclone. The particles will finally settle down. The cyclone separator shown in Fig. 14.15 is merely a gravity settler while in the form of two concentric helices and utilizes the centrifugal force generated by the spiraling gas to separate the particulate matter from the polluted gas stream. A simple cyclone collector consists of a cylinder with a tangential inlet and an inverted cone attached to the base. Gas enters the cyclone through the tangential inlet, which imparts a whirling motion to the gas. Suspended particles will be forced toward the wall on which they collect and slide down into the conical collector. Near the bottom of the cone, the gas turns abruptly upward and forms an inner spiral, which leaves through the pipe or duct extending into the center of the cyclone body.

There are three types of cyclones which are under industrial use. They are: (1) high-throughput cyclone, (2) conventional cyclone, and (3) high-efficiency cyclone. High-throughput cyclones process high volumes of waste air as input, but are operating at low efficiencies. The conventional cyclones are in between high-throughput and high-efficiency cyclones. Cyclones can also be arranged to operate in multiples to produce higher efficiencies. The efficiency of removal is not only a function of the size of the particle, but also of the other variables such as the airflow.

High Efficiency Cyclones
Small diameter cyclones (10 m or less) are more efficient than conventional. This is probably the efficiency of particulate removal of a given cyclone design increases as the ratio of centrifugal force to drag force increases.

$$\text{Ratio} = \frac{\text{Centrifugal force}}{\text{Drag force}}$$

After substituting in and simplifying the ratio reduces to:

$$\text{Ratio} = \frac{[\text{particle diameter}]^2 [\text{particle density}] [\text{particle tangential velocity}]}{[\text{gas viscosity}] [\text{cyclone diameter}]}$$

$$\approx \frac{(D_p)^2 (\rho_p) (v_p)}{(\mu_g) (D)}$$

Thus, it can be seen that for a given set of conditions the operating efficiency will increase with a decrease in cyclone diameter. However, this does not mean that a small diameter cyclone is inherently more efficient than one of large diameter, although it does mean that a smaller diameter cyclone of particular proportions is inherently more efficient than a large diameter cyclone of the same proportions.

Particle Size Micron	Conventional Cyclone	High Efficiency Cyclone	Efficiency (%)
5	50-80	50-80	50-80
5-20	80-95	80-95	80-95
15-50	95-99	95-99	95-99
40	95-99	95-99	95-99

In a high efficiency cyclone, gas enters tangentially through the inlet cone, which provides the swirling motion necessary to throw the dust particles to the outer diameter of the tube. Acceleration takes place in the cone, and then it remains constant from there to the bleed-off for the secondary circuit. There is an increase in velocity and dust concentration. The clean air travels out through the end of the tube without changing direction, and 10% of the primary air circuit, plus the collected dust, is bled off and thrown into the primary dust hopper. Any number of small diameter cyclones can be operated in parallel to achieve the desired capacity.

14.9.1.4 Electrostatic Precipitator

The basic principle of an electrostatic precipitator (ESP) is to give particles an electric charge and then put them in an electrostatic field that drives them to a collecting wall. A gas stream containing suspended particulates is allowed to pass between two electrodes electrically insulated from each other, and between which there is a considerable difference in electric potential. The high-voltage electrode usually has a small cross-section and one curvature, e.g., a wire. The other electrode could be a plate or a surface of only slight curvature. The high voltage on the electrode of small cross-section ionizes the gas and aerosol particles. A corona is formed around the electrode, which attach to the particulates making them ionic; they are then attracted to the large collecting electrode. There they are allowed to flow down or are drained by gravity and collected at the bottom. The ESP may be a gravity settler or centrifugal separator, but as the electrostatic force drives the particles more powerfully to the collecting plate, it is more effective on smaller particles than the gravity settlers and cyclone separators.

An ESP uses electric forces to separate suspended particles from gases.

This is accomplished in two basic steps:

1. A corona-charging field provides the particles with an electrical charge.
2. A high-voltage collecting field attracts the charged particles to the collecting electrode.

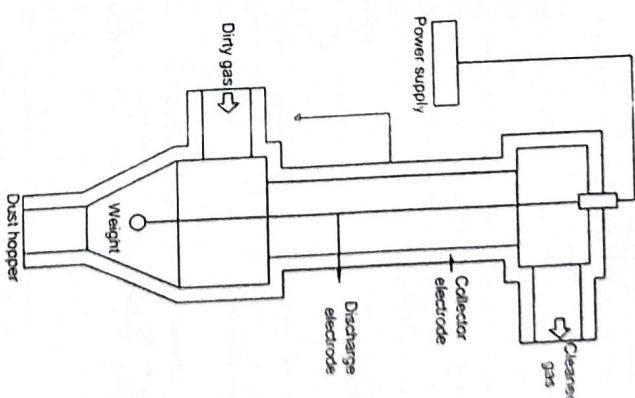


Figure 14.16 Electrostatic precipitator.

Fig. 14.16 shows one "gas passage" of a horizontal electrostatic precipitator. Many of such lanes are arranged in parallel in one casing so that the overall gas volume finds a sufficient section to flow through. In order to obtain an effective corona discharge, the discharge electrode is supplied with 15,000 to 80,000V negative DC current. The corona-discharge charges the particles in the gas stream.

The particle charge is given by:

$$\text{Particle charge} = \text{charging field} \times \text{particle radius}^2$$

$$q = \lambda (E_0) (r_p)^2$$

Under the influence of the electric field built up between the discharge electrodes and the grounded collector electrodes, the ionized particles accelerate toward the collector electrodes.

In general, in all these particulate collecting systems—gravitation settling chambers, cyclone separators, or ESPs—the driving force acting on the particle to push it to the collecting wall against the resistance offered by the viscous medium which is proportional to the particle diameter. For gravity settlers and cyclone separators, this force is proportional to the cube of the diameter of particles of constant density. In ESPs, though the resistance force offered by the viscous medium is Stokes' drag, the force driving the particle to the wall is electrostatic which is proportional to the square of the particle diameter.

The parallel plate two-stage ESP is shown in Fig. 14.17. The gas passes between the plates, which are electrically grounded. Between the plates are rows of wires, held at a voltage of typically $-40,000\text{V}$. The power is obtained by transforming ordinary alternating current to high-voltage, and then rectifying it through some kind of solid-state rectifier. This combination of charged wires and grounded plates produces both the free electrons to charge the particles and the field to drive them against the plates. On the plates the particles lose their charge and adhere to each other and the plate, forming a "cake." The cleaned gas then passes out of the far side of the precipitator.

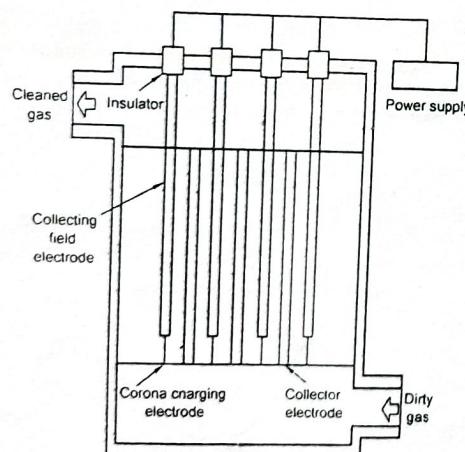


Figure 14.17 Two stage electrostatic precipitator.

Dust collection efficiency of ESP varies greatly according to the electrical resistivity of the collected dust. In the case of high resistivity dust, an abnormal phenomenon known as the back corona problem may occur, and this seriously reduces the dust collection efficiency of ESP.

Advantages of Electrostatic Precipitators

1. Pressure drop and hence power requirement is small compared to the other devices; economical and simple to operate.
2. 99% efficiency obtainable. Very small particles can be collected, wet or dry.
3. Can handle both gases and mists for high volume flow.
4. Can be operated at high temperatures and pressures.

14.9.1.5 Gas Filtration for Particulate Removal

Two main types of gas filters are in use for the removal of particulate matter from industrial gases:

1. Packed bed or depth filters.
2. Fabric elastic filter.

Fabric filters are used for cleaning industrial gases with a particulate loading gravity of 1 g/m^3 while depth filters are used only for gases containing particles of the order of 1 ng/m^3 . The performance efficiency of any filter is determined from the following criteria: (1) pressure loss, (2) collection efficiency, and (3) lifetime or dust holding capacity.

1. Pressure loss is expressed in mm of water and gives the required fan power. Air is a major factor that determines the operational cost.
2. The collection efficiency (mass percentage of dust collected) determines the performance of a filter, and is measured instantaneously or cumulatively since the efficiency varies with dust adhered to the filter which varies with filtering time.
3. The lifetime or dust holding capacity of any filter is determined by actual experimentation under operational conditions and this determines the major portion of the initial costs. It is the maximum capacity of the filter to hold the dust per unit area of the filter medium for a certain range of pressure drop. Normally filters will have $0.3\text{--}2\text{ kg}$ of dust per square meter of filter paper.

14.9.1.6 Classification of Fabric Filters

Classified according to the methods of cleaning, there are three types of baghouses; shaker, reverse-air, and pulse-jet baghouses. The filtering element is usually shaped in tubular form as shown in Fig. 14.18, called filter bags.

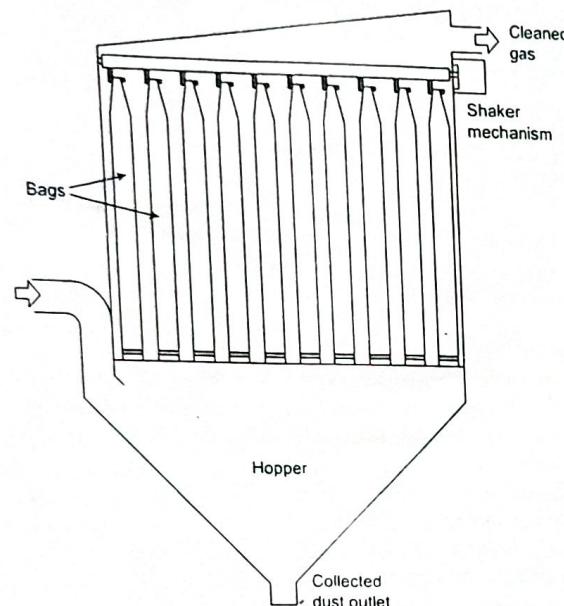


Figure 14.18 Cross-section of baghouse.

Filter bags may range from 1.8 to 9 m in length, and may have diameters of around 20 cm. Several of these bags are grouped together and put in to a compartment, and several of these compartments are put together and assembled inside a structure called a baghouse. The capacity of a compartment is determined by the area of the fabric filter.

Bag Filter

The bag filter is designed and engineered for filtering dust in gas emission from all industry areas through a bag-shaped fiber filter so that the dust can be separated from the gases.

Furthermore, by pre-coating, such as injecting calcium hydroxide in just ahead of the bag filter, oil mist or noxious gases such as hydrogen chloride too, is possible to remove simultaneously. The bag filter is grouped into the pulse jet type, reverse air type, dual reverse, and shaking blow-off type according to the method of shaking off the dust, which are selected in consideration of gas temperature, properties of substances, moisture, and so on.

Dust removal efficiency can be reached up to 99.9% or larger, and if the bag is pre-coated, gases, too, can be adsorbed simultaneously with up to 90% or larger efficiency.

- A wide variety of gases are possible to collect.
- The $0.05 \text{ g/m}^3 \text{ N}$ dust concentration is possible to attain regardless of concentration at inlet.
- Pressure loss in 80–200 mm H_2O .
- Fine particles down to $0.1 \mu\text{m}$ are possible to collect.
- Required power except for fan power is small.
- Continuous operation is possible to perform and maintenance is easy to control.
- Both facility and maintenance cost are low because of the simple construction.
- Recovered dust is possible to re-use because of dry type dust collecting design.

The bag filter is ideal in the following fields of industry:

- Battery production
 - Electrical and electronic production
 - Electrical equipment production
 - Metal machining
 - Automobile component production
 - Other industrial processes requiring the collection of heavy metal dust
- The engineering performance of the bag filter can also be put to effective use in the treatment of combustible and explosive dust such as wood dust, coal dust, or hydrogen storage alloy dust, and in the design of hoods at dust generating sources.

Absorption

Sorption comprises the general phenomenon of the assimilation of a gas by a solid or a liquid. When the gas is taken on only at the surface or in the capillaries of the solid to form a surface compound or condensate, the phenomenon is designated as adsorption. When the sorbed gas forms a homogeneous solution with the liquid or is taken deep into the internal structure of a solid, the transformation is called absorption.

Spray Tower

In spray towers the water is introduced through nozzles, which direct the spray toward the bottom of a circular or rectangular chamber (Fig. 14.19). The polluted gas enters at the bottom, and as it flows upward the dust

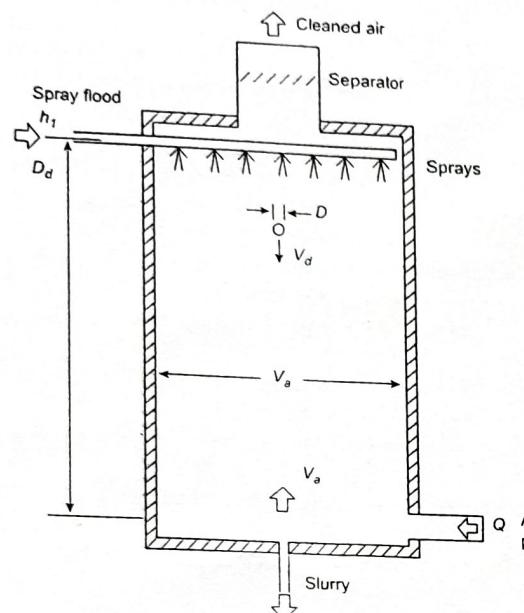


Figure 14.19 Spray tower.

particles collide with the liquid droplets generated by the nozzle spray. The liquid droplets and their captured dust particles impinge on the water eliminator and are removed from the gas stream. This is the simplest type of counter flow gas scrubber with a moderate contact between phases and so used only for remaining coarse dust when high efficiency is not necessary.

The pressure drops in a spray tower are typically low, on the order of 1–2 inches of water. The liquid/gas ratio is generally around 20–100 gallons per 1000 cubic feet of polluted air. The liquid used in the scrubbing process is normally recirculated in order to minimize the need for excessive amounts of water. Low energy is normally required, and these simple spray towers are easy to operate and maintain.

One of the major disadvantages is the relatively large amount of water used and the low efficiency in removing mists smaller than $5 \mu\text{m}$ in diameter. The towers generate a polluted water stream, which is the by-product of the operation. This wastewater carries in the contaminants which are in the air. It must be further treated before discharge. Installation and operation

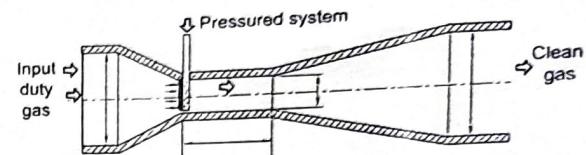


Figure 14.20 Venturi scrubber.

of spray towers is an inexpensive matter when compared to other processes. The problem is in the high cost of treating the wastewater which is generated during their use. In addition, operating expenses will include the pump and fan power requirements.

Venturi Scrubbers

Venturi scrubbers offer high-performance collection of fine particles, usually smaller than 2–3 mm 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 velocities, of the order of 60–120 m/s. Due to the high speed action, the feed liquid is atomized with a uniform fashion across the throat through several low pressure spray nozzles directed radially inward as shown in Fig. 14.20. The droplets accelerate in the throat section, and due to the velocity difference between the particles and the droplets, the particles are impacted against the slow moving droplets. The acceleration continues to some extent into the diverging section of the venturi. The gas–liquid mixture is then directed to a separation device such as a cyclone separator where particulate matter is separated from the gas stream. The affecting mechanisms for collection of particulates in the scrubber are inertial impaction, diffusion, electrostatic phenomenon, and condensation and agglomeration, the principal mechanism is inertial impaction. The application of venturi scrubbers is more often in Kraft mill furnaces, metallurgical furnaces, sulfuric acid concentrators, etc., for removing mists and dusts from gases.

Centrifugal Scrubbers

The wet centrifugal collector utilizes centrifugal force and the wet impingement principle in collecting light to heavy loading of all size granular dust (Fig. 14.21). Dry dust particles impinge against the wetted peripheral surfaces, thus reducing re-entrainment of the particle into the gas stream. As the incoming gas is spun down the inlet cones, the water and collected solids are separated from the gas stream.

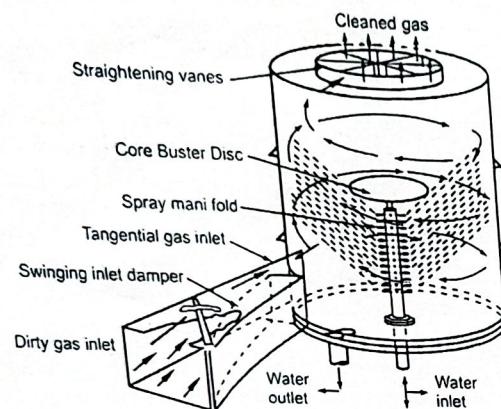


Figure 14.21 Centrifugal scrubbers.

Packed Beds and Plate Column 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 sub-divided streams.

Packed Scrubber

In a packed scrubber, fiberglass, saddles, coke, or broken stone, etc., are used as the collection material (Fig. 14.22). The polluted gas stream moves upward in a countercurrent flow packed scrubber, and comes in contact with the scrubbing liquid stream which is moving downward over the packing in a film. The gas stream passes through the packing pore spaces and captures the particles by the inertial impaction. Because of the good mass transfer characteristics of the packing, efficient collection of fine particles by diffusion is also possible. Smaller packing increases the efficiency of collection but its shape does not appear to affect the collection efficiency. Sometimes packing towers encounter plugging problems, which can be reduced by employing sprays to wash the packing or by using low density spheres, etc., agitated by gas flow chemical foam packing is being employed recently which drains slowly from the scrubber with captured particles and is replaced with fresh material.

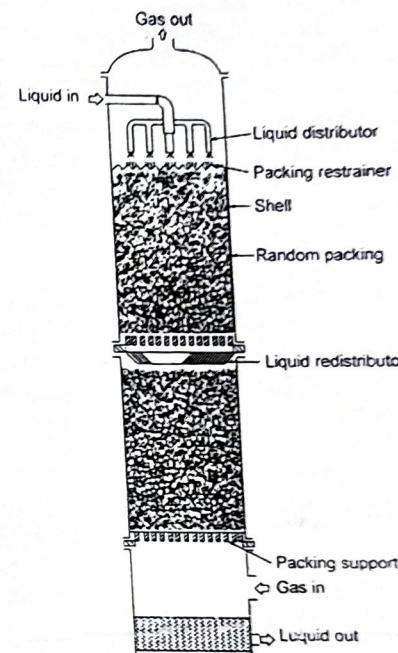


Figure 14.22 Packed tower.

In an ideal situation, the liquid is distributed uniformly and wets the surfaces of the packing. The tower packing provides a large area of contact between the liquid and the gas, encouraging intimate contact between the two phases. The inlet liquid is called *fresh* or "weak" liquid. The outlet liquid is called *rich*, or "strong liquor," because it has picked up some of the pollutant gas and particulate matter. The entering gas at the bottom is called the *rich gas*, since it is rich with pollutants, and the cleaner air exiting at the top is called *lean gas*, since it has lost most of the pollutants. The countercurrent operation is most beneficial for separation, because the fresh liquid contacts the lean or cleaner gas at the top and the strong liquor contacts the rich gas at the bottom. In this manner, the gas with a weak concentration of pollutants is scrubbed with fresh water, and the strong liquor, which has already absorbed some pollutants, comes into contact

with a dirtier gas at the bottom. From a practical point of view, mass transfer is good when concentration gradients are appreciable. The amount of liquid present at any time in the packed section of the tower is called the total holdup. This increases with increasing flow rate of liquid, but it is independent of the gas flow rate up to the loading point. For a given liquid flow rate, the loading point is the gas velocity above which the total holdup increases substantially, with further increase in gas velocity, the liquid fills up all the voids and the packing tower becomes a bubbling unit, and it is said to be flooded. It is difficult to keep a stable operation under these conditions, and the liquid will become entrained and carried by the exit stream of air.

Pressure drops in packed towers range between 1 and 8 inches of water. The typical liquid to gas ratio are 10–20 gallons per 1000 cubic feet. Higher removal efficiencies are obtained here, and a lower water consumption rate is the norm; it is about 0.75–3.7 gallons per 1000 cubic feet per minute of polluted air treated. However, one of the major disadvantages of packed towers is the high-pressure drop in the system (more than 3 times higher than the pressure drop in a spray tower). There are also greater clogging and fouling possibilities and more maintenance costs, along with wastewater treatment and disposal. These packed scrubbers are more expensive to install and operate than spray towers. Maintenance of the packing adds another cost to the operation.

14.9.1.7 Tower Packings

There are several types of tower packings. Some are made from cheap, inert, and light materials such as porcelain, graphite, or clay. Some are made from fibrous materials such as glass or steel wool. However, plastic packings are becoming widely used. They are light and essentially unbreakable. With plastic packings, towers of light construction may be used, and breakage is not likely as is the case with ceramic packings.

Polyethylene packings called tellerettes, of a helical-torpid shape, are especially effective. A good tower packing should be:

1. Inexpensive.
2. Chemically inert to the gas and liquid in the tower.
3. Strong enough and light.
4. Made to provide adequate passages for the two phases without excessive pressure drop.
5. Durable.
6. Made in a shape providing a large contact area per unit volume.

Packings may be dumped at random when they are in the size range 0.25–2 inches. Packings are usually stacked when their size is in the range 2–8 inches, of course, these large packings are normally used in large towers.

In general, packed towers vary in diameter from 1.1 to 20 inches. The depth of the packing may vary from an inch to several feet depending on the application and type of packing used. Coarse beds are used to remove particles larger than 5μ at superficial gas velocities varying between 1 and 15 ft/s. Fine beds are used to remove particles smaller than 5μ at low superficial gas velocities on the order of 1–50 ft/min.

Packed towers are limited to handling low concentrations of particulate matter, since excessive concentrations will cause accumulation on the packing, and eventually plug the bed. Packed towers are more efficient in transfer operations than spray towers, but for very short heights, spray towers approach the performance of a packed tower, and thus, they are preferred due to lower pressure drops.

Tray or Plate Column

The tray or plate column is cylindrical tower housing with perforated plates. The liquid enters from the side of the column at the top and cascades down in a zigzag flow. The polluted air enters at the bottom. The clean air exists at the top, and the liquid leaves at the bottom of the column. The horizontal perforated plates are called sieve trays with typical three-sixteenth inch holes on half inch square centers. The trays are spaced 1–3 ft apart. The liquid, discharged onto one side of the top tray, flows across it and over a weir, then to a downcomer, which directs the liquid to the next tray down. This process is repeated until the liquid reaches the bottom. The polluted air entering at one side of the bottom rises up through the openings in each tray and through the liquid preventing it from draining through the holes. This is repeated until the clean air emerges at the top of the column. The function of the trays or "special packing" is to facilitate the contact between the liquid and gas streams. This column may be used to separate dust and gaseous pollutants from air.

Adsorption

Certain solids have different affinities for different gases. If a gaseous mixture comes in contact with an adsorbent solid, some of the components of the gas stream will concentrate on the surface of the solid and separate from the main stream. Thus, adsorption is a process dealing with the contacting of a solid with a fluid mixture to remove one or more components of the mixture. There are basically three types of adsorption. The first type is physical

adsorption or condensation of toxic or obnoxious gases and vapors on solids at temperatures above the dew point. The second type is chemical adsorption or chemisorption, where a chemical bonding occurs between the adsorbed pollutants and the solid adsorbent. The last type is ion exchange solids, where an exchange of ions takes place. The solids give up ions for the ions they adsorb from the fluid stream. This is mostly applied in water softening where the solids give up sodium ions to the water in exchange for magnesium and calcium ions, and this exchange decreases or removes water hardness. Of the three types of adsorption, physical adsorption is the most important in air pollution control.

Some of the important adsorbents and their respective applications are listed in Table 14.3 to aid in the proper selection of these solids in removing pollutants.

Table 14.4 shows the various devices and the efficiency with which the particular particle size can be removed.

Table 14.3 Important Adsorbents

Adsorbent	Application
Activated alumina	Drying of air, gases and liquids
Activated carbon	Gas purification, solvent recovery, elimination of odors
Anhydrous calcium sulfate (CaSO ₄ , desiccant)	Drying and purification of gases
Bauxite	Drying of gases and liquids
Lithium chloride solution	Drying and purification of gases, reducing odor, dust, and smoke
Silica gel	Dehydration and purification of gases; adsorption of organic solvent (acetone, benzene); separation of hydrocarbons.

Table 14.4 Devices That Can Be Used for Particulate Matter Removal

Device	Minimum Particle Size (m)	Efficiency (%)
Venturi	>0.5	<99
Electrostatic precipitator	>1	<99
Bag filter	<1	>99
Spray chamber	>10	<80
Cyclonic spray chamber	>3	<80
Impingement scrubber	>3	<80
Centrifugal settler	>5	<80
Gravitational settler	>50	<50

14.10 METHODS OF CONTROL OF EMISSIONS FROM POINT SOURCES FOR OXIDES OF SULFUR, NITROGEN, AND CARBON

The control equipment to be discussed would be oxides of sulfur, oxides of nitrogen, oxides of carbon and hydrocarbons.

The principal gaseous pollutants of concern in air pollution are SO_x, NO_x, CO, the hydrocarbons, and other organic and inorganic gases. In general, these emissions may be controlled by absorption, adsorption, and incineration. The general methods by which gaseous pollutants can be removed from the industrial gaseous effluent stream are by sorption of gaseous pollutants by absorption in a liquid, by adsorption on a solid, and by decomposition or conversion of the pollutant, from toxic form to non-toxic stable form, chemically either by combustion or by catalytic incineration.

Liquid absorption is one of the most versatile techniques used for reducing the pollutant levels from various industrial gaseous effluents. In this process due to a concentration gradient the pollutant from the gaseous phase is transferred across the gas-liquid interface and the concentration decreases in the direction of mass transfer.

Removal of gases by adsorption is another technique that is used. This is a mass transfer process in which the gas is bonded to a solid and a surface phenomenon. The gas (adsorbate) penetrates into the pores of the solid (adsorbent) but not into the lattice itself. The bond may be physical binding, where electrostatic forces hold the pollutant gas or chemical bonding by reaction with the surface. The adsorption process is endothermic, while the desorption process is exothermic, and both are reversible. Gases with higher molecular weights and lower boiling points are preferentially adsorbed and these displace gases which are less preferentially adsorbed effecting separation. For example, organic vapor in air can be preferentially adsorbed by activated carbon than air.

For destruction of gaseous pollutants by combustion, one has to consider the safety aspects of combustion and improper combustion products. Many times the industrial gaseous effluents are not directly combustible and require addition of a fuel. However, certain gaseous effluents from petroleum refinery and blast furnaces are flammable directly without the addition of any fuel. Thermal incineration is one of the best ways to destroy them. This incineration process burns organic compounds and renders them harmless by giving off carbon dioxide and water. The proper length of residence time must be given so that complete combustion takes place. The temperature

should be high enough so that total destruction of the toxic wastes occurs. Incinerators require residence times ranging from 0.5 to 1.0 s, with temperatures ranging from 1200 to 1600°F. In general, destruction efficiencies are above 95%.

14.10.1 Removal of Oxides of Sulfur

Fossil fuel burning in power plants and industrial furnaces are the major sources of SO_2 production in addition to the mobile sources. The following are the control technologies adopted for reducing SO_x emissions:

1. Dilution of SO_x emissions by increased stack height
2. Use of alternate fuels
3. Fuel desulfurization
4. Reduction of sulfur in the combustion process
5. Flue gas desulfurization

There are a number of leading processes for removing SO_2 from flue gases. These include limestone injection (wet absorption), wet flue gas desulfurization, the Lurgi adsorption process, and the catalytic oxidation (catox) process.

SO_x reduction technology wet type desulfurization system—flue gas desulfurization system (limestone-gypsum process).

Limestone-water slurry is mainly used as absorbent in the absorber installed in the flue. In the absorber, flue gas is brought into contact with the absorbent to remove SO_x in the gas. Reaction products are collected in the form of gypsum. This is normally used in fossil power stations (coal, heavy oil), etc. The volume of SO_x emissions per unit of electricity generated by fossil power stations in Japan in 1988 is 0.38 g/kWh, which is far below the average of major countries in Europe and America (United States, France, Canada, United Kingdom, former West Germany) of 6.70 g/kWh.

Limestone injection is one of the most popular processes under development. SO_x produced from burning oil and coal react with the calcined products of limestone and dolomite to give some stable removable salts of calcium and sulfur. In this process, limestone and/or dolomite is pulverized along with coal in a mill; it is then fed to the high temperature zone of a furnace, where it is calcined to give CaO and MgO . The air polluted with SO_x enters a preheater and then goes to the furnace where the temperature is above 1200°F. The alkaline earth additives react with SO_2 and O_2 to give calcium sulfate, CaSO_4 , called gypsum, some calcium sulfite, CaSO_3 , is also produced. At this stage 20–30% of the sulfur oxides are removed. The sulfates, fly ash, and the unreacted lime pass through the air preheater on their

way to the scrubber; here water spray creates an intimate contact with the unreacted lime and the remaining SO_2 . Sulfates and sulfites are formed and removed along with particulate matter. The spent liquor from the scrubber and the sulfates, sulfites, and ash are allowed to a settling tank. The scrubber liquor is recycled in order to reduce water requirements and minimize water pollution. The sulfates, sulfites, and ash are, most likely, used as landfill.

14.10.2 Fuel Gas Desulfurization

Wet flue gas desulfurization processes include the use of lime or dolomite and/or sodium alkali. When lime and alkali are used, the process is called dual-alkali, simply because two alkali feeds are used, namely, pebble lime and soda ash.

When using lime or limestone, a slurry is prepared of calcium hydroxide $\text{Ca}(\text{OH})_2$ or calcium carbonate (CaCO_3). It is used to remove the sulfur oxide from the flue gas stream. SO_x reacts with the lime to form CaSO_4 and calcium sulfate (CaSO_4). The two products precipitate from the solution. The lime slurry moves on to the scrubber (see Fig. 14.23), where the polluted gas makes intimate contact with it and reacts with the calcium. Then the slurry and products of the reaction, along with the gas, move on to a settling tank or a particulate removal unit, where residence time will be essential for the particulate matter to settle down. The solids are removed into a container, while some of the slurry is recycled to go

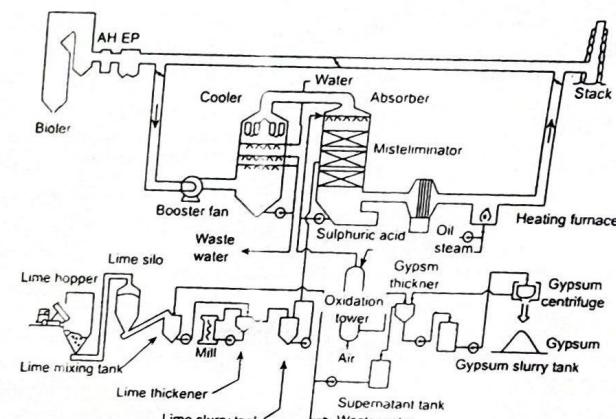


Figure 14.23 Wet type desulfurization system.

through the process again. The clean gas moves up the stack. Fresh quantities of lime are added as needed. The solids removed are disposed of in a sanitary landfill. The clarified liquid is recycled to be used in the scrubber unit again.

14.10.3 CATOX Process

CATOX process is an **oxidation/reduction process**. This process basically consists of passing the flue gas through a fixed catalyst bed where SO_2 , in the presence of O_2 , is converted to SO_3 (Fig. 14.24). The SO_2 is then absorbed in recirculated sulfuric acid in an absorption tower. Since sulfuric acid is a salable product, there is no solid waste product, assuming that a market can be found. In the "CATOX" process, fly ash is first removed from the flue gas by a high-temperature ESP, and SO_2 is then catalytically oxidized to SO_3 which is then recovered as sulfuric acid. For achieving good combustion efficiency, V_2O_5 at 400–500°C is used as a catalyst. In another improved efficiency process, SO_2 and O present in the stack gas are passed through the surface of an active carbon catalyst where they are absorbed and the catalyst catalyzes the oxidation of SO_2 to SO_3 . The moisture present in the pores of active carbon

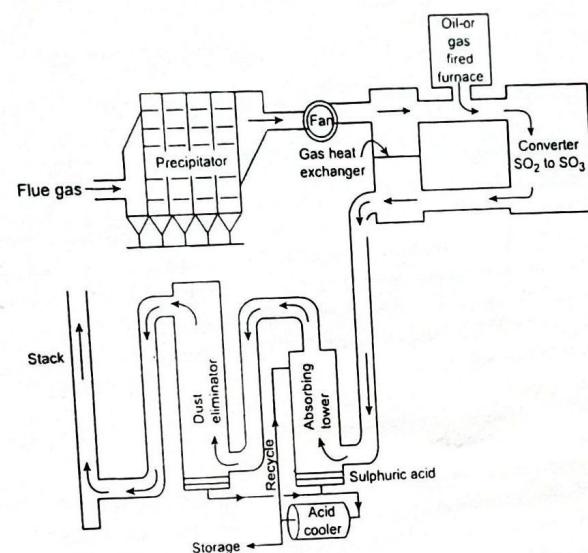


Figure 14.24 CATOX process.

reacts with SO_3 to form H_2SO_4 . Complete combustion of SO_2 to SO_3 can be achieved by combined effect of adsorption and catalysis of active carbon.

14.10.4 Alkalized Alumina Process

In the alkalized alumina process, developed by U.S. Bureau of Mines, dust-free flue gas is fed to a reactor in which the porous form of sodium aluminate ($\text{Na}_2\text{O}\cdot\text{Al}_2\text{O}_3$), adsorbent sorbs SO_2 at a temperature of 315°C (Fig. 14.25). In this process, the SO_2 and O_2 in the flue gas react with the adsorbent. The spent material is then contacted with a reducing gas such as hydrogen in a regenerator at about 680°C to produce hydrogen sulfide.

14.10.5 Simplified Limestone/Lime Gypsum Process

The simplified wet-type desulfurization system is made cost-effective by simplifying the conventional limestone/lime gypsum process. The open spray tower is adopted for the absorber with high performance spray nozzles and simple internal structures. Gypsum treatment section is also simplified by using continuous gypsum centrifuge.

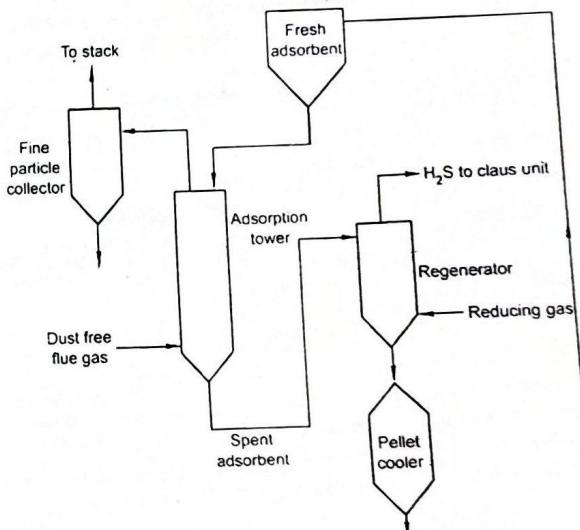
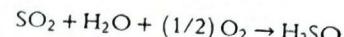
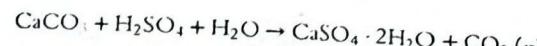


Figure 14.25 Alkalized alumina process.

1. Absorber Tower Section



2. Absorber Sump Section



or



Simplified configuration of equipment and using inexpensive CaCO_3 or $\text{Ca}(\text{OH})_2$ as absorbents are to be used as effective absorption of oxides of sulphur. Process by-products, mixtures of gypsum and ash, are normally utilized as retardants for cement manufacturing.

14.10.6 Wet Limestone-Gypsum Flue Gas Desulfurization System

Wet limestone-gypsum flue gas desulfurization (FGD) system removes SO_2 contained in the flue gas in contact with limestone slurry droplets as an absorbent when the flue gas containing SO_2 passes through the absorber. Limestone slurry absorbs SO_2 , then it is oxidized by air at the lower part of absorber to produce calcium sulfate which is extracted from the absorber as gypsum slurry, and finally dewatered and reused in the form of gypsum powder.

Chemical reaction: $\text{CaCO}_3 + \text{SO}_2 + 2\text{H}_2\text{O} + (1/2)\text{O}_2 \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O} + \text{CO}_2$

1. Regardless of SO_2 concentration, SO_2 removal efficiency of more than 90% can be achieved.
2. By-product gypsum can be reused as material of cement or wallboard.
3. Limestone, which is supplied stably, is used as an absorbent.
4. Single absorber tower, which has integrated function of pre-scrubbing, absorption, and oxidation, is adopted. Moreover, it also removes particulate in the flue gas with high removal efficiency.

14.10.7 Removal of Oxides of Nitrogen

It is relatively easy to remove SO_2 from combustion gases by dissolving SO_2 in water and reacting it with alkali. Aqueous SO_2 quickly forms sulfurous acid, which reacts with alkali and then is oxidized to sulfates. Collecting NO_x is not nearly as easy this way because NO , the principal NO_x present in combustion gas streams, has a very low solubility in water.

When gas, coal, or fuel oils are burned with air, the nitrogen in the air combines with some of the oxygen according to the reversible reaction:



Whenever NO is formed, the rate of its decomposition becomes very slow under reaction conditions. It is usually formed at high temperatures, and an equilibrium concentration of approximately 2% in air is obtained at 3800°F. Unlike sulfur oxides, which quickly react with water to form acids, NO must undergo a two-step process to form an acid.

- There are two possible approaches for controlling NO_x in combustion gases:
1. Modification of the combustion processes to prevent the formation of NO_x .
 2. Treatment of the effluent gases to convert the NO_x to N_2 .

14.10.8 Scrubbing Methods for Effluent Gas Treatment for Reduction of NO_x

The scrubbing techniques for NO_x control can be further sub-divided into (1) absorption by liquids and (2) adsorption by solids.

14.10.8.1 Absorption by Liquids

From power plants with 2000–15,000 ppm levels of NO_x in the effluent gas, the following process can be adopted for NO_x control. Further these methods can also remove SO_2 :

1. Absorption by lime slurry when gypsum and nitric acid can be recovered as by-products.
2. Magnesium hydroxide scrubbing recovering concentrated NO_x as by-product.
3. Absorption by sulfuric acid, which produces nitric acid and sulfuric acid.
4. Absorption by lime/sodium hydroxide.

From nitric acid plants, tail gas emissions vary from 0.1 to 0.69 vol% with an average of 0.37%. Using sodium and calcium hydroxide solutions, a number of scrubbing technologies have been developed.

14.10.8.2 Catalytic Reduction

This process is usually used to treat the tail gas from nitric acid plants, which has been a nuisance for many years, especially because of the offensive reddish brown plume that is usually associated with nitric acid plants. The catalytic treatment usually uses platinum, palladium, or rhodium as catalysts.

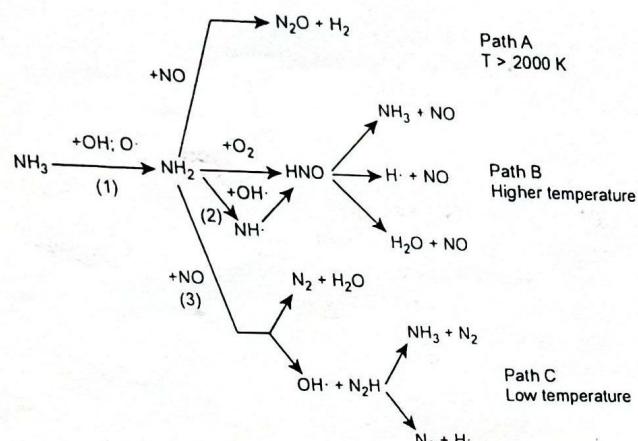
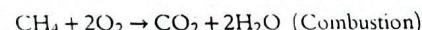
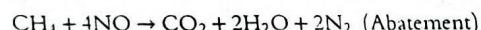


Figure 14.26 Simplified reaction mechanism of NO reduction or NO formulation with NH_3 .

for speeding the reaction of the NO_x with the reducing agent, which is normally methane or natural gas. The reactions involved are:



Selective Catalytic Reduction for Removal of NO_x

Selective catalytic reduction (SCR) is one of the most efficient methods for removal of NO_x pollutants. Here, anhydrous aqueous ammonia, which is a selective reductant, is injected into the polluted flue gas through a bed containing the catalyst. Both ammonia and NO_x combine to form an ammonium salt intermediate by the action of the catalyst. The intermediate compound then decomposes to give elemental nitrogen and H_2O . The NO_x reactions take place at a small range of temperatures between 500 and 950°F, and the details are shown in Fig. 14.26. The type of catalyst determines this range. Operating below the optimum range will not give the energy necessary to initiate the desired reaction; while operating at a temperature above the maximum, oxidation of ammonia to either NO_x or ammonium nitrate and ammonium nitrite would take place. It is very

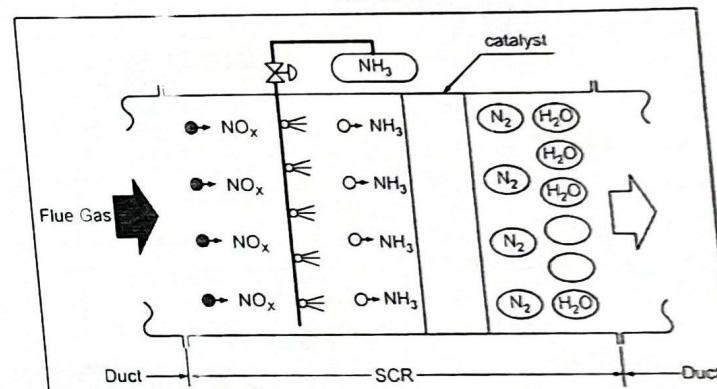
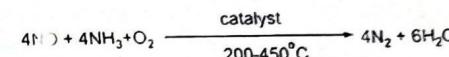


Figure 14.27 Typical configuration of selective catalytic reduction system.

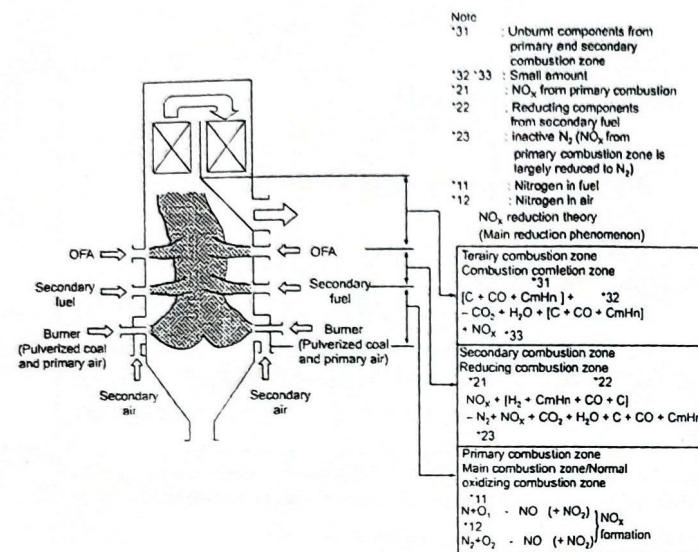
important to operate in the proper temperature range. This is usually gained from pilot plant tests and experience. The flue gas from industrial boilers is usually the input feed in this type of catalytic reduction process.

Outline of Selective Catalytic Reduction System

The flue gas NO_x removal process developed by Kawasaki is a selective catalytic NO_x reduction system, in which NO_x in the flue gas is decomposed to N_2 and H_2O by NH_3 , while flue gas passing through the catalyst layer as shown in Fig. 14.27.

14.10.8.3 Three-Stage Low NO_x Combustion System

1. In case of three-stage combustion system, reducing combustion is limited only to the secondary combustion zone, so that reducing atmosphere space is very narrow (Fig. 14.28). Furthermore, since measures are taken so that combustion gas with a strong reducing capability does not directly strike the water wall, adverse effects from such things as reducing corrosion and slagging on the heating surfaces inside the furnace due to reducing atmosphere, even in the case of super low NO_x combustion, are extremely small compared to other NO_x reduction systems such as Overfire Air (OFA) combustion system, which expose a large part of the furnace inside to reducing atmosphere.

Figure 14.28 Three-stage combustion type low NO_x system.

- Normal oxidizing combustion is performed in the primary combustion zone (main combustion zone), where most of the fuel burns and combustion efficiency is very high. The unburnt parts from the secondary fuel in the secondary combustion zone (reducing combustion zone) is burnt in the tertiary combustion zone (combustion completion zone). Consequently, combustion efficiency in a three-stage type low NO_x boiler is as high as in ordinary boilers without NO_x reduction.
- Due to the features mentioned above, the NO_x value in a three-stage combustion type low NO_x boiler can reach to 100 ppm or less with ordinary bituminous coal. The NO_x value decreases if the combustion gas remains longer in the secondary combustion zone.

Primary Combustion Zone

In the "normal combustion type" non-low NO_x burner, normal oxidizing combustion with an air ratio of 1.0 or over is performed. The amount of fuel here is 65–75% of total boiler fuel and the flame is raised to a very high temperature and a high combustion efficiency is obtained because the minimum combustion air needed for complete combustion is applied, and also flame length is adjusted to be as short as possible. Consequently,

the flame in this zone is a bright "golden color" and good combustion can be confirmed at a glance. Generation of NO_x in the primary combustion area is not controlled at all and the aim is only to reach 100% combustion efficiency.

Secondary Combustion Zone

25–35% of the fuel for the boiler is blown in from the secondary fuel port. This secondary fuel includes air for transport but any other air is strictly excluded to improve its performance as a denitrification agent. The denitrification reaction is as follows:

1. The secondary fuel. Consequently, the longer the gas remains in the secondary combustion zone, the lower NO_x becomes.

Tertiary Combustion Zone

30–40% of all the air used for combustion is injected from the OFA port and the unburnt components from the secondary combustion zone are burnt. The OFA port is positioned so that it is in the ideal gas temperature zone from the viewpoint of improved combustion of the unburnt components, and for control of new generation of thermal NO_x. OFA is injected in stripes on the horizontal cross-section of the furnace, and there are a number of OFA ports so the OFA is completely mixed with the combustion gas from the secondary combustion zone. In the tertiary combustion zone, combustion efficiency increases in accordance with the increase of the space between the OFA ports and the furnace exit. However, this increases the size and weight of the boiler, so the size of this space is determined from the total cost including facility costs and running cost of the boiler.

14.10.8.4 Incineration

Incineration is widely used in industry when the fumes from a stack contain toxic pollutants, especially those with offensive odors. A wide range of odorous air pollutants are destroyed by the incineration process. Among these are mercaptans, hydrogen sulfide, cyanide gases, and hydrocarbons. Three types of incineration processes are encountered, depending on the range of temperature used to effect the desired reaction.

Flame Incineration

If the contaminated gas stream contains pollutants which approach lower limit of flammability, this stream is passed through a combustion chamber, a certain quantity of natural gas and fresh air to support combustion are fed to

the chamber; the operating temperature is of the order of 2500°F or higher. Hydrocarbons are burnt to CO₂ and H₂O. The exit gas stream is odorless, and the polluted air is preheated by the countercurrent exchange of heat with the odorless stream.

Thermal Incineration

When the combustible contaminants exist in very small concentrations, and thus cannot support combustion, thermal incineration becomes more economical to use than flame incineration, since the temperature, since the temperature needed here is of the order of 1250°F. A gas burner raises the temperature of the polluted stream to 1000–1500°F, causing thermal degradation of the fumes.

VOCs are very serious air pollutants. Thermal incineration is one of the best ways to destroy them. This incineration process burns organic compounds and renders them harmless by giving off CO₂ and water. The proper length of residence time must be given so that complete combustion takes place. The temperature should be high enough so that total destruction of the toxic wastes occurs. Incinerators require residence times ranging from 0.5 to 1.0 s, with temperatures ranging from 1200 to 1600°F. In general, destruction efficiencies are above 95%.

One of the major advantages of thermal incinerators is the near total destruction of the hazardous waste without any residual waste being generated. Maintenance of the equipment and the initial cost are relatively reasonable. If the toxic stream contains halogenated compounds such as chlorine and fluorine, materials of construction must be carefully chosen because of the prevailing high corrosivity feed, materials such as stainless steel or fiber-reinforced plastics are used. Many times, a scrubber issued prior to the release of the effluent gas, especially since any halogenated acid gases must not be released into the atmosphere.

Catalytic Incineration

A catalyst is a compound which changes the rate of a chemical reaction without being changed chemically itself. The desired reactions take place at the surface of the catalyst at temperatures ranging between 600 and 900°F. The catalytic oxidation of ammonia gives NO_x, which are in turn absorbed by water to give nitric acid. SO₂ is oxidized catalytically to give SO₃, which is absorbed in weak acid to give stronger sulfuric acid. A large number of hydrocarbons are catalytically decomposed to give innocuous compounds. Sulfur and metal-bearing compounds poison the catalyst rapidly and render

its use less attractive economically. Again, noxious odors are practically eliminated with this process.

Catalytic incineration destroys organic fumes and renders them harmless by giving CO₂ and water as products of combustion. Here, the catalyst plays its role in speeding up the reaction by allowing the combustion to take place at a lower temperature, around 600°F. The inlet stream of toxic wastes is heated in the recovery unit; it then moves on to a catalyst where it is converted into the harmless substances. A plate-and-frame arrangement of the catalyst is the normal way of using it. This way the toxic waste will come into good contact with the catalytic substance, where it is burned and rendered harmless at a relatively low temperature. Catalysts used are normally platinum alloys, copper chromite, or platinum itself along with some others like copper oxide, chromium, manganese, or nickel. They are usually placed on chemically inert materials like ceramics.

FURTHER READING

- [1] B. Bastami, U.S. CPI start to feel effects of Bhopal tragedy, *Chemical & Engineering* (March 18, 1985) 27–33.
- [2] K.P. Chechernov, Development of ideas about reasons and processes of emergency on the 4th unit of Chernobyl NPP 26.04.1986 Slavutich, Ukraine International Conference "Shelter-98", November 25–27, 1998.
- [3] T.R. Detwyler, *Man's Impact on Environment*, McGraw-Hill Book Co., New York, 1971.
- [4] S. Draggon, J.J. Cohrssen, R.E. Morrison (Eds.), *Environmental Impacts on Human Health, the Agenda for Long-term Research and Development*, Praeger, New York, 1987.
- [5] D.M. Elsom, *Atmospheric Pollution: Causes, Effects, and Control*, Pergamon Press, Oxford-Blackwell, Inc., New York, 1989.
- [6] Air pollution: plant killer, *Environmental Science and Technology*, 4 (8) (1970) 635–643.
- [7] E.H. Haskell, *The Politics of Clean Air, EPA Standards for Coal-Burning Power Plants*, Praeger Publishers, New York, 1982.
- [8] M. Heylin, India's chemical tragedy: death toll at Bhopal still rising, *Chemical Engineering* (December 10, 1984) 5–7.

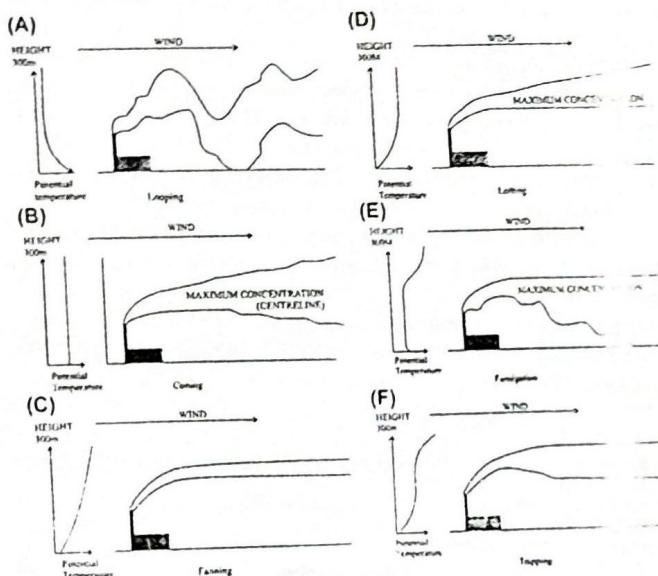


Figure 14.11 Plume characteristics.

All industrial emissions are released through stacks (chimneys) of varying heights. These represent the stationary sources of air pollution with the exhaust gases dispersed over a region. Normally the plume is a parcel of gaseous effluents released from a stack will be at a higher temperature than the surrounding environment due to which it will be buoyant and have drifted to the surrounding environment due to which it will be moving upward with buoyancy action. Atmospheric stability and the wind turbulence conditions existing will determine the behavior of the plume emitted from a stack of any industry.

There are a well-known set of characteristic behaviors observed for plumes (Fig. 14.11). These are:

Looping: In a well-mixed turbulent boundary layer on a hot day (forced by buoyancy), the turbulent eddies may be large and intense enough to advect the whole plume down to the ground. This can result in extremely high plume concentrations in the vicinity of the source.

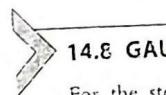
Coning: This is the kind of form assumed for a Gaussian plume, when the boundary layer is well mixed, and turbulent eddies are smaller than the plume scale. The plume forms a cone downstream.

Fanning: In a stable boundary layer, the plume spreads out horizontally at its level of neutral buoyancy. Vertical motion is weak, so there is little upward spread, but the plume forms a "fan" when viewed from above. The plume is not well mixed in the vertical, which implies relatively slow dilution, but there are not likely to be high plume concentrations at the ground. Unfortunately, this kind of plume may be the precursor to a "fumigation" event (see Fig. 14.11E below) if the inversion is subsequently mixed to ground level.

Lofting: At early evening, if a surface inversion is developing, vertical motion may be inhibited below the plume while remaining active above; the plume is diluted but does not reach the ground. This is a favorable situation.

Fumigation: There is a strong inversion restricting mixing above, and the plume is mixed throughout the boundary layer. This can occur quite rapidly. For example, after sunrise when the nocturnal inversion is being eroded from below by buoyant eddies, plume-level air of high concentration may be brought down to the surface over a wide area.

Trapping: There is a relatively well-mixed layer with inversions above and below it, which trap the plume at a particular height. This might occur at night when there is a low-level inversion above the Nocturnal Boundary Layer (NBL) and a higher level inversion left over from the previous days Convective Boundary Layer (CBL). In between is the relatively well-mixed residual layer.



14.8 GAUSSIAN PLUME MODEL

For the steady-state concentration downwind from a continuous point source, the Gaussian Plume Model was presented by Sutton and further developed by Pasquill and Gifford. In this model, the concentration distribution perpendicular to the plume axis is assumed to be Gaussian distribution in both horizontal and vertical planes, and the extent of plume growth in these planes is measured by the standard deviation.

In the Gaussian plume approach the expanding plume has a Gaussian, or normal, distribution of concentration in the vertical (z) and lateral (y) directions. Fig. 14.12 depicts the nature of the plume coming out. The coordinate system has been set up to show a cross-section of the plume, with z representing the vertical direction and x being the distance directly downwind from the source.

As stack emissions will be at elevated temperatures, they will have some initial upward velocity and buoyancy, and the plume, before it takes up a symmetrical path about the center line, will travel some distance downwind,