

# COMBUSTION APPLICATIONS

In general, the technical combustion processes that are in use today were developed without any guidance from the scientific principles involved. This is primarily because combustion science is of comparatively recent origin. However, we should expect newer developments which would make an increasing use of the knowledge acquired as a result of research in the past few decades.

Although empirical work in the field of combustion is still necessary, it is increasingly giving way to the powerful methods evolved from the scientific approach. The areas which are finding successful application are, e.g., the principles of flame stabilization as applied to flame holding devices, the theory of turbulent flames as applied to the efficient utilization of combustion space, the theory of ignition as applied to starting, reaction kinetics as applied to theoretical performance ceilings, flame structure studies as applied to the design of burners and combustion chambers, etc. Chemical thermodynamics has been successfully used for the computation of properties of combustion gases which act as the working medium in I.C. engines as well as other technical combustion processes. The present need is to design a compact, lighter, noiseless and a more efficient fuel burning equipment which should give a smokeless exhaust.

At present there are hundreds of burners and fuel burning equipment available for each type of fuel. It is not possible to go into details of their construction, advantages, and disadvantages. However, the basic principles of some fuel-burning equipment are discussed in this chapter, along with an indication of the areas which need further investigation.

The fuel burning equipment may be classified according to the type of fuel used.

Solid fuel, i.e., mostly coal, is burned in two ways:

- (i) large particles on fuel beds, and
- (ii) small particles in pulverized form.

Liquid fuels from gasoline to heavy fuel oils are first either vaporized or atomized, and then burned in an atmosphere of air. Gaseous fuels are usually burned in pre-mixed flames. Liquid or gaseous fuels are also burned in diffusion flames.

## 17.1 COAL BURNING EQUIPMENT

### Over Feed Stokers

Basically, the solid fuel burners are the same as the gas producer described in Chapter 2, the difference is in respect of the height of various zones and the air supply. The majority of industrial burners operate on the over feed principle. The fresh or 'green' coal is dropped onto the fuel bed. The fuel bed thickness usually varies from 10 to 30 cm and can be divided in four zones. The topmost zone is formed as the "distillation zone" or "green coal zone", the next zone in sequence is the reduction zone, followed by the "oxidation zone", and the "ash zone".

The primary air for combustion enters from below the fuel bed. This passes upwards, through the grate and the ash zone, and gets heated, in turn cooling the ash. The oxygen in the primary air reacts with a part of the carbon in the coke bed to form carbon dioxide in the oxidation zone. When the oxygen becomes depleted from the rising hot gases through the fuel bed, the coke reduces the carbon dioxide back to carbon monoxide in the reduction zone. The oxidation reaction:  $C + O_2 \rightarrow CO_2$ , being exothermic, promotes the reaction. The reaction  $C + O_2 \rightarrow CO_2$  being endothermic, lowers the temperature of the products. In the distillation zone, the combustion gases consisting of  $CO$ ,  $CO_2$ , and  $H_2$ , heat up the fresh coal so that the moisture is vaporized and the volatile matter emanates from the coal

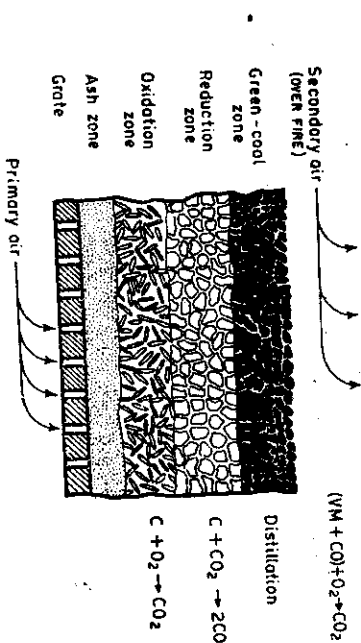


Fig. 17.1 Diagrammatic cross-section of an over-feed fuel bed (with permission of McGraw-Hill, from M. L. Smith and K.W. Slatson: *Fuels and Combustion*, 1952, p. 241).

particles. The volatile matter and carbon monoxide then react with the oxygen of the secondary air which enters from above to complete the burning. Figure 17.1 shows the various zones of reaction in an over-feed fuel bed.

Various mechanisms are used for the firing of coal and the removal of ash. The most common firing method is by hand. It is suited to domestic furnaces and other small-units-only. For big-units, mechanical stokers are used which provide a continuous supply of coal with uniform distribution. Many types of mechanical stokers are in common use.

#### Travelling-grate or Chain-grate Stoker

This is a very popular type of mechanical firing device. Coal is fed from a hopper onto a grate, moving through the combustion chamber. A travelling-grate stoker differs from a chain-grate one in respect to the construction of the grate. The grate consists of a number of cast iron links or bars interlocked to form a grate. The travelling-grate stoker has more closely interlocking bars. The coal enters at one end and by the time it reaches the other end, the combustion is complete and the ash falls into the ash pit. Figure 17.2 shows the travelling-grate stoker with a rear firing arch which helps in the rapid ignition and complete combustion of coal.

The spreader stoker consists of a distributor, feeder, hopper, and horizontal grate. The spreader mechanism has blades fitted to a rotating

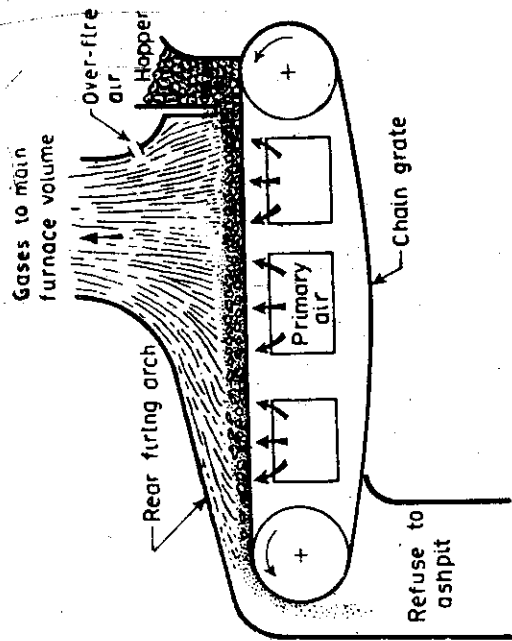


Fig. 17.2 Travelling-grate stoker (with permission of McGraw-Hill, from M. L. Smith and K.W. Stinson: *Fuels and Combustion*, 1952, p. 245).

cylinder which throws the coal evenly over the grate. Small particles burn before reaching the fuel bed as they travel through the flame, while the heavier particles burn as in a fixed bed.

In the inclined grate over feed stoker, the fuel is fed at the top of an inclined reciprocating grate. The grate is in the form of a wide Y-shape. The fuel moves down as it burns and the ash is removed at the lower end.

#### Under Feed or Retort Stokers

In under feed stokers, the fresh fuel is forced into the fire from below by a power ram or screw and moves out to the sides as it burns. The ash which accumulates at the sides is removed by agitating a heap of ash into a hot coke zone and forming a clinker which can be pulled with tongs. (The main advantage of this mechanism is that the volatile matter distilled from the fresh coal passes through the oxidation zone, thus ensuring complete combustion of the volatile matter.)

Figure 17.3 shows the cross-section of a single retort under feed stoker. The grate is usually inclined and thus the burned fuel and the

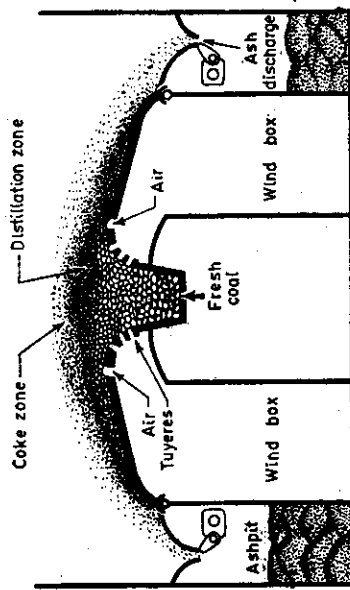


Fig. 17.3 Single retort under feed stoker (with permission from *Fuels and Combustion*, op. cit., p. 251).

ash automatically move outwards as the fresh fuel is supplied. The air for combustion is supplied through tuyeres. Sometimes, travelling grates are also used with an under feed mechanism for the easy removal of ash. Large size under feed stokers are built as multiple retort units. Several hoppers and power rams are operated alongside, distributing the coal over the grate surface.

(The factors which control the efficiency of such stokers are: proper ratio of primary and secondary air, net air-fuel ratio, size of fuel particles, uniform distribution of coal and air over the grate, and size and shape of the combustion chamber.) Some of the unburnt fuel may pass

through the grate, while the fusion of ash or clinker formation may result in an uneven distribution of air. Such factors will reduce the heating rate or the efficiency of the stoker. The space and time available for the volatile matter and carbon monoxide to burn completely is also important.

#### Pulverized Coal Burners

Coal in the pulverized form can be burned in a similar fashion as oil or gas. The main advantages of pulverized coal burners are: high efficiency, greater flexibility in their control and operation, flexibility in the quality of coal to be used, and easy design of burners. These advantages are offset by the high cost of pulverizing the fuel and costly coal-handling equipment. Another major disadvantage of pulverized coal burners is that most of the ash is carried along with the exhaust. Normally, pulverized burners are found to be economical for the units consuming more than 1 t of coal per hr. Such units discharge a huge amount of fine ash in the atmosphere. This ash also gets softened and deposits on furnace walls, boiler tubes, baffles, etc., drastically reducing the heat transfer capacity. It also erodes and corrodes the surfaces. Therefore, adequate slag-removing equipment and expensive fly-ash collectors are required to maintain the efficiency of the boiler and other equipment, as well as to protect the environment.

In pulverized coal burners, more than 85% of the coal particles should pass through a 240 mesh screen, i.e., its diameter should be less than 0.063 mm. These finely ground particles are blown into the combustion chamber by the hot primary air. This cloud of coal then burns inside the combustion chamber in a manner similar to that of a droplet liquid fuel. The burning of these particles is completed in two stages: in the first stage the volatile matter burns in a spherical diffusion flame surrounding the particle, and in the second stage, the remaining coke undergoes burning at the surface.

The flame speed on the pulverized fuel depends upon the volatile matter present in the coal and its ash content. Higher volatile matter and lower ash content give higher flame speeds. Pulverized coal gives maximum flame speeds at a fuel-air ratio three to six times the stoichiometric value. The maximum flame speed achieved is of the order of 14 to 15 m/s. In order to carry the coal particles through a horizontal pipe, the air velocity should be more than 20 m/s.

As the coal and air enter the furnace, the speed falls, and thus a stable flame is obtained. The flame should stabilize at a distance of 10 to 30 cm from the nozzle.

The size of the combustion chamber depends upon the speed and size of the coal particles. The time required for a coal particle to burn depends upon the size of the particle and the temperature of the furnace.

Distillation takes place in about 0.005 s. In commercial furnaces, half of the coal particles are burned in about 0.05 s. Within 0.1 to 0.3 s, about 95% of the particles are consumed. If the combustion is not complete, coal particles may be carried away by the fuel gases. However, carbon monoxide is usually not present in pulverized fuel burners.

Furnaces for pulverized fuel are classified according to the firing method as vertical, horizontal, and tangential. In vertical furnaces, the primary air and fuel are fired downward. The location and quantity of the secondary and tertiary air may be adjusted to regulate the depth of the flame. The tangential firing produces intense turbulence, permitting high rates of heat release.

#### Cyclone Furnace

In a cyclone furnace, small coal particles usually with a diameter less than 6 mm are burned in suspension with air. The coal particles along with the primary air are fired tangentially into a cylindrical chamber as shown in Fig. 17.4. The fuel swirls forward into the main chamber

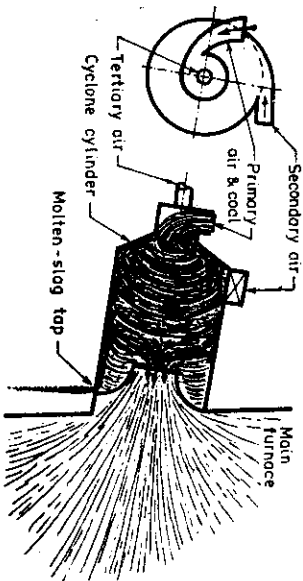


Fig. 17.4 Cyclone furnace (with permission from: *Fuels and Combustion*, op. cit., p. 265).

where it meets the high speed tangential stream of secondary air. Some tertiary air is supplied at the axis of the chamber to ensure the burning of any fine coal particles, suspended near the centre of the vortex. The temperature developed inside the furnace is high. Therefore, the ash melts away and the ash globules are carried to the wall by centrifugal force. The furnace is a bit inclined to permit the molten ash to flow down. Large coal particles may adhere to the molten ash where they are subsequently burned. A high combustion efficiency is attained with about 10 to 15% excess air. This furnace separates out most of the ash from the flue gases and only about 10% of it is carried through.)

We may mention here that pulverized fuel firing systems, e.g., the cyclone furnace have come into being as a result of better understanding

of the mechanism of solid fuel combustion. If the properties of any coal from the mines are known, it is possible to predict beforehand whether a particular fuel will be suitable for a particular furnace or not. Also, the lower grades of coal can now be burned more efficiently. The design of a furnace or a combustion chamber has been improved because of a better understanding of the primary and secondary air requirements and air velocities. Furnace temperatures can be controlled depending upon the limitation of the refractory. Suitable temperatures can be maintained which can melt the ash and simplify its removal. The effect of various impurities present, e.g., sulphur etc. can be predicted.

However, we have yet to optimize the designs of furnaces for smaller and more efficient coal burning equipment. Because of the better availability of coal as compared to the supply of liquid or gaseous fuels, a compact unit, light in weight which may compete with the I.C. engines and gas turbines for automobiles or aircrafts is still a far cry.

## 17.2 OIL BURNERS

Various grades of fuel oil are in use for domestic and industrial heating. Kerosene oil is generally used as an illuminant and as a heating agent, while heavier grades of oils are used in industrial burners and furnaces. The combustion of gasoline, aviation kerosene, and diesel oil is dealt with separately.

Kerosene is extensively used in lamps and stoves. Three main types of lamps are available:

- (i) Yellow flame wick lamp,
- (ii) wick fed mantle lamp, and
- (iii) pressure fed mantle lamp.

In the yellow flame wick lamp, the kerosene burns at the top of the wick producing a yellow diffusion flame. Due to incomplete combustion, incandescent carbon particles in the flame radiate light. The use of a mantle greatly increases the illuminating power of the kerosene lamp. Kerosene vapours are supplied and burned inside a mantle. The kerosene vapours are either supplied through a wick or under pressure through a nozzle. The domestic stoves generally in use are of two types:

- (i) Wick type, and
- (ii) pressure type.

In wick type stoves, kerosene rises through either a circular wick or through a number of wicks placed around a cylinder. The wicks come out in the annular space between two concentric cylinders. These cylinders are perforated and heated by the burner flame itself. The fuel gets vaporized, and the somewhat preheated air enters through the perforations to give a slow smokeless flame.

In pressure type stoves, the kerosene is kept in a small reservoir. This reservoir is pressurized by a small hand pump which compresses the air inside the reservoir. Due to the pressure, the kerosene rises through a tube to the burner head where it gets vaporized. These vapours then come out of a small jet placed below the burner head. The vapours mix with most of the air required for combustion and impinge on the hot burner head, giving a stable turbulent blue flame.

Industrial burners normally operate with cheap heavier oils. The combustion of such oils requires that either the oil should be vaporized or at least atomized in the form of small fuel droplets. These vapours (or mist of oil) are then required to be thoroughly mixed with air to give a stable flame. The finer the atomization, the more rapid will be the evaporation, resulting in more rapid and efficient combustion. If the fuel jet cracks before vaporizing, then the undesirable petroleum coke is formed.

Oil burners may be classified as follows:

- (i) Vaporizing burner,
- (ii) rotating cup burner,
- (iii) mechanical or oil-pressure atomizing burner,
- (iv) steam or high-pressure air atomizing burner, and
- (v) low-pressure air atomizing burner.

## Vaporizing Burners

Vaporizing burners are similar to the wick and pressure stoves discussed earlier. They operate on a similar principle for industrial heating. In industrial pot type burners, the oil is fed by gravity to the bottom of a pot by a pipe, or by drip feed. The fuel is evaporated by the radiant heat from the flame and the nearby heated surface. The vapours rise in the pot and mix with the primary air entering through the holes in the surrounding walls. The fuel-air mixture near the bottom of the pot is too rich to support combustion. Consequently, the flame rises to a position just above the rim. At this point enough air is available to give a good burning mixture. Some soot formation is inevitable in such burners which necessitate periodical cleaning.

## Rotary-cup Burners

Rotary-cup burners are extensively used in steam boilers. Such burners are capable of using a variety of oils without any major modifications in their design. The oil flows through a tube in the hollow shaft of the burner and into the cup. The cup is rotated at speeds from 3,500 to 10,000 rpm by an electric motor or an air turbine. The centrifugal force spreads the oil into a thin film on the inside walls of the cup. A centrifugal fan rotates with the shaft to force the primary air from a cone surrounding the rotating cup. About 10 to 15% of the theoretical air is thus supplied as primary air. The angle at which the

air hits the fine oil mist may be adjusted by regulating the relative position of the cup and the air cone. An additional atomizing effect is obtained as the air blasts the fuel mist. (The shape of the flame is controlled by the shape of the cup and the position of the air nozzle. The secondary air is usually supplied by a natural draft through air shutters in the furnace wall.) A turn down ratio of upto 5:1 can be obtained from such burners. Figure 17.5 illustrates a rotary-cup burner.

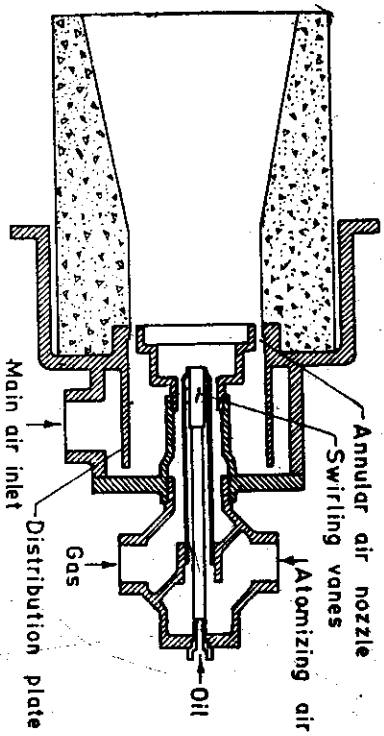


Fig. 17.5 Rotary-cup oil burner.

#### Mechanical or Oil Pressure Atomizing Burners

Oil pressure atomizing burners are the oldest and most commonly used burners for large land and marine boilers. The principle of atomization for all burners is: fluid pressure when released through a small orifice tends to break into a spray.

In this type of burner, the fuel oil is first preheated so that the oil viscosity is in the range of 10 to 30 centistokes. This oil is then fed tangentially under high pressure into a conical swirl chamber. About half of the initial oil pressure is consumed in generating rotational energy in the liquid, which then flows out from the orifice at the nozzle tip at high velocity in the form of fine droplets forming a cone of oil mist.

Figure 17.6 shows the details of a simplex pressure-jet oil burner. The turn down ratio of pressure-jet burners is very low, and is about 2:1. However, a nozzle designed to recirculate part of the oil reaching the whirl chamber permits the turn down ratio to be as high as 10:1. The air is normally supplied under pressure into the combustion chamber, but the natural draught can also be utilized. For large capacity boilers, a greater number of burners are employed instead of a single large

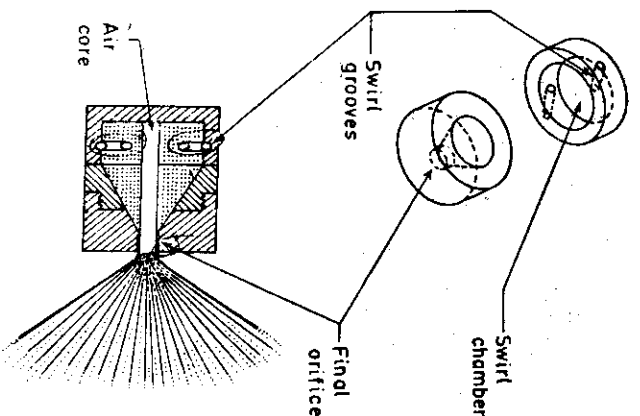


Fig. 17.6 Details of simplex pressure-jet oil burner.

capacity burner as it gives better atomization at lower pressure. The turn down operation is also simplified, as by shutting off one or more burners, the heat input rate can be reduced.

#### Steam or High Pressure Air Atomizing Burners

Steam or high pressure air atomizing burner operates like a "scentspray". A high velocity stream of air or steam impinges upon an issuing stream of oil in a manner such that it is torn into thin filaments and dispersed in the form of a fine spray. For heavier oils or for boilers, steam is preferred as it also preheats the oil and is available at high pressure. However, compressed air gives better combustion and mixing of air and fuels.

Figure 17.7 shows an industrial steam atomizing burner. As with most steam atomizers, the steam and oil flow side by side, thereby preheating the oil so that the viscosity of the oil is reduced, resulting in smaller oil droplets. The pressure of the air or steam required for such atomizers is usually greater than  $1 \text{ kg/cm}^2$  and may be as high as  $7 \text{ kg/cm}^2$ , depending upon the viscosity of the oil. Air and fuel may either mix inside the burner or totally outside it, i.e., inside the combustion chamber. The turn down ratio of such a burner is about 5:1.

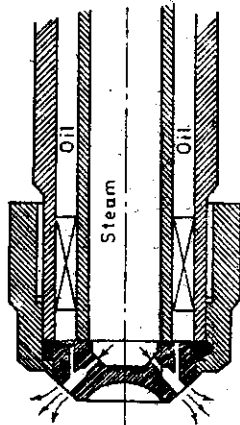


Fig. 17.7 Steam atomized oil burner.

The primary air used for atomization is normally less than 5% of the total air required.

In low pressure air atomizing burners, the principle is the same, the only difference is that the air pressure is low and is about 0.035 to 0.15 kg/cm<sup>2</sup>. Such burners are more suitable for lighter, less viscous oils, such as kerosene. The primary air required for atomization is comparatively higher, of about 20% or more.

If we were to look at the various oil burners now available, we shall find that the design of almost all the burners is as a result of the long experience gained in the use of fuel oils. Based upon the broad principles, e.g., small droplets, better mixing of air and fuel, or vaporizing the fuel, burners can be designed which result in the more efficient burning of the fuel oil. Oil burners have been evolved as a result of repeated trials rather than systematic design calculations. Every factor such as the ratio of primary to secondary air, the viscosity of the oil, the steam or air pressure, and the amount of turbulence desired, is controlled after careful observation of its influence on the performance on the burner. Fundamental research on the burning of single fuel droplets has given a good insight into its mechanism. But as compared to the actual conditions of burning, this is an oversimplification of the problem. Lot of research work is in progress on the mechanism of spray combustion too, but the gap between the work done so far, and that required for the direct application, is still wide.

### 17.3 GAS BURNERS

Gas burners are mainly used for purposes of cooking and heating in homes, and for ovens and furnaces in industries. They may be divided into three main classes:

- (i) Non-aerated burners,
- (ii) aerated burners, and
- (iii) surface combustion burners.

Non-aerated burners are used where long, lazy flames are required, e.g., in baking furnaces. In these burners, the fuel enters from a pin hole jet or a slot and all the oxygen is supplied by the air around the flame. This type of burner include the small domestic Bray-jet (batwing) burners to the industrial size Hypact burners. The air is supplied by natural convection only in the case of small burners or by forced convection in the large ones. The main advantage of such burners is that they give comparatively low temperatures and very high turn down ratios, as high as 130 : 1. A stable flame is obtained irrespective of wide pressure or velocity fluctuations.

Aerated burners are the most widely used type of gas burners for domestic and industrial uses. These are based on the famous Bunsen burner principle illustrated in Fig. 17.8. The fuel enters a tube through a jet. The suction induced by the jet of gas draws the primary air. The quantity of the primary air can be controlled by the shape and size of the primary air port. The primary fuel-air mixture flows through the tube to the burner top or port where the flame is stabilized. The mixture velocity is so adjusted that it exceeds the burning velocity of the mixture, but is less than the blow off velocity. The secondary air is supplied from the atmosphere by entrainment, through the outer

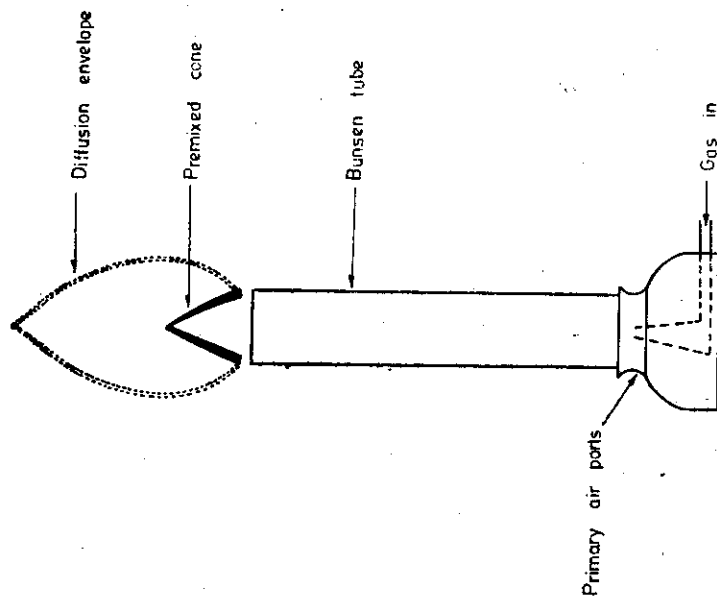


Fig. 17.8 Bunsen burner.

envelope of the flame. If the primary air supply is insufficient, the flame becomes long, slightly smoky, and luminous; and if the primary air supply is increased, the flame becomes short and non-luminous.

Depending upon the pressure of the gas admitted to the burner, the aerated burners may be either the atmospheric or high pressure type. All such burners generally operate in a stability zone bounded by the lifting, yellow tip, and flashback limits as shown in Fig. 17.9. For most gas burners a turn down ratio of 5:1 is desirable. Figure 17.10 shows the cross-section of a typical atmospheric gas burner.

In general, an atmospheric gas burner must have the following characteristics:

- (i) Be controllable over a wide range of turn down without flashback,
- (ii) provide uniform heat distribution over the heated area,
- (iii) be capable of completely burning the gas,
- (iv) should be such that no lifting of flames away from the ports occurs,
- (v) provide ready ignition with the flame travelling rapidly from port to port,
- (vi) operate quietly during ignition, burning, and extinction, and
- (vii) should withstand severe heating and cooling during the life of the appliance.

In the past, gas burners were designed from a few empirical relations, but as a result of fundamental studies, the design of the modern gas burner has become far more precise. All the above characteristics of a gas burner depend on port design and port arrangement which is the

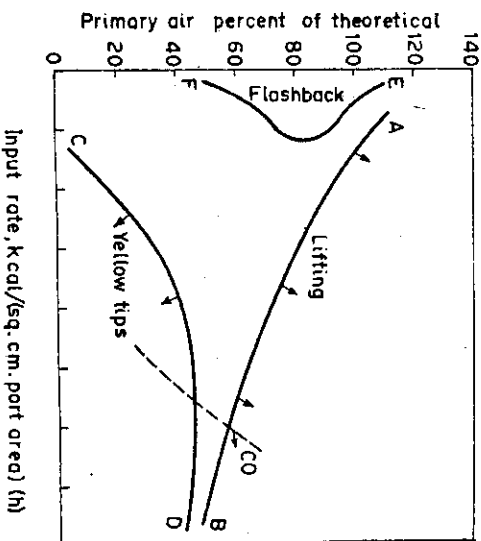


Fig. 17.9 Characteristic limit curves for an atmospheric gas burner (with permission from *Fuels and Combustion*, op. cit., p. 199).

starting point in a burner design. The number and size of ports can be determined from the heat input rating and the type of the gas to be used. The selection of the primary air for which a burner should be designed is dependent on the burner application, input rating, and flexibility desired.

To obtain stable flames at the selected primary aeration, the gas input rating should be such that the burner adjustment is located in the stable flame zone, and preferably in the design area. In order to obtain a flexible performance, the adjustment point in the stable flame zone should be located as far as possible from the three curves of Flashback, yellow tipping, and lifting limit. In many gas appliances, a wide range of gases can be used by varying the orifice and the primary air shutter opening. The secondary air complements the primary air, the combined primary and secondary air is necessary for complete combustion. If the primary aeration is increased, it will provide better mixing of fuel, gas and air, but it may also result in poor combustion due to the increased amount of recirculation of combustion products.

In pressure type aerated burners concentric primary air and gas jets under pressure are used in place of the simple gas jet. Separate jets can be used to induce secondary air, or they can be first fed into a mixing chamber. Large furnaces may be heated by multiple gas jets set in a common head, each jet being surrounded by compressed air, with a concentric orifice for the supply of air. The premixed stoichiometric proportions of gas and air can be burned in a tube or a narrow tunnel.

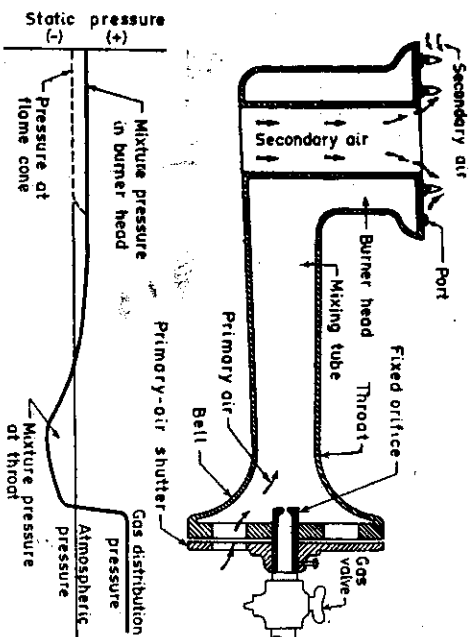


Fig. 17.10 Cross-section of an atmospheric gas burner and a diagram showing the static pressure at different positions (with permission from *Fuels and Combustion*, op. cit., p. 198).

The aerated burner can support a laminar or turbulent flame, depending upon the heat release rate required. Turbulence is sometimes generated by a fan which helps in the proper mixing of fuel and air.

In surface combustion phenomenon gas premixed with more than 100% primary air is fired tangential to the incandescent porous refractory surface of the furnace. The incandescent surface apparently has a catalytic and radiant effect which promotes very rapid and complete combustion even at high burning rates. Most gas burners can be used for different gases by minor adjustments in the fuel jet and/or burner head.

As a result of the systematic research carried out in the field of combustion, it has become possible to design a gas burner which is efficient and stable in operation.

#### 17.4 COMBUSTION IN I.C. ENGINES

Of all the prime movers gasoline and diesel engines are the most universally used. A major part of combustion research has been carried out with an aim to understand the mechanism of combustion in these engines and to improve their performance.

##### Combustion in S.I. Engines

It is a well-known fact that a higher compression ratio gives an improved efficiency of the engine, but the use of a higher compression ratio in a gasoline engine results in the phenomenon of "knock" which is undesirable in engines. The other important variables which affect the performance and knock tendency of the engine are: ignition timing, air/fuel ratio, turbulence, fuel properties, humidity, engine speed, initial temperature of air, engine temperature, load, delay time, etc.

In a spark ignition engine, gasoline is vaporized and mixed with air in the carburetor. This mixture then enters the cylinder where it is compressed, and at about 20-25° before t.d.c., the spark is passed through the mixture. The mixture around the spark is ignited and a flame travels through the unburned charge. This burning of charge occurs at almost constant volume resulting in a very high pressure which is then utilized for developing power.

Before the spark is passed, the mixture is heated up due to the compression of the charge and the contact with hot cylinder walls, piston and cylinder head. This increase in temperature may result in pre-reactions. These pre-reactions will further heat up the charge resulting in crackings, dehydrogenation, and polymerization of the charge. Some oxides of carbon, water, and oxygenated products are formed during the pre-reactions, thereby reducing the thermal value of the charge. The extent of such pre-reactions depends upon the type of hydrocarbon

present in the fuel, temperature of air, and engine and compression ratio. Tetraethyl-lead appears to have little effect on the pre-reactions of paraffinic fuels, but delays the auto-ignition. In a high speed engine, the flame front must traverse the combustion chamber in about 0.001 to 0.003 s. This will require a flame speed of about 30 m/s, while in a quiescent condition in a glass tube, the flame speed is measured and found to be 1 m/s. Thus a high degree of turbulence is a must for the proper burning of the charge. Various shapes of cylinder heads are in use to improve turbulence.

Due to the overheated parts in the engine cylinder, e.g., exhaust valve or spark plug, etc., sometimes the preignition of charge takes place. This results in the burning of the mixture before the piston reaches the t.d.c. The phenomenon of pre-ignition is undesirable because it reduces the power output of the engine. Pre-ignition should not be confused with auto-ignition which results in detonation or knocking in the engine. Pre-ignition is the burning of the charge before the spark passes. Auto-ignition is the sudden burning of the end charge due to the higher temperature and pressure caused by the burning of the major portion of the charge.

As the flame front moves from the spark plug, it results in the release of heat and increase of the cylinder pressure. The combustion process increases the pressure and temperature of the unburned charge ahead of the flame front which may suddenly burn as the auto-ignition temperature is reached. The violent combustion of this part of the charge sets up the pressure differential which results in knock. The auto-ignition due to the charge may result in a detonation wave. The knocking sound due to the auto-ignition is of a lower pitch than that of a detonation wave. The detonation wave reaction requires 25 to 50  $\mu$ s, and the wave travels at a speed of about 1000 to 2000 m/s.

The auto-ignition of the charge takes place in about 400 to 1000  $\mu$ s. The detonation wave may originate in the gases behind the flame front or ahead of the flame front in the auto-ignited charge. The higher compression ratio, engine temperature, air temperature, and load and spark advance result in the higher intensity of detonation, while a higher octane number, turbulence, engine speed, and humidity suppresses the detonation. The intensity of detonation changes with the air-fuel ratio in a manner similar to its burning velocity. A slightly rich mixture gives maximum burning velocity, i.e., higher temperature and pressure, which lead to detonation. A leaner or richer mixture lowers the intensity of detonation.

The effect of various factors on the performance of S.I. engines are well-known and need no mention here. Some additives have very good anti-knock characteristics.

The exhaustive research work done in the field of I.C. engines has resulted in a much improved performance and design of the engines.



And at present the I.C. engines are once again catching the attention of scientists all over the world. However, this time it is not with the aim to improve upon the engine efficiency, but to improve the exhaust emitted by the I.C. engines. The main aim is to reduce the poisonous side products and the unburned fuel, thus safeguarding the already polluted environment.

### Combustion in C.I. Engines

Compression ignition engines appear to be similar to spark ignition engines but there is a marked difference in their combustion processes. In a C.I. engine the liquid fuel enters the cylinder in the form of fine atomized droplets instead of vapours. Also the injection of fuel takes place not in the beginning of the compression stroke, but almost at the end of it, into the already compressed air. The compression ratio of the C.I. engine is very high, and is above 18 to 22 as compared to the compression ratio of 6 to 8 of the S.I. engine. The high compression ratio provides a temperature which is higher than the auto-ignition temperature of the fuel at the moment when the fuel is injected into the engine cylinder.

An initial delay period, i.e., the undesirable time interval, between the point of initial injection and actual ignition is always present. In the absence of the delay period, the fuel burns smoothly as it enters the cylinder. But, because of the initial delay period, the fuel accumulated during the period burns suddenly. The remaining fuel burns almost instantaneously as it enters.

The delay period consists of the physical and chemical delay. The physical delay is the time required by the atomized droplets to vaporize and mix with air. In the chemical delay period, some chemical oxidation reactions occur raising the temperature of the mixture from 550 to 1100°C.

The physical delay is practically constant and does not vary with temperature changes. However, the increased injection pressure, smaller nozzle size, and higher density of air (i.e., higher compression ratio) produce better atomization, thus reducing the droplets size and the physical delay period. The chemical delay period depends upon the molecular structure of the fuel, pressure, and temperature at the end of compression, turbulence, etc.

The cetane number of a fuel is indicative of the auto-ignition temperature and the delay period of the fuel. Higher cetane rating fuels have a low auto-ignition temperature and a low delay period. Normally, paraffin gives the highest cetane number, while the corresponding olefin, iso-paraffin, naphthene, and naphthalene give a continued decrease in the cetane rating. Also, the greater the number of carbon atoms in the chain of a hydrocarbon compound, the higher the cetane number. An increase in the compression ratio and the engine speed decreases the

delay period. A longer delay period gives a higher intensity of diesel knock.

The main problem at present with the C.I. engines is the same as with the S.I. engines, i.e., the control of the poisonous and smoky exhaust emitted by them.

### 17.5 COMBUSTION IN GAS TURBINES AND-JET ENGINES

There are two main types of gas turbines, viz., the stationary type and aviation type used for industrial applications and propulsive purposes respectively. The stationary gas turbines usually operate with heavier and cheaper oils. In aircraft gas turbines or jet engines, aviation gasoline or kerosene is used as fuel because the vapour pressure and solidification temperature of these fuels are suitable for high-altitude operations.

The important requirements of the combustion chamber of a steady-flow engine, apart from maintenance needs, are high combustion efficiency, stable combustion at all operating conditions, easy ignition and starting, minimum loss of pressure, and uniform distribution of temperature at chamber outlet. To meet these requirements the combustion chamber is designed suitably. In the past the design has mostly been empirical but with better knowledge of the aerodynamics of fluid flow, air-fuel mixture formation and flame stabilisation, better procedures have been adopted. Theories such as the turbulent flame propagation theory and stirred reactor theory are now being used for the scientific design of the combustion chambers. The main components of the gas turbines combustion chamber are the air casing, diffuser, flame tube or liner and fuel injector as shown in Fig. 17.11.

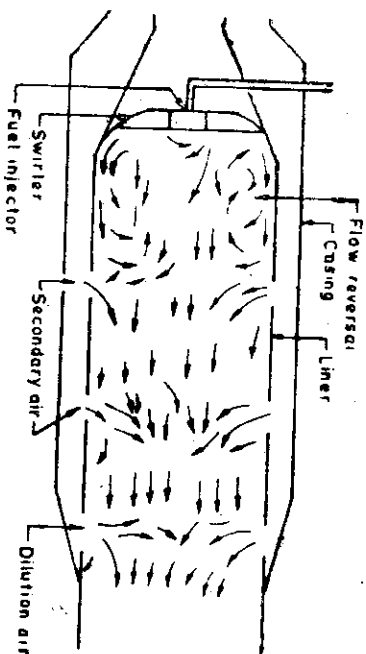


Fig. 17.11. Gas turbine combustion chamber.

The combustion chamber has three main regions:

- (i) Primary zone,
- (ii) secondary zone, and
- (iii) dilution zone.

In the primary zone air-fuel mixture formation and flow reversal takes place which assists in the stabilisation of the flame. Subsequent combustion takes place in the secondary zone and finally dilution of gases with by-pass air. In the primary zone the air-fuel mixture is near stoichiometric composition to aid in ignition and to sustain the flame. The fuel is usually injected through a swirller along with primary air for better atomization and mixture formation. As a result of the interaction of the primary zone, air-fuel mixture, and secondary air-flow reversal, the flame is stabilised in the flame tube. The flame tip is usually prevented from reaching the dilution zone. The overall air-fuel mixture ratio in the secondary zone and dilution zone are of the order of 60:1, depending on requirements to bring down the temperature to a reasonable value. In aircraft application, as air pressure changes with altitude, the rich and lean limits are narrowed. Thus, apart from flame stabilization and good combustion, the pressure drop should be less. As both these aspects are mutually incompatible, a compromise is usually made for design purposes.)

(The main types of gas turbine combustion chambers are:

- (i) Tubular chamber,
- (ii) tubo-annular chamber, and
- (iii) annular chamber.

#### *Tubular Chamber*

This is a good choice for a small gas turbine of a lower power output range and is of a through flow type. For high power output the tubular system tends to be too long and heavy and for aircraft application it results in an engine of large frontal area and drag.

#### *Annular Chamber*

In annular chamber the flame tube is mounted concentrically inside an annular casing. It is a very good form of an aerodynamic layout which results in a compact unit of lower pressure loss than other designs. A slight drawback of the unit is the significant change in temperature distribution of the outlet gases due to changes in velocity profile at inlet.

#### *Tubo-annular Chamber*

This comprises a group of cylindrical flame tubes arranged inside a single annular casing. It signifies an attempt to combine the compactness of the annular chamber with the best features of the tubular design. The main problem with tubo-annular chamber is that of achieving a satisfactory and consistent air-flow pattern though the design of the diffuser presents some difficulty.)

### **Fuel Injection**

The usual systems employed are the swirl spray atomiser and vapourizing system. Studies on fuel droplets burning in arrays has solved some of the problems of air-fuel mixture formation in the gas turbines combustion chambers. There is a renewal of interest in the air-blast type of atomisers.

### **17.6 ROCKET ENGINES**

The characteristic of rocket propulsion is that the thrust is obtained by the combustion of solid or liquid propellants, wholly contained within the rocket system. Usually the fuel and the oxidizer are carried separately, but occasionally a single propellant combining both fuel and oxygen, is used to produce the propelling fluid. The rocket propulsion unit, therefore, does not depend on the presence of an atmosphere of air, rather a rocket engine operates better in a vacuum. Since rocket motors generate high temperature gases at pressures of about 10 to 70 kg/cm<sup>2</sup> or more, and operate in atmospheres of 1 kg/cm<sup>2</sup> or less, a convergent-divergent nozzle is usually used through which the gases expand to the surrounding conditions. The nozzle expansion pressure ratios are much greater than those encountered in gas turbines and ram jet engines.

Rocket propellants may be classified as: solid and liquid propellants. Generally, solid propellant rockets have been used for Jet Assisted Take Offs (JATO) of aircraft, meteorological sounding rockets, and rocket projectiles. Liquid propellant rockets have been used for guided missiles and piloted aircraft, and have been the subject of most intensive development in recent years. Some of the desirable characteristics for a propellant are: ability to produce high chamber temperature, low molecular weight of the gaseous products of combustion, high density of the propellants to reduce the physical dimensions of the missile, ease of storage and handling and readily ignitable.)

A monopropellant is one which is capable of reaction and release chemical energy without the addition of an oxidizer. Monopropellants have been used widely in solid propellant rockets, but have not been favoured for liquid propellant rockets. Some of the monopropellants that have been used are: nitroglycerin [C<sub>3</sub>H<sub>5</sub>(ONO<sub>2</sub>)<sub>3</sub>], trinitrotoluene [C<sub>6</sub>H<sub>2</sub>(CH<sub>3</sub>)(NO<sub>2</sub>)<sub>3</sub>], nitromethane [CH<sub>3</sub>NO<sub>2</sub>], and hydrogen peroxide [H<sub>2</sub>O<sub>2</sub>].

Bipropellant systems have been most widely employed in liquid propellant rocket engines. Among the fuels that have been used are: ethylalcohol [ethanol: C<sub>2</sub>H<sub>5</sub>OH], methyl alcohol [methanol: CH<sub>3</sub>OH], gasoline [C<sub>8</sub>H<sub>18</sub>], hydrazine [N<sub>2</sub>H<sub>4</sub>], furfural alcohol [C<sub>4</sub>H<sub>6</sub>OCH<sub>2</sub>OH], aniline [C<sub>6</sub>H<sub>5</sub>NH<sub>2</sub>], ammonia [NH<sub>3</sub>], and hydrogen [H<sub>2</sub>]. Among the

liquid oxidizers that have been applied to bipropellant systems are: oxygen [O<sub>2</sub>], nitric acid [HNO<sub>3</sub>], and hydrogen peroxide [H<sub>2</sub>O<sub>2</sub>].

Modern solid propellants may be divided into two general classes: double-base propellants and composite propellants, on the basis of their composition and physical structure. Double-base propellants are homogeneous colloidal mixtures of components such as nitrocellulose [C<sub>6</sub>H<sub>7</sub>O<sub>2</sub>(NO<sub>2</sub>)<sub>2</sub>] and an explosive plasticizer such as nitroglycerin [C<sub>3</sub>H<sub>5</sub>(ONO<sub>2</sub>)<sub>3</sub>]. Other substances such as dinitrotoluene, potassium nitrate, etc., are added to act as stabilizers, plasticizers, coolants, colouring or darkening agents, etc. Composite propellants are made by embedding a finely divided solid oxidizing agent in a plastic reducing agent as fuel, and are heterogeneous in structure. The oxidizing agents include: ammonium nitrate [NH<sub>4</sub>NO<sub>3</sub>], potassium perchlorate [KClO<sub>4</sub>], lithium perchlorate [LiClO<sub>4</sub>]. Minor constituents may be added to modify the properties of the binder or to catalyze the combustion process.

The design of the components of a liquid fuel rocket is greatly influenced by the fluid characteristics. Liquid hydrogen has come into prominence despite its several drawbacks such as the need to store it at very low temperatures and its very low density. A solid fuel rocket is simpler in construction than a liquid fuel rocket, and provides a high degree of reliability and ease of storage of the solid propellants such as in military applications. Solid propellants are quite safe to handle and complete rockets can be stored fully charged with their propellants.

The present day designs of rocket engines may be regarded as one stage further than the turbojet units. They provide thrust by a jet of still smaller diameter with higher jet velocities and the rocket propulsion unit is lighter in weight than the turbojet unit. A rocket engine may be preferred over the turbojet unit when the duration is very small or the flight velocity is very high. The flight outside the earth's atmosphere is, at present, possible only with the help of rocket engines.

## AIR POLLUTION 18

Air pollution is not a new phenomenon. The early cave man who discovered fire for heating and cooking was also affected by the undesirable smoke which made breathing difficult. This forced him to abandon his cave and make a better ventilated hut. This allowed him to take full advantage of fire, while providing an outlet for the unwanted smoke. This solution was simple till the urbanization and industrial growth shifted the problem of smoke from inside to outside, i.e., from a domestic problem it became a problem of the town.

The next attempt to keep the air clean was to raise the height of the chimneys so that the smoke could be blown out at a higher level where it could diffuse and drift away. With the rapid growth of population, industrialization, and increasing use of automobiles, the capacity of our atmosphere to absorb the poison is diminishing.

Today, the magnitude to which pollution has reached not only threatens the health and well-being of the population in a particular city, but also produces effects on a global scale. The contamination of air, water, oil, and food has become a threat to the continued existence of many plants and animals and may ultimately threaten the very survival of the human race.

Air pollution may be defined as the presence of undesirable substances in the air either by natural means or due to the activities of men. The natural undesirable substances are dust, spores, pollen, bacteria, sea salt, hydrogen sulphide, ammonia, ozone, etc. In small concentrations, few of these may have a beneficial effect but the high concentrations are definitely not desirable. The man-made pollutants are smoke, carbon monoxide, sulphur dioxide, oxides of nitrogen, various hydrocarbons, fumes of acids, etc.

### 18.1 TYPES OF AIR POLLUTION

Air pollution may be broadly divided into:

- (i) Grit and dust,
- (ii) smoke, and
- (iii) gaseous pollutants.

#### Grit and Dust

Grit and dust occur naturally as sea salt, sand, road dust, pollen, etc. It is also emitted as mineral dust from quarries, sand and cement, etc. from batch mixing plants, stone crushers and mills and as coal dust from chimneys. Grit is of size greater than  $75 \mu\text{m}$  and dust 1 to  $75 \mu\text{m}$ . These particles, in concentrations normally found in the atmosphere, are not as such hazardous to health, but are a great nuisance.

#### Smoke

Smoke is produced by the burning of all kinds of fuels and is emitted with flue gases. Smoke consists mainly of the carbonaceous particles of sizes less than  $1 \mu\text{m}$ . These particles may adhere together to form soot. Such solid particles of soot, fine dust, and minute droplets of tar and oil form smoke. Smoke formation is usually due to the incomplete combustion of fuel. Smoke mixed with fog produces smog. However, the photochemical smog is an organic fog containing very little moisture.

#### Gaseous Pollutants

Gaseous pollutants are oxides of sulphur, carbon monoxide, oxides of nitrogen, various hydrocarbons, chlorine, hydrogen sulphide, ozone, fumes of various acids, etc. The toxic effect of the different constituents is different on the human body and plants. Higher concentrations of a few gaseous pollutants can be tolerated, but others can be very harmful even in smaller concentrations. Some pollutants have no direct harmful effect, but after undergoing some chemical or physical change, they become undesirable.

### 18.2 COMBUSTION GENERATED AIR POLLUTION

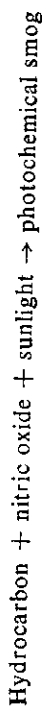
The subject matter that we shall discuss here is mostly confined to combustion generated air pollution. Accordingly, we can classify air pollution into the following two main categories:

- (i) Air pollution from the combustion of fossil fuels, and
  - (ii) air pollution from automobiles.
- We make such a division because usually the undesirable effects of the pollutants are noticed only when the above two different types of smog are formed producing eye irritation, poor visibility, respiratory trouble, etc.

Sooty, sulphurous smog, formed due to the combustion of fossil fuels used for heating and in industries, is a common feature of the urban and industrial complexes of Europe, and eastern and central North America. This type of smog is usually formed during the winter season and continues throughout the day and night. Humidity is necessary for the formation of such a smog. When moist air is cooled below the dew point, water vapour condenses on the solid particles available, forming fog. This fog formation, in the presence of high concentration of smoke, is called smog.

The trouble due to smoke was felt as way back as in the seventeenth century in London. However, after the 1930 Meuse-valley smog, air pollution was recognized as the cause of severe respiratory trouble and death of many people. Smog is usually broken up by the wind and not by the heat from the sun, as most of the sunshine falling on the smog is reflected, and little heat penetrates to evaporate the water. Such a smog is chemically reducing in nature.

The smog formed from the automobile exhaust is quite different in nature. This type of smog appears only on sunny days, lasts for five to seven hours, and is attributed to the following photochemical reaction:



This type of smog was first recognized at Los Angeles in the year 1945 and occurs quite frequently in an irradiative climate such as that of the south western United States. The chemical smog due to the presence of ozone is found to be oxidizing in nature. It is found to be very harmful for field crops, ornamental plants, and trees.

### 18.3 EFFECTS OF AIR POLLUTION

That air pollution has harmful effects on human health is now established beyond doubt. It has been observed that during smoggy days the death rate is far more than on normal clear days. The old and the infants are unable to withstand the ill-effects of air pollution. Its effect is also more pronounced on cigarette smokers. Chronic bronchitis is very much prevalent in the heavily polluted cities of United Kingdom. Chronic cardiopulmonary and asthmatic patients feel poorly when the level of air pollution is high.

An acute pain and irritation of the eyes is a common complaint due to auto-smog. It has been found that the urban communities subjected to the polluted air suffer from acute lower respiratory tract, and lower pulmonary tract diseases, and have reduced resistance to bacterial and viral infections of the lungs. For pulmonary cancer and pulmonary emphysema, air pollution may be one of the major causes. Apart from the few diseases mentioned above, prolonged exposure to even a low

concentration of pollutants has a marked effect on the general health of people and plants. It has now been established that photochemical smog and automobile exhaust are responsible for the destruction of forests, field crops, and other plants as far away as 125 km from Los Angeles.

Table 18.1 indicates the threshold limit values of the various pollutants to which any worker may be repeatedly exposed without any adverse effect.

TABLE 18.1 Common Pollutants and their Limits

Pollutant	Threshold limits	Threshold of smell	Acute danger to life
Ammonia (NH <sub>3</sub> )	p.p.m. 5	mg/m <sup>3</sup> 35	p.p.m. 5
Carbon dioxide (CO <sub>2</sub> )	5,000	9,000	500 p.p.m. 20% by vol.
Carbon monoxide (CO)	50	55	absent 0.3% by vol.
Chlorine (Cl <sub>2</sub> )	1	3	0.02-0.05 900 p.p.m.
Formaldehyde (HCHO)	5	6	— 650 p.p.m.
Hydrochloric acid (HCl)	5	7	— 1,000 p.p.m.
Hydrocyanic acid (HCN)	10	11	2-5 3,000 p.p.m.
Hydrogen fluoride (HF)	3	2	— 700 p.p.m.
Hydrogen sulphide (H <sub>2</sub> S)	10	15	0.1 200 p.p.m.
Lead	—	0.2	—
Nitrogen dioxide (NO <sub>2</sub> )	5	9	1.3 200 p.p.m.
Ozone (O <sub>3</sub> )	0.1	0.2	0.015
Perchloroethylene (CCl <sub>2</sub> :CCl <sub>2</sub> )	100	670	50
Phenol (C <sub>6</sub> H <sub>5</sub> OH)	5	19	0.5
Phosgene (COCl <sub>2</sub> )	0.1	0.4	0.5
Sulphur dioxide (SO <sub>2</sub> )	5	13	3.4 400 p.p.m.
Trichloro-trifluoroethane (CF <sub>3</sub> CO <sub>2</sub> CF <sub>2</sub> Cl)	1,000	7,600	—
Zinc oxide (ZnO)	—	5	—

#### 18.4 POLLUTION FROM COMBUSTION OF FOSSIL FUELS AND ITS CONTROL

Apart from the pollution by combustion products, the increased use of fertilizers, pesticides, and various chemicals is responsible for air pollution.

##### Grit and Dust

There are two major sources of grit and dust:

- (i) Nature, and
  - (ii) industries.
- Along with the flue gases, ash and unburned carbon particles are also emitted, which increase the concentration of grit and dust. The pulver-

rized fuel fired furnaces especially, throw a large quantity of ash in the atmosphere.

The basic control measures are: reduction in the flow velocity of flue gases, flow reversal, placing baffles or obstruction in the passage, and creating a vortex in the flue gases before allowing them to escape into the atmosphere. There are various shapes and sizes of the flue gas passages which enable to trap most of the ash and coal particles. The periodical cleaning of ash collectors is most essential for their satisfactory working. However, a small pressure loss invariably occurs in such ash collectors.

A more efficient method of removing particles from flue gases is the electrostatic precipitator. The dust laden gas passes between the two electrodes, one highly charged and other earthed. A high potential difference of 30 to 70 kV is applied between the electrodes. The particulate matters are charged and attracted by the earthed electrode. The dust collected on the electrode loses its charge and can be removed either by rapping or by irrigation. The temperature of the flue gases, size of the particles, and flow velocity affect the efficiency of such dust collectors. Their initial cost is higher but the pressure loss is low.

Passing the gases through fabric bag filters or through wet washers are the other methods used to remove the dust and other particles, but are less frequently used with the flue gases due to the higher pressure loss and high temperature of the gases.

##### Smoke

Smoke is produced on account of the following reasons: insufficient time for combustion, low temperature in the combustion chamber, insufficient supply of the primary or secondary air, improper mixing of the fuel, poor quality of the fuel, poor design of the combustion chamber or furnace, over loading of the furnace, etc. Smoke is generally taken as a measure of the efficiency of combustion. A slight haze at the top of the chimney indicates good combustion, absence of smoke indicates an excess supply of air, while dark smoke is an indication of incomplete combustion.

Industries, railway engines, and thermal power stations are the major sources of smoke. In cold countries during the winter season, domestic fire used for heating also contributes a lot, specially because the smoke emitted is released at a much lower level.

A properly designed coal burner should produce smoke only during the lighting up period. To reduce the smoke, sometimes oil or gas fired after burners are used, which raise the exhaust gas temperature and burn any organic compounds.

The smoke density from a chimney is measured by comparing the colour of smoke with the shades of gray on a card. The Ringelmann chart or its modified forms are used which give the readings from R<sub>1</sub>

to  $R_4$ . Telesmoke compares the smoke visibility with two translucent glass discs in a telescope corresponding to  $R_2$  and  $R_3$ . Carbosmoke and smokescope also follow the same principle as the telesmoke. Bacharach or the shell smoke meter is a small portable instrument used for oil fired furnaces. A measured quantity of the flue gas is drawn with the help of a hand pump through a filter paper. The stain obtained is matched against a scale of ten circles shaded from 0 (white) to 9 (black). Shade 6 represents the just visible smoke, while 9 is equivalent to  $R_1$ .

### Sulphur Dioxide

Sulphur dioxide is emitted in the atmosphere by geophysical activities, e.g., volcanoes, by some industrial process, such as the smelting of metallic ores containing sulphur compounds, and mainly by the combustion of fuel containing sulphur compounds.

The sulphur dioxide emitted with exhaust gases quickly disperses under normal conditions and is ultimately lost by absorption in vegetation, soil, water, and by chemical reaction, producing  $H_2SO_3$ ,  $H_2SO_4$  and  $(NH_4)_2SO_4$ . Sulphur dioxide is responsible for the fast corrosion rate of metals and other surfaces exposed to the polluted air. The removal of sulphur dioxide from exhaust gases has become possible, but the processes used and tested in the past are quite costly. One way is that before firing the fuel the sulphur is removed. But this is difficult, though it is used in crude oil refining. For solid fuels the sulphur dioxide is removed from the exhaust gases.

At Bankside (oil fired) and Battersea (coal fired) thermal power stations in the United Kingdom, the exhaust gases are water washed, thus absorbing sulphur dioxide. This water is taken from and again discharged into the Thames along with the solution of calcium sulphate to neutralize its effect. Some other methods, e.g., the Howden-I.C.I., Grillo-Ags, and Fulham-Simon processes were also tried. In the above processes, exhaust gases are washed with lime, hydrated oxide compounds between magnesium oxide and manganese dioxide, and ammonium liquor respectively. But all these processes are found to be costly and corrode the equipment. The best solution for the present is to use an alternative source of energy, e.g., hydro-electricity, natural gas, LPG, coal containing less amount of sulphur, etc., in areas where the sulphur dioxide concentration is higher. With concentrations greater than 4 ppm sulphur dioxide gives a pungent smell.

### Carbon Monoxide

Carbon monoxide is produced during the combustion of almost all types of fuels. However, it is not as harmful as other pollutants, because it produces no organic diseases or even residual functional disturbances, though it is an extremely toxic substance.

Carbon monoxide combines with haemoglobin at a greater rate than oxygen to form carboxyhaemoglobin, but dissociates less readily than oxygen. Therefore any person exposed to a higher percentage of carbon monoxide is deprived of oxygen. The rate of formation of carboxyhaemoglobin depends upon the concentration of carbon monoxide in the air and its level in the blood goes on increasing till a particular maximum level is reached. Equilibrium is maintained at this level until death intervenes. The effect of carbon monoxide is more pronounced at higher altitudes and on persons suffering from cardiovascular disease, on smokers, and anaemic persons. The effect is detrimental for persons in a precarious oxygen balance such as cardiopulmonary patients. A concentration producing 20% carboxyhaemoglobin produces headache and other subjective symptoms, but fortunately such a concentration is well above those usually occurring in auto-smog and by smoking.

Though, in general, carbon monoxide is not much harmful at the concentration that is produced in polluted urban areas, it still produces some impairment of vision and psycho-motor performance if a person is exposed to it for a long duration. The carbon monoxide concentration can be reduced by increasing the supply of air, and by proper mixing of fuel and oxidant resulting in more efficient combustion.

### 18.5 POLLUTION FROM AUTOMOBILES AND ITS CONTROL

In a number of cities, automobiles are the major cause of polluted air. Carbon monoxide, various hydrocarbons and oxides of nitrogen are the major pollutants emitted by automobiles which result in photochemical smog. For gasoline engines there are three different types of emissions:

- (i) Evaporative emission,
- (ii) crankcase emission, and
- (iii) exhaust emission.

In diesel engines, the first two types of emissions are almost negligible and only the exhaust emission is important.

#### Evaporative Emission

There is always some loss of fuel through the fuel line in gasoline engines. The primary source of such losses is the fuel tank and the carburetor. While the fuel is added to the tank, an equal volume of gasoline vapour is displaced into the atmosphere. Such a loss is called the filling loss. Tank breathing is another cause of petrol vapour emission. During the day time, when the ambient temperature is increasing, the fuel evaporates to the atmosphere, while during the cooling period the air is sucked into the tank. This is known as the

breathing of the fuel tank. The fuel tank temperature is also increased as warm air passes under the tank while the automobile is running, resulting in the evaporation of some fuel. Mostly lighter hydrocarbons are emitted by the fuel tank. About 5 to 10% of the hydrocarbons released by the vehicles are due to the evaporative loss from the fuel tank in uncontrolled cars.

Similarly, about 5 to 10% of the hydrocarbons out of the total emitted by any uncontrolled automobile are emitted by the carburetor. The carburetor loss increases with the stop and go type of driving. When the engine is turned off, the carburetor bowl is heated by the conduction of heat from the hot engine. This is known as "hot soak". The loss depends upon the volume of bowl, temperature of the engine after it is turned off, type of fuel, etc. During running and long duration parking, the carburetor loss is quite low. The fuel tank and carburetor do not contribute to the emission of carbon monoxide or oxides of nitrogen. The evaporative losses can be reduced by using the pressurized fuel system, or by insulating the fuel tank, thus reducing the temperature fluctuations. In another control system, the vents in the fuel tank and carburetor are sealed and connected to a canister having activated carbon, which absorbs the hydrocarbon vapours emitted during the period when the vehicle is not in use. When the engine is started, a part of the air is sucked through this canister which evaporates the hydrocarbon vapours from the activated carbon. This air-fuel mixture is then burned in the engine.

#### Crankcase Emission

During the compression and power strokes in a gasoline engine, a part of the mixture leaks through the piston rings into the crankcase. This is called "blowby". Blowby consists of 70 to 80% unburned fuel air mixture and 20 to 30% burned products. The amount of blowby depends upon the engine loading. At higher loads the blowby is more and it is a minimum during deceleration and idling. Crankcase emission contributes nearly 20 to 25% of hydrocarbons, 1 to 2% of carbon monoxide, and 1 to 2% of oxides of nitrogen out of the total emission from an uncontrolled vehicle. Blowby also increases with engine wear.

The control of blowby is rather simple and inexpensive. It is controlled by a procedure commonly known as PCV (positive crankcase ventilation). In this system the road draft tube is removed and the gases from the crankcase are introduced into the intake manifold, or the air cleaner or both. Thus the blowby is recycled. All cars manufactured in the United States of America after 1963 are installed with the PCV system. This system can also be installed in old cars.

#### Exhaust Emission

Most of the pollutants emitted by any vehicle come out as exhaust. Exhaust gases also contain the maximum number of pollutants. They contain unburned hydrocarbons, partially burned hydrocarbons, oxides of nitrogen, carbon monoxide, carbon dioxide, water vapour, hydrogen sulphur compounds, lead, particulate matters, etc. Exhaust gases contribute to about 60 to 65% of hydrocarbons, 98 to 99% of carbon monoxide and oxides of nitrogen, of the total emitted by any automobile. The oxides of nitrogen combine with hydrocarbons to form photochemical smog. Radiation from the sun readily dissociates nitrogen dioxide into nitric oxide and atomic oxygen. This reactive oxygen reacts to form ozone and other products notably peroxyacetyl nitrate (PAN), formaldehyde, aerosols, etc.

#### Causes of Exhaust Emission

The major pollutants emitted by the exhaust gases are hydrocarbons, carbon monoxide, and the oxides of nitrogen.

The potential source of exhaust hydrocarbon is partial or complete engine misfire. However, a properly maintained engine does not misfire. Therefore, the other cause of hydrocarbon emission is the wall quenching effect which restricts the flame to burn the fuel air mixture near the wall. The mixture trapped in the combustion chamber crevices such as between the top, piston and the combustion chamber wall is also an important source of exhaust hydrocarbons. A part of the hydrocarbon gases is retained in the cylinder with burned gases, and some gases are burned during exhaust after mixing with the hot exhaust gases. At higher temperatures, some hydrocarbons are found on account of the chemical equilibrium.

The cause of carbon monoxide is obviously the burning of fuel under rich conditions. Carbon is first converted to carbon monoxide and it is then converted to carbon dioxide, provided sufficient oxygen is available. High exhaust temperature also dissociates some carbon dioxide into carbon monoxide. Chemical equilibrium calculations quite accurately predict the concentration of carbon monoxide found in the exhaust under stoichiometric and fuel rich conditions.

About 95% of the total oxides of nitrogen emitted by the engine is in the form of nitric oxide (NO). This is because at very high temperatures during combustion, the nitrogen of the atmosphere reacts with oxygen to form nitric oxide. However, during the expansion stroke and during exhaust, the decomposition of NO is rather slow as compared to the sudden expansion and cooling of the exhaust gases so the concentration of nitric oxide is effectively frozen near its peak level. At low temperature combustion, as in the case of very lean mixtures,

the nitric oxide concentration in the exhaust is quite low and is independent of flame reaction.

**Effect of Control Means on Exhaust Pollutants**

Various means are suggested to control the hydrocarbon, carbon monoxide, and nitric oxide concentrations in the exhaust of any vehicle. Some of them are impracticable because they result in lowering down the efficiency or power output, and some are not economical. The summary of a few design and operating parameters are given in Table 18.2.

TABLE 18.2 Effect of Control Means on Exhaust Pollutants

Control means	Exhaust pollutants		
	CO (Direct)	CO (Indirect)	Hydrocarbon Oxides of nitrogen
Mixture leaning to about 10% lean	↓	—	↘
beyond 10% lean	↓	—	↗
Improved mixture quality	→	↓	↘
Inlet air heating	→	↘	↘
Increased idle speed	→	→	↘
Spark retard	→	→	↘
Reduced compression ratio	→	↗	↘
Reduced chamber S/V	→	→	↘
Increased valve overlap	→	↗	↘

In the above table, two columns are used for carbon monoxide emission. The indirect effect is the carbon monoxide effect due to the change in the practical air/fuel ratio caused by that particular control means. The direction of the arrow shows whether a particular pollutant increases or decreases, vertically downward arrows are used to indicate primary control means.

**Effect of Air/Fuel Mixture**

The effect of air/fuel ratio on the emission of carbon monoxide, hydrocarbon, and oxides of nitrogen are given in Fig. 18.1. The hydrocarbon concentration decreases with an increase in the air/fuel ratio. The carbon monoxide concentration also decreases with an increase in the air/fuel ratio. The concentration of nitrogen oxides first increases rapidly with a maximum value at about 16:1 and again decreases for leaner mixtures. The reduction in the hydrocarbon and carbon monoxide concentrations with leaner mixtures is obviously the result of the better availability of oxygen. The concentration of nitrogen oxides

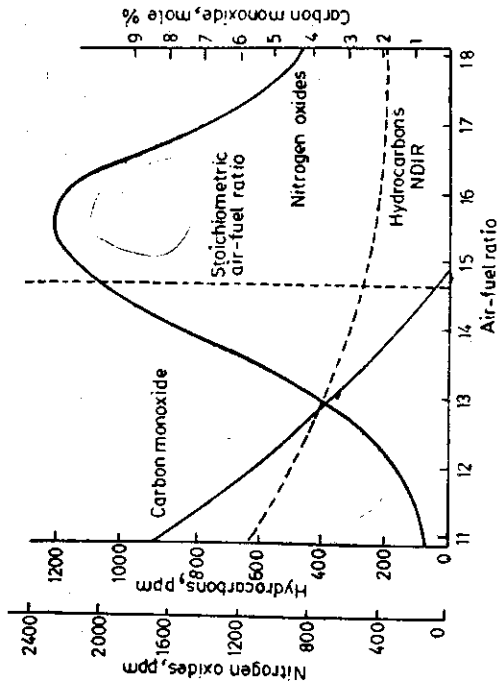


Fig. 18.1 Air-fuel ratio versus hydrocarbons, carbon monoxide and oxides of nitrogen (with permission of John Wiley and Sons, from James N. Pitts Jr. and R.L. Metcalf (Ed.): *Advances in Environmental Science and Technology*, 1971, Vol. II, p. 66).

also depends upon the flame temperature. It can be observed that by providing a slightly lean mixture, though the concentrations of hydrocarbon and carbon monoxide are reduced drastically, the concentration of nitrogen oxides is a maximum. The concentrations of all the three pollutants decreases for still leaner mixtures. However, the operation of present gasoline engines at such lean mixtures is not practicable.

**Improved Mixture Quality**

Proper mixing and vaporization reduces the carbon monoxide concentration slightly near the stoichiometric air/fuel ratio. Similarly the hydrocarbon concentration is also reduced, while the concentration of the oxides of nitrogen increases. The mixture quality can be improved by supplying the mixture through a large vaporization tank instead of the carburetor.

**Inlet Air Heating**

The effect of air heating is the same as of improving the mixture quality, because the heated air helps in vaporizing the fuel properly.

**Spark Retard**

Spark retard is one of the primary techniques for reducing the concentrations of hydrocarbons and oxides of nitrogen. This variable reduces



both the undesirable pollutants. The application of this technique is easy and the magnitude of the effect large. By spark retard, the combustion process is completed later in the expansion stroke, and the effective surface to volume ratio and, therefore, the wall quenching effect are decreased. Secondly, by reducing the time between the combustion and the exhaust, the exhaust temperature is increased and the exhaust reactions are promoted.

#### Surface to Volume Ratio

The surface to volume ratio is one of the most important design variables for the reduction of hydrocarbon emission. As the flame near the wall is quenched, the mixture present in the quenched zone is not burned. The thickness of the quenched zone depends upon the pressure, temperature, mixture ratio, turbulence, and residual gas dilution. The surface to volume ratio at the time when the flame reaches the wall depends upon the number of cylinders, compression ratio, stroke to bore ratio, etc. The surface to volume ratio can be decreased by increasing the displacement per engine cylinder and by increasing the stroke compared with the bore as by decreasing the compression ratio. However, these modifications have a practical limitation. Further modifications result in power loss and reduced efficiency.

#### Compression Ratio

Compression ratio reduction results in the reduced emission of hydrocarbons and oxides of nitrogen, thus its effect is similar to the effect of spark retarding. The reduction in hydrocarbon emission is attributed to the decrease in the surface to volume ratio, increased exhaust system, oxidation due to increased exhaust temperature, and the increase in residual gases. However, as is well-known, the cycle efficiency and power output both decrease with the decrease in the compression ratio.

#### Valve Overlap

At low engine speed and load, high valve overlap causes high dilution of the cylinder charge with inert exhaust residual. This, in turn, lowers the peak combustion temperature and thereby reduces the formation of oxides of nitrogen.

#### Advanced Control Systems

The above mentioned control systems are incapable of meeting the strict and lower emission limits imposed by a few states for car manu-

facturers. Therefore, the following measures are adopted and are under investigation for further reduction in the pollutant concentration.

- (i) Thermal reactors,
- (ii) catalytic exhaust reactors for the oxidation of hydrocarbons and carbon monoxide,
- (iii) catalytic exhaust reactors for the reduction of oxides of nitrogen,
- (iv) exhaust gas recirculation, and
- (v) heterogeneous combustion.

#### Thermal Reactors

The oxidation of unburned hydrocarbons is completed in thermal reactors, which are nothing else but a specially designed exhaust system. This exhaust system retains the heat of exhaust gases, provides better turbulence and more time for the reaction due to increased volume in the exhaust system. The heat is retained through proper insulation and by providing radiation shields. The temperature is also raised by providing a rich mixture so that the exhaust gases contain carbon monoxide which on oxidation in the exhaust system release more heat. The air can be supplied into this reactor with the help of an air pump driven by the engine. Such reactors are known as "rich thermal reactors". In "lean thermal reactors" a lean mixture is supplied to the engine, thus the exhaust itself is oxidizing. But due to the lower temperatures obtained in lean thermal reactors, the reduction in the hydrocarbon emission is less as compared to the rich thermal reactors which also give a lower emission of the oxides of nitrogen and also lower the efficiency.

#### Catalytic Exhaust Reactors

The catalytic exhaust reactors for the oxidation of hydrocarbons and carbon monoxide are frequently called "catalytic mufflers". They contain some catalysts, generally activated platinum, or a platinum group supported on an alumina base. The catalyst eliminates the need of the high temperature required for increased oxidation rates. There are numerous catalysts with different compositions patented in the USA.

#### Reducing Reactors

Reducing reactors are used for the reduction of nitric oxide to elemental nitrogen. This reaction occurs in a reducing atmosphere, i.e., in an exhaust which has a higher concentration of carbon monoxide as compared to that of oxygen. The construction of this type of reactor is similar to the oxidizing reactor. The requirement for separate reducing and oxidizing catalysts leads to the application of dual cata-

lytic reactors for the control of both hydrocarbon and nitric oxide concentrations.

#### Exhaust Gas Recirculation (EGR)

EGR is an effective means of reducing the nitric oxide concentration. The main aim is to reduce the flame temperature by mixture dilution. Water and steam were also tried which resulted in reduced flame temperatures and hence reduced the nitric oxide concentration. But the exhaust gas circulation has the added advantage that it heats the charge and is readily available. It has been found that the nitric oxide concentration can be reduced by about 60%, but the fresh charge contains about 12% exhaust gases. However, it is observed that EGR increases the hydrocarbon emission. EGR can be used in combination with the catalytic reactor which results in the reduction of the emission of all pollutants.

#### Heterogeneous Combustion

Heterogeneous combustion or charge stratification is another means which can be used for reducing emissions. The open chamber system developed by Ford emits lower than normal exhaust emission. Such a combustion system provides better control over the location, timing, and stoichiometry of the combustion process. In another type of heterogeneous combustion, the engine combustion chamber is divided in two parts. A restriction or throat separates the two chambers. In both types of systems, the rich mixture is first burned to reduce the nitric oxide concentration, the carbon monoxide and hydrocarbons are then burned with the remaining air. The fuel can be kept off the wall, thus reducing the quenching effect. However, such a combustion chamber gives higher surface to volume ratio which results in high heat rejection and loss in thermal efficiency.

#### 18.6 EMISSION BY DIESEL ENGINES

Diesel engines are not subjected to as much scrutiny as gasoline engines. There are a few distinct reasons for this. One reason is that the diesel engine powered vehicles are hardly 0.5% in number in the USA, and thus their total contribution is much less as compared to the gasoline engines. The second major reason is that diesel engines are found almost exclusively in large trucks and buses which normally operate on highways; i.e., away from urban areas, where pollution is not as severe. Thirdly, the amount of hydrocarbons and carbon monoxide emitted by the diesel engine is much less in comparison to the gasoline engine. Table 18.3 shows the comparison of emission by uncontrolled gasoline and diesel engine powered vehicles.

It is observed that in the case of diesel engines, the evaporative and crankcase emissions are very low. The evaporative loss is low, because the diesel fuel is not as volatile as gasoline. Also, the fuel supply system is a closed pressurized system where the fuel is supplied into the engine in the liquid state. Crankcase emissions are also very low, because during the compression stroke only the fresh air gets compressed, and, therefore, the blowby contains very little unburned hydrocarbons.

TABLE 18.3 Comparison of Typical Emissions of Hydrocarbons, Carbon Monoxide, and Oxides of Nitrogen from Uncontrolled Gasoline and Diesel-powered Vehicles\* (with permission of John Wiley and Sons, from James N. Pitts Jr. and R.L. Metcalf (Ed.): *Advances in Environmental Science and Technology*, 1971, 11: 70)

Source	Gasoline-powered automobiles	Diesel-powered vehicles
<i>Exhaust</i>		
Hydrocarbons,** ppm	500-1200	200-500
Carbon monoxide, %	2.5-4.5	0.1-0.3
Oxides of nitrogen, ppm	300-2000	2000-3000
<i>Crankcase</i>		
Hydrocarbons, g/day	~100	Very low†
<i>Fuel tank and carburetor</i>		
Hydrocarbons, g/day	~80	Very low‡

\*From the California State Department of Public Health, and the Air Resources Board.

\*\*As measured by nondispersive infrared analyzer (NDIR) and expressed as hexane.

†Expressed as nitrogen dioxide.

‡Probably less than 10% of that from gasoline engines.

However, the oxides of nitrogen emitted with the exhaust are much higher in a diesel engine as compared to a gasoline engine. The main reasons are the higher compression ratio, leaner mixtures, and higher flame temperatures. The hydrocarbon and carbon monoxide concentrations emitted by a diesel engine are very low, the main reason being that the diesel engine operates with lean mixtures. This promotes a more efficient combustion of the fuel.

Diesel engines exhaust smoke and odours which normally are not associated with gasoline automobiles. Smoke results from overfueling, which can be controlled by proper maintenance.

#### 18.7 EMISSION STANDARDS

Lately, emission standard requirements in many states of the USA have increasingly become more stringent every year. The stan-

dards are different for various types of vehicles. Present-day standards in the Federal Government and California State require that there should be no emission from the crankcase of a light duty gasoline vehicle, while the evaporative loss of hydrocarbons should be less than 6 g/test. Table 18.4 shows the exhaust emission standards that were required to be met in previous years. The requirements were continuously made more stringent as research indicated the technical feasibility of such goals to be achieved. Table 18.4 indicates the emission by an uncontrolled vehicle.

TABLE 18.4 Exhaust Emission Standards for Light Duty Vehicles (with permission of John Wiley and Sons from James N. Pitts Jr. and K.L. Metcalf (Ed.): *Advances in Environmental Science and Technology*, 1971, II: 77)

Uncontrolled emissions, g/mile	Exhaust emission standards		Remarks
	Model	Year	
1970	HC	2.2	Federal and California
	CO	23	Federal and California
1971	HC	2.2	Federal and California
	CO	23	Federal and California
1972	NO <sub>x</sub>	4.0	California
	HC	1.5	California
1974	NO <sub>x</sub>	3.0	California
	HC	1.5	California
1975	NO <sub>x</sub>	2.3	Federal and California
	CO	12	California
NO <sub>x</sub> <sup>†</sup> 5.7	CO	1.0	California

\*HC—Hydrocarbons, as measured by nondispersive infrared analyzer (NDIR)

\*\*CO—Carbon monoxide

†NO<sub>x</sub>—Oxides of nitrogen, expressed as nitrogen dioxide

The requirements for a heavy duty diesel vehicle are not too difficult to achieve. Federal government requirements limit the smoke from 1970 model diesel engines to an opacity that should not exceed 40% during acceleration and 20% during the engine lagging mode. The hydrocarbon and carbon monoxide concentrations emitted by a diesel vehicle are usually within the standards prescribed for heavy duty vehicles. The 1972 standard requirements in California State for a heavy duty vehicle, limits the hydrocarbon emission to 180 ppm while the carbon monoxide limit is 1.0%. The concentration of carbon monoxide in a diesel engine exhaust is usually 0.1 to 0.3%.

# APPENDICES

# APPENDIX A

TABLE A.1 Coal, Reserves and Production

Country	Date	Reserves (Million tonnes)		Production (Thousand tonnes)		
		Measured	Inferred		Average 1964-68	1972
World Total	...	...	...	6641200	1988300	2144800
Afghanistan	1965	...	...	85	139	...
Algeria	1957	9	11	20	31	...
Argentina	1966	374	76	450	390	675
Australia	1965-67	3000	13000	16000	30252	49056
Austria	1966	...	3	3	39	...
Belgium	1964-67	495	1301	1796	17966	10500
Botswana	1961	506	...	...	...	...
Brazil	1966	3175	7500	10675	2154	2497
Bulgaria	1965	1147	...	1147	512	384
Burma	1960	13	8	21	13	16
Canada	1966	42600	18400	61000	8267	15810
Chile	1966	96	122	218	1490	1332
China	1913	...	...	1011000	288000	400000
Colombia	...	...	...	12500	2954	2800
Czechoslovakia	1966	5540	6033	11573	26886	27925
France	1966	...	...	2800	48850	29763
German Dem. Rep.	1956	...	...	50	1981	815
Germany, Fed. Rep. of	1967	70000	...	...	125784	102707
Greenland	1967	2	...	...	27	4
Hungary	1966	...	...	714	4228	3671
India	1966	12710	93550	106260	67322	74771
Indonesia	1962	500	345	845	308	179
Iran	1961	...	...	1000	286	1000
Ireland	1967	22	26	48	196	82
Italy	...	...	...	...	410	151
Japan	1961	5723	13525	19248	49172	28098
Korea, Dem. People's Rep. of	...	...	...	...	15720	...
Korea, Rep. of	1962	85	1100	1185	10832	12403
Madagascar	1963	60	...	...	2	...
Mexico	1966	182	3284	3466	1293	2170
Mongolia	...	...	...	...	54	106
Morocco	1960	15	81	96	441	547
Mozambique	1963	...	...	700	275	336
Netherlands	1956	2394	...	2394	9541	2812
New Zealand	1967	297	533	830	637	418

(Contd)