9

Diesel Electric Power Plant

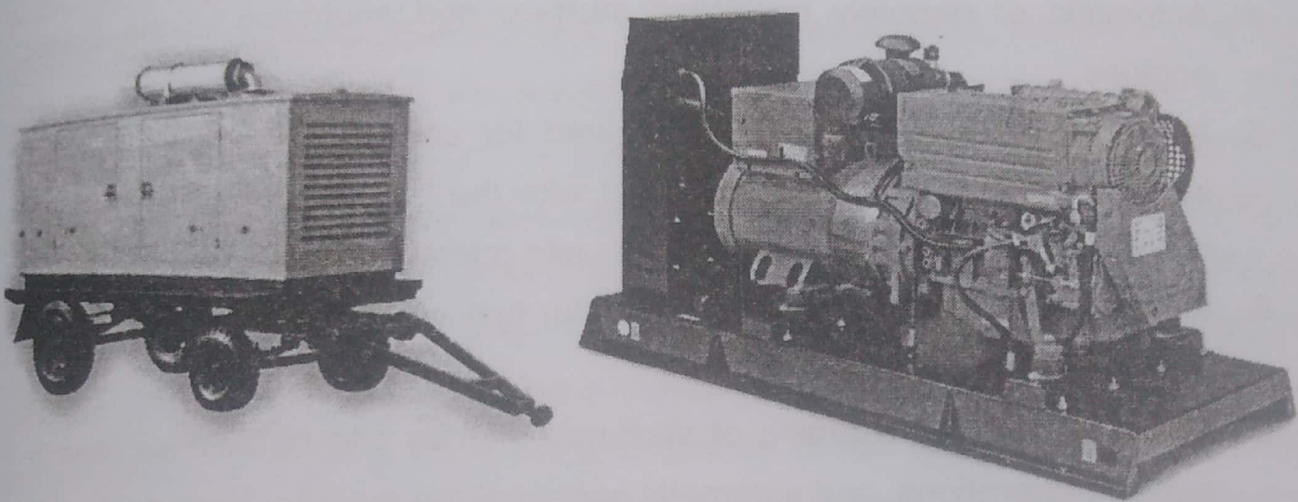
9.1. Overview

Since the invention of Diesel engine at the end of the 19th century, has found increasing applications either as continuous or as a peak source of electric power generation due to its excellent qualities in respect of operation. Diesel electric plants in the range of 2 to 50 MW capacities are used as central stations for small supply companies and are universally adapted to supplement hydroelectric and thermal electric power stations where stand-by generating plants are essential for starting from cold and under emergency conditions. In many countries, the demand for Diesel electric plants has increased in recent years for electric power generation because of difficulties experienced in construction of new electric power plants and extension of old electric power generating plants. A long-term planning is required for the development of thermal and hydroelectric plants which cannot keep pace with the increased load demand. The Diesel engine driven generators used for electric power generation are more reliable and long-lasting compared with other types of plants.

With the rapid development of electric generation from other sources made Diesel plants to disappear from field as their generation cost was considerably high. However, Diesel plants are more efficient than any other engine driven generators of comparable size. Its capital cost is less. It can be started and brought into the service quickly. It can burn a fairly wide range of Diesel fuels. Its manufacturing periods are short and, therefore, a Diesel station may be rapidly extended to keep pace with load growth by adding generating units of suitable sizes. With such a formidable list of merits to its credit, it does not monopolies the power production market because, there are hurdles in the way of adopting these units for power generation. Other power plants (both conventional and renewable) are in good competition due to high cost of Diesel fuel. The Diesel electric power plant will provide the most economic means of generating electricity on small scale particularly where there is no convenient site for micro-hydro plants and fuel is cheaply available and load factor of load centers are considerably high.

9.2. Diesel Power Plants

Diesel power plant finds most applications as both base load and peak load plants and is used extensively as emergency plants. Most electrical installation equipped with one or several electric generators driven by Diesel engines. Diesel power plants are divided into two main classes: mobile and stationary (photographs shown in figure 9.1). Mobile Diesel plants mounted on trailers can be used for temporary or emergency electrical supply to large undergoing projects for supplementing electricity supply systems that are temporarily short of power. Commercial mobile Diesel electric power plants can range from 1 kW to a few hundreds kilowatts employing 2-stroke for low power ratings and 4-stroke Diesel engines for large power ratings. Presently there are mobile Diesel electric power plants available commercially that can produce power to a few megawatts, however, they are less common. Stationary Diesel electric power plants mostly use 4-stroke diesel engines, with power ratings of 110, 220, 330, 440, and 735 kW. Stationary Diesel power plants are classed as average in their power rating if the rating does not exceed 750 kW; large Diesel power plants can have a power rating of 2200 kW or more. The advantages are favorable economy of operation, stable operating characteristics, and an easy and quick start-up. The main disadvantage is the comparatively short interval between major overhauls. Diesel power plants are used mainly for servicing areas remote from transmission lines or areas where sources of water supply are limited and where the construction of a steam power plant or of a hydroelectric power plant is not feasible.



(a) (b)

Figure 9.1: Diesel Electric Plants (a) Mobile (b) Stationary

The economic efficiency of a Diesel power plant is improved considerably if the waste heat of the engine (55–60% of total heat release in currently available engines) can be used for preheating of fuel and oil or for domestic heating within the power station building or adjacent premises. In Diesel power plants with a high power rating (above 750 kW) the waste heat can be used in a heating system serving a whole block or a whole township in proximity to the power station.

Three basic levels of automatic protection; against exceeding maximum or minimum limits for the temperature of cooling water and oil, the oil pressure, and the rotational speed (rpm) is built into all commercial mobile and stationary Diesel power plants. Protection is also provided in the event of a short circuit in the line. For most stationary Diesel power plant producing electric power on a larger scale, the following automatic protection systems are incorporated:

1. Automatic regulation of the rotational speed (rpm).
2. Temperature of the cooling water and oil.
3. Automatic emergency signaling and protection in the event of a breakdown.
4. Automatic or remotely controlled start-up and shutdown of the Diesel engines.
5. Automatic check of conditions required for connecting load to the line, synchronization with other units and with the power system, and a load connection and load distribution with units operating in parallel.
6. Automatic refilling of the feeder tanks for fuel, oil, and water and of the air feed vessels.
7. Automatic (trickle) charging of start-up batteries and of batteries used in auxiliary operations, and automatic control of the auxiliary equipment.

9.3. Field of Use and Applications

Diesel electric power plants play a very important role in electric power generation. The main fields of use of Diesel electric power plants are as follows:

Peak-load Plant: The Diesel plants are used in coordination with thermal or hydroelectric plants as peak load plants. Diesel electric plant is particularly preferred as peak load plant since it can be started quickly and has no standby losses as in the case of thermal plants where boilers must always be kept at elevated temperature.

Mobile Plants: The first mobile Diesel power plants were built in 1934 in the former Soviet Union and were known as Diesel trains. Such Diesel trains have all the power plant equipment installed on platforms or in trailers. The power ratings of the presently used Diesel trains are typically 1, 2.5, 4.5, and 10 MW. Automated mobile Diesel power plants with a power rating up to 10 kW are often mounted on a single-axle truck trailer. Power plants rated 20 kW or more are usually installed on two-axle, covered trailers. A mobile Diesel power plant includes the Diesel-electric unit itself, spare parts, instruments and accessories, a set of cables for making connections to the load, and fire-fighting equipment. Such mobile plants comprises not only the Diesel-electric unit but also the power distribution cabinet (or panel), a cabinet containing the automatic controls, the remote control console, heating and ventilation equipment, rectifiers, and the storage batteries that feed the automatic controls or automated systems. The electric part of the power plant of a mobile Diesel electric plant consists of a synchronous generator delivering power at a voltage of few kilovolts, assembled or unitized compartments containing high-voltage leads (overhead leads or cables), distribution equipment for voltages of 230–400 volts (required for lighting and for auxiliary motors of the power plant), the storage battery, and operating power circuits and the battery charger. Mobile Diesel power plants are widely used in agriculture and forestry and by expeditionary involved in geological exploration. In these applications, Diesel power plants can be used as a source of electricity for energy or lighting networks; they can be used as the main, auxiliary, or standby power source.

Emergency and Stand-by Units: Diesel electric plants are widely used for emergency purposes or as standby units, since they can pick load quickly. Diesel electric plants can be used to supply part load when required. For example, it can be used with hydroelectric plant as stand-by unit if sufficient water is not available due to less rainfall. Such plants are normally idle but are used in the event of power interruption, which would mean financial loss or danger in key industrial processes, tunnel lighting and operating rooms of hospitals and other sensitive areas.

Nursery Station: Nursery stations are referred to thóse stations which can be moved from one location to other for supplying electrical power. Since main grid cannot extend to every corner of the country till there is enough load. At times the extension of grid may not be possible due to constructional difficulties. Diesel nursery stations of small capacity can be installed to supply the load to a small town during the process of development and it can be removed to another required place till the main grid for tapping the power is made available.

Central Stations: Diesel electric plants can be used as central station where demands are of small (5 to 10 MW). However, the limit is generally decided by the cost of the plant and local conditions regarding the availability of fuel and water, space requirements and non-availability of the grid. Such supply units are commonly used in practice for commercial purposes and public utilities, for example; hospitals, shopping arcades, municipalities and strategic installations. Central stations are mostly installed in holiday resorts, especially those located in remote areas or hill stations, where supply from utility company is uneconomical due to long transmission lines or constructional difficulties.

Starting Stations: Small and medium Diesel electric plants are used to run the auxiliaries for starting the large steam power plants.

9.4. Classification of Diesel Engines

The Diesel engines are generally classified as 4-stroke engines and 2-stroke engines. The 4-stroke engine develops power after every two revolutions of crank shaft whereas 2-stroke engine develops power with each revolution of crank shaft. Generally, 2-stroke engines are favored for small Diesel power plants and 4-stroke engines are preferred for medium and large plants. The selection is, however, decided according to the merits and demerits. For comparing the merits and demerits of 2-stroke engines and 4-stroke engines of the same size and speed, their advantages and disadvantages are de... below:

Advantages

1. Theoretically, a 2-stroke engine develops twice the power of 4-stroke engine at the same speed. The actual power developed is 1.7 to 1.8 times of the power developed by 4-stroke engines. This is because; some of the power is used for compressing the air in crank case and effective compression stroke is less than 4-stroke engine for the same stroke.
2. The 2-stroke engine is much lighter and more compact, and occupies less floor area for the same power developed.
3. The turning moment of 2-stroke engine is more uniform than 4-stroke engines. This ability of the engine reduces the size of the flywheel required. This further requires lighter foundations and reduces the installation cost to a greater extent.
4. It provides mechanical simplicity and, therefore, gives higher mechanical efficiency.
5. The starting of 2-stroke engines is much easier than 4-stroke engine.
6. The capital cost of the plant with 4-stroke engines is considerably less.

Disadvantages

1. The thermodynamic efficiency of 2-stroke engine is less than 4-stroke as the effective compression ratio is less than the 4-stroke engine of the same dimensions.
2. The cooling of the engine presents difficulty as the quantity of heat removed per minute is large. Oil cooling of the piston is necessary as there is possibility of overheating the piston due to firing in each revolution.

3. The scavenging is not complete particularly in high speed engines (above 1000 rpm) and hence the fresh charge is highly contaminated, which reduces the thermal efficiency of the engines.
4. The lubricating oil consumption is more as the operating temperatures are higher.

Diesel engines can also be categorized on the basis of speed factor k_s, which is given by:

$$k_s = \frac{nv}{3048000} \qquad 9.1$$

Where n is the rotational speed in revolutions per minute measured at the crank shaft and v is the linear speed in centimeters per minute of the piston inside the cylinder. The speed factor categorizes the engine according to its rotational speed. If the speed factor is less than 1.2, the engine is classified as low speed, between 1.2 and 3.5, it is categorized as medium speed and for speed factor greater than 3.5, it is classified as a high speed engine.

9.5. The Thermodynamic Cycle of Diesel Engine

Diesel engine works on the thermodynamic cycle known as the Diesel cycle. The Diesel cycle consists of two reversible adiabatic processes, one constant pressure line and one constant volume line as shown in the pV diagram of figure 9.2. In order to obtain the expression for efficiency of this cycle, the cylinder is assumed to contain air as the working substance.

Assuming that heat is supplied by placing a hot body in contact with the end of the cylinder and heat is rejected by placing a cold body in contact with the cylinder. During the two adiabatic processes there will be no heat transfer. Supposing that the cylinder is full of air; the condition of this air is represented by point (3) on the pV diagram. Assume that the pressure at this point be p_3 and the volume V_3 and the absolute temperature T_3. The air is compressed adiabatically to point (4) by the piston during its inward stroke. The air therefore occupies the clearance volume of the cylinder. Heat is then supplied to the air during the constant pressure expansion represented by process (4) – (1). At point (1) the air supply is stopped; this point is then referred to as the cut-off point. The air is then allowed to expand adiabatically to point (2), which thus occupies the whole volume of the cylinder. The cold body is then applied to the cylinder and heat is abstracted at constant volume until the pressure falls to the point (3). This completes the cycle.

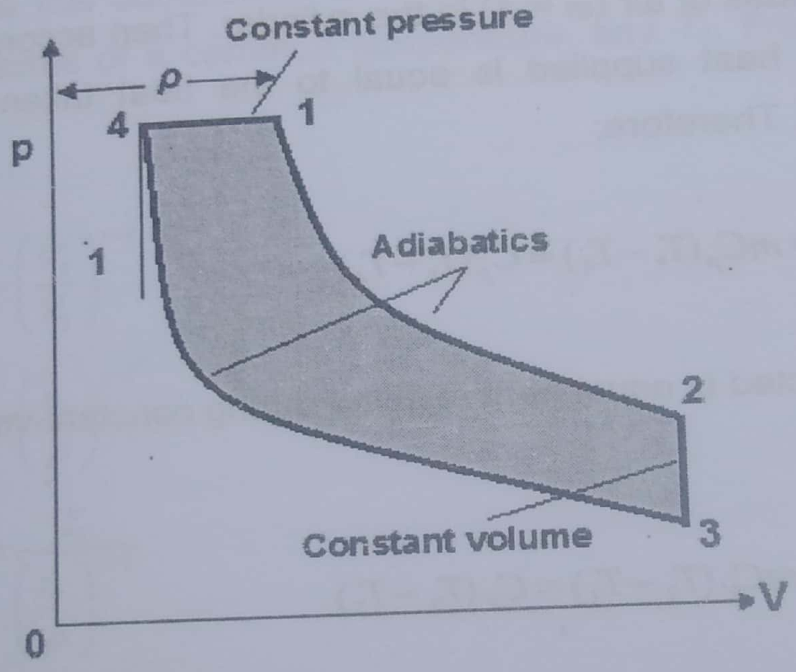


Figure 9.2: pV Diagram of Diesel Cycle

It should be noted that this cycle cannot be regarded as reversible unless a graduated system of heating and cooling is assumed during the constant-pressure and constant-volume operations, which does not occur in practice. Let us assume that:

p_1, V_1, T_1 = pressure, volume and temperature at (1)

p_2, V_2, T_2 = conditions at (2)

p_3, V_3 and T_3 = conditions at (3)

ρ = Volume at cut-off

r_v = Compression ratio, which for most Diesel engines is from 15 to 20 but can be as high as 23.5. Also let the clearance volume be unity. Then:

$V_4 = 1$, $V_1 = \rho$ and $V_2 = V_3 = r_v$

Compression ratio: $$\frac{V_3}{V_4} = r_V \qquad 9.2$$

Expansion ratio: $$\frac{V_2}{V_1} = \frac{r_V}{\rho} \qquad 9.3$$

Cut-off point ratio: $$\frac{V_1}{V_4} = \rho \qquad 9.4$$

Consider a unit mass of air ($m = 1$) in the cylinder. Then according to the laws of thermodynamics, heat supplied is equal to the heat taken during constant pressure (4) – (1). Therefore:

$$Q_S = mC_p(T_1 - T_4) = C_p(T_1 - T_4) \qquad 9.5$$

Similarly heat rejected is equal heat rejected during constant-volume process; (2) – (3). Therefore:

$$Q_R = mC_V(T_2 - T_3) = C_V(T_2 - T_3) \qquad 9.6$$

Therefore: Work done = Heat supplied – Heat rejected

$$W = Q_S - Q_R$$

Or
$$W = C_p(T_1 - T_4) - C_V(T_2 - T_3) \qquad 9.7$$

Thermal efficiency is given by the ratio of work done to the heat supplied, therefore:

$$\eta = \frac{W}{Q} = \frac{C_p(T_1 - T_4) - C_V(T_2 - T_3)}{C_p(T_1 - T_4)} \qquad 9.8$$

$$\eta = 1 - \left(\frac{C_V}{C_p}\right)\frac{(T_2 - T_3)}{(T_1 - T_4)}$$

Since the ratio of C_p to C_V is equal to γ, then:

$$\eta = 1 - \left(\frac{1}{\gamma}\right)\frac{(T_2 - T_3)}{(T_1 - T_4)} \qquad 9.9$$

In order to reduce this equation to its final form it is necessary to express all temperatures in terms of a common temperature, say T_1. From adiabatic (1) – (2), we have:

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{\gamma-1} \qquad 9.10$$

Or $$\frac{T_1}{T_2} = \left(\frac{r_V}{\rho}\right)^{\gamma-1}$$

Or $$T_2 = \frac{T_1}{\left(\frac{r_V}{\rho}\right)^{\gamma-1}} \qquad 9.11$$

In a similar fashion from adiabatic (3) – (4), we have:

$$T_3 = \frac{T_4}{(r_V)^{\gamma-1}} \qquad 9.12$$

From constant-pressure line (4) – (1)

$$\frac{p_4V_4}{T_4} = \frac{p_1V_1}{T_1}$$

Since $p_4 = p_1$, then:

$$\frac{T_4}{T_1} = \frac{V_4}{V_1} = \frac{1}{\rho}$$

Or $$T_4 = \frac{T_1}{\rho} \quad 9.13$$

Substituting T_4 from equation 9.13 in equation 9.12, we have:

$$T_3 = \frac{T_1}{\rho (r_V)^{\gamma-1}} \quad 9.14$$

Substituting equations 9.11, 9.13 and 9.14 in equation 9.9 for T_2, T_4 and T_3 respectively, we obtain the air standard efficiency of a Diesel cycle as:

$$\eta = 1 - \frac{1}{\gamma}\left(\frac{\dfrac{T_1 \rho^{\gamma-1}}{r_V{}^{\gamma-1}} - \dfrac{T_1}{\rho r_V{}^{\gamma-1}}}{T_1 - \dfrac{T_1}{\rho}}\right)$$

Or $$\eta = 1 - \frac{r_V{}^{\gamma-1}}{\gamma}\left(\frac{\dfrac{\rho^{\gamma}}{\rho} - \dfrac{1}{\rho}}{1 - \dfrac{1}{\rho}}\right)$$

Or $$\eta = 1 - \frac{r_V{}^{1-\gamma}}{\gamma}\left(\frac{\rho^{\gamma} - 1}{\rho - 1}\right) \quad 9.15$$

Example 9.1: Determine the efficiency of a Diesel engine working on an idealized Diesel cycle with a compression ratio of 16 and cut-off taking place at 6% of the stroke. Assume that the ratio of specific heat at constant pressure to specific heat at constant volume is 1.4.

Given that:

$r_v = 16$

$\gamma = \left(\dfrac{C_p}{C_v}\right) = 1.4$

Let the clearance volume be unity, then the total cylinder volume is: 1 x r_v = 16. Then from figure 9.2 the swept volume is therefore: 16 – 1 = 15. Volume of 6% of stroke is therefore: $\frac{6}{100}\times 15 = 0.9$. Then the volume to the cut-off point 0.9 plus the clearance volume (which is unity) is:

$$\rho = 1 + 0.9 = 1.9$$

Therefore using:

$$\eta = 1 - \frac{r_V^{\;1-\gamma}}{\gamma}\left(\frac{\rho^{\gamma}-1}{\rho-1}\right)$$

Or

$$\eta = 1 - \frac{(16)^{1-1.4}}{1.4}\left(\frac{1.9^{1.4}-1}{1.9-1}\right)$$

Or

$$\eta = 1 - 0.38 = \mathbf{0.62\ or\ 62\%}$$

It must be noted that the efficiency of Diesel cycle depends on the value of r_V and ρ. The efficiency increases with the former and decreases with the latter. In practice the values of r_v and ρ are fixed by operating considerations. The Diesel cycle is also called the constant-pressure cycle, because the heat is supplied at constant pressure. Diesel power plants produce energy though the combustion of chemical fuel, in most cases Diesel derived from petroleum, into mechanical energy. This energy is then used to power an alternator which in turn generates electricity. Diesel is preferred to other fuel types as these engines have a higher thermal efficiency than other commercial generators of equivalent size.

To calculate thermal efficiency of a Diesel engine, the heat input from the combustion of fuel must be known. If heat produced by w kg of oil of calorific value CV or higher heating value (HHV) in Kcal, then the heat produce Q will be:

$$Q = w \times CV = w \times HHV$$

This heat Q is the heat input to the system. The thermal efficiency can be calculated by dividing the horsepower (HP) of the engine in equivalent heat units by the heat input to the engine from combustion of fuel. The heat equivalent of 1kWh is 860 Kcal. Then the overall power plant efficiency is:

$$\eta_{thermal} = \left(\frac{HP(kWh) \times 860}{Q}\right) \times 100 \qquad 9.16$$

The engine horsepower can be determined by knowing the work done by the piston of area A moving through a displacement L (also called length of stroke) in a cylinder and compressing the working fluid at a mean effective pressure p_m. Then the force F exerted by the piston on the working fluid is:

$$F = p_m A$$

The work done by the piton in a to-and-fro movement along the stroke length L which constitutes the total displacement of the piston of $2L$, is then:

$$W = F \times 2L = p_m A \times (2L)$$

The movement of the piston along the stroke length $2L$ (2-stroke) transforms the linear motion into rotational motion at the crank shaft. If n is the rotational speed in revolutions per minute of the flywheel attached to the crank shaft, then the work done per minute at the crank shaft will be:

$$W = 2 p_m LAn$$

In the to-and-fro movement of the piston, the piston compresses the working fluid in one movement along the stroke length, referred to as the compression stroke, in which case the piston does the work. On expansion of working fluid, the piston is pushed away and the working fluid does work on the piston, referred to as the power stroke. The result is a 2-stroke operation, and the work done on the piston is then: $p_m LAn$. The metric horsepower, which is equal to 4500 kgf-m of the work done per minute, is then:

$$HP = \frac{p_m LAn}{4500} \qquad 9.17$$

For a 4-stroke engine, there are four movements along the stroke length in which case only one is the power stroke, the horse power is then:

$$HP = \frac{p_m LAn}{2 \times 4500} = \frac{p_m LAn}{9000} \qquad 9.18$$

Example 9.2: A 4-stroke single cylinder Diesel engine is to be used for domestic electric power generation. The Diesel engine has a piston diameter (bore) of 17 cm and a stroke of 27 cm. The compression ratio is 15.5, the cut-off 4.4% of stroke, and the mean effective pressure of 5 bars. The engine speed is 300 rpm and the fuel consumption is 1.45 kg of oil per hour, having a calorific value of 10635 kcal per kg. Calculate the thermal efficiency of the engine and the electrical power that can be produced if the electrical efficiency is 90%. Compare the thermal efficiency with the standard efficiency of the thermodynamic cycle, assuming that the ratio of specific heat at constant pressure to specific heat at constant volume is 1.4.

Given that:

Piston diameter: D = 17cm

Length of stroke: L = 27cm = 0.27m

Compression ratio: r_v = 15.5

Mean effective pressure: p_m = 5 bars or 5 kg/cm^2 (approximately)

HHV or calorific value = 10635 kcal per kg

Fuel consumption: w = 1.45 kg of oil per hour

Area of piston or cylinder bore: $A = \frac{\pi D^2}{4} = \frac{3.14 \times (17)^2}{4} = 226.86 \text{ cm}^2$

The metric horsepower HP of a 4-stroke engine is given by:

$$HP = \frac{p_m ALn}{2 \times 4500}$$

Therefore: $HP = \frac{5 \times 226.86 \times 0.27 \times 300}{2 \times 4500}$ = 10.2 hp (metric)

Thermal efficiency is given by:

$$\eta_{thermal} = \frac{HP(kWh) \times 860}{Q}$$

Converting 10.2 metric HP into kW; that is: 10.2 x 0.735 = 7.5 kW. This is the mechanical power output P_{mech} from the Diesel engine in terms of kW. Therefore using the above expression, the thermal efficiency is:

$$\eta_{thermal} = \frac{7.5 \times 860}{1.45 \times 10635} = \mathbf{0.418 \text{ or } 41.8\%}$$

The air standard efficiency of the thermodynamic cycle of a Diesel engine (Diesel cycle) is evaluated as follows: The compression ratio is 15.5, so that the swept volume is 15.5 – 1 = 14.5. Volume of 4.4% of stroke is, $\frac{4.4}{100} \times 14.5 = 0.638$. Then the volume to the cut-off point 0.638 plus the clearance volume (which is unity) is: $\rho = 1 + 0.638 = 1.638$

Therefore using:

$$\eta = 1 - \frac{r_V^{\,1-\gamma}}{\gamma}\left(\frac{\rho^{\gamma} - 1}{\rho - 1}\right)$$

Or

$$\eta = 1 - \frac{(15.5)^{1-1.4}}{1.4}\left(\frac{1.638^{1.4} - 1}{1.638 - 1}\right)$$

Or

$$\eta = 1 - 0.372 = \mathbf{0.627 \text{ or } 62.7\%}$$

The thermal efficiency is always less than the air standard efficiency of the Diesel cycle. Since the electrical efficiency of the generator is 90%, therefore the electrical power output will be:

$$P = \eta_{electrical} \times P_{mech} = 0.9 \times 7.5 = \mathbf{6.75\ kW}$$

The engine rotational speed is 300 rpm, which has to be increased through a gearbox to a value suitable to drive commercially available generators.

9.6. Components of Diesel Power Plant

The various components of a Diesel electric power plant are shown schematically in figure 9.3. The detail description of the major components and their working is discussed in the following sub-sections.

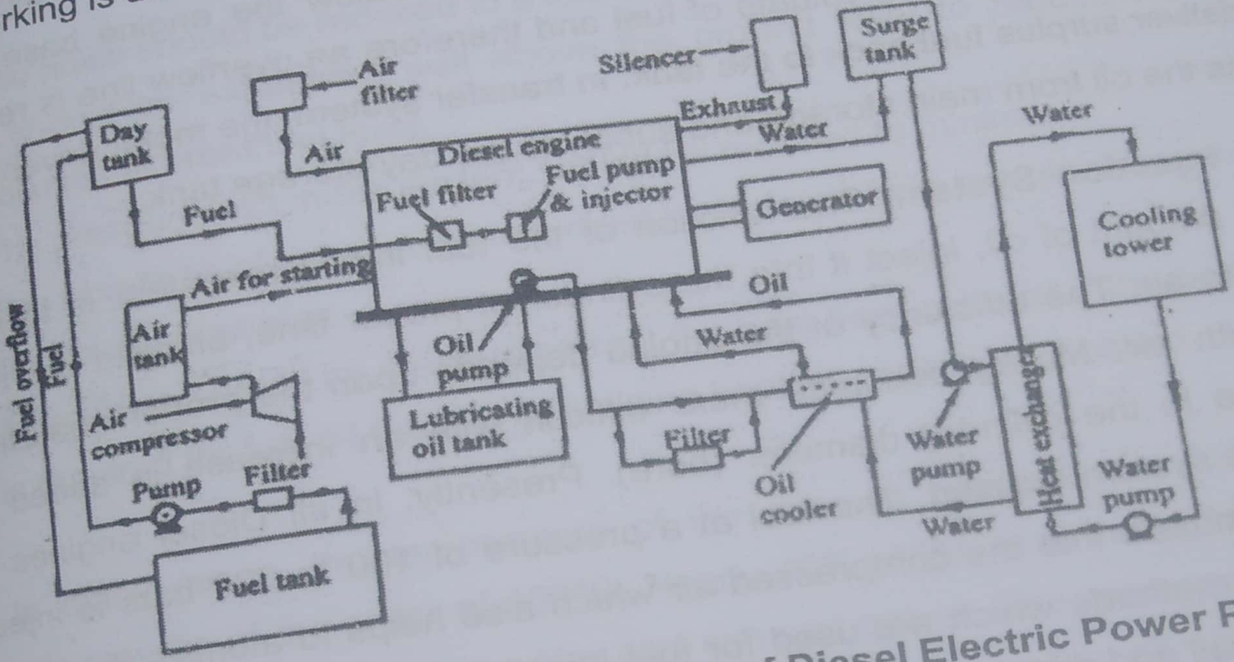


Figure 9.3: Schematic of Components of Diesel Electric Power Plant

Fuel Storage and Fuel Supply System: It consists of a main storage tank, strainers, fuel transfer pump and all-day fuel tank. The fuel oil is supplied at the plant site by rail or road. The oil is stored in the main storage tank. From the main storage tank, oil is pumped to all-day tank at short intervals. The fuel storage an supply arrangement generally depend on size of plant and type of engine use The location of storage tank above ground or below ground depends upon lo conditions. The over-ground tanks have the advantages of detecting the l easily, low maintenance and easy cleaning. On the other hand, undergro tanks have the advantage of reduced fire hazards. If heating is required, the generally done in the storage tank by passing the hot jacket water through dipped in the storage tank. The heating requirement depends upon the c conditions and viscosity of the fuel used. The oil from day-storage tan under gravity to the engine pump. From all-day tank, fuel oil is passed

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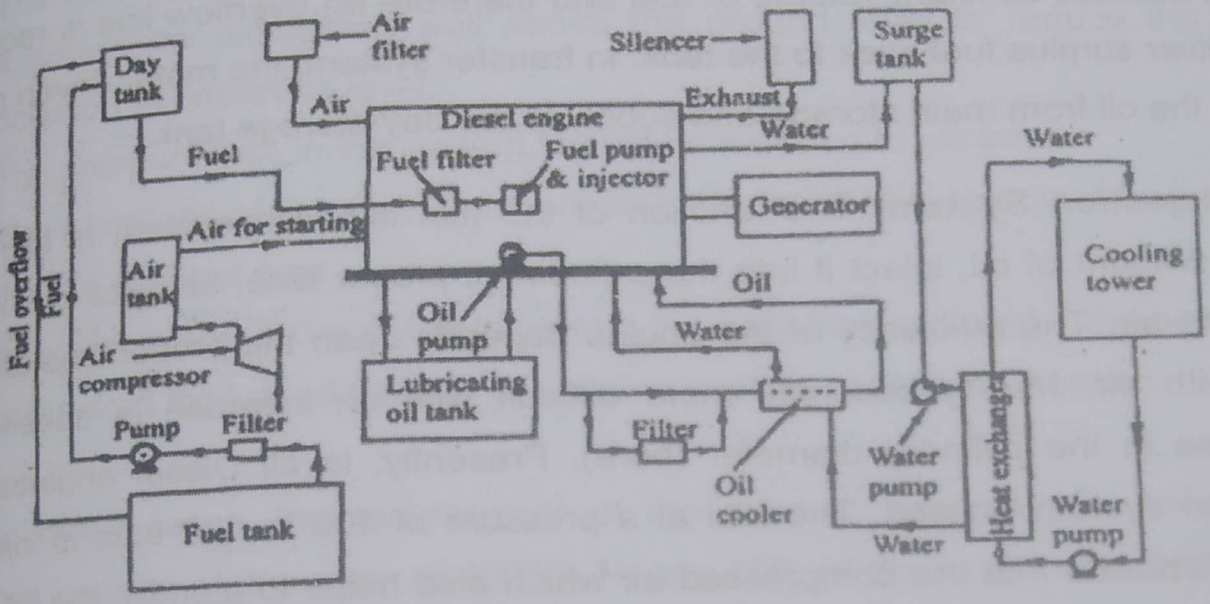

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Fuel Injection System: The function of the fuel injection system is to meter small amount of oil, inject it into the cylinder at proper time, atomize and mix it with the air. The efficiency of the engine depends upon the proportionalizing of fuel with air. Mixing becomes more difficult with an increase in speed and increase in the cylinder diameter (bore). Presently, in all Diesel engines fuel injection system is used. The fuel at a pressure of 100 to 200 bars is injected through nozzle into the compressed air which also helps to atomize the oil. The common methods which are used for fuel injection system are individual pump, common rail and distributor system.

Air-supply System: This system supplies necessary air to the engine for fuel combustion. It consists of pipes for the supply of fresh air to the engine manifold and filters to remove dust particles from air. A large Diesel engine power plant requires considerable amount of air at 4 to 8 m^3/kWh. The air contains lot of dust and, therefore, it is necessary to remove this dust from air before entering into the cylinder which may act as abrasive and would cause excessive wear in the engine cylinder. An air-supply system of a Diesel power plant incorporates filter with an intake. The filters used may be oil-impingement, oil-bath or drag type depending upon the type and concentrations of dust in the air. In cold weather, the ambient air temperature may reach significantly low level that it causes misfiring at low loads on the plant. In order to avoid this, the air intake system needs heating, the necessary heating of air is provided by using the heat from the exhaust gases.

Exhaust System: This system leads the engine exhaust gas outside the building and discharge it into atmosphere. A silencer is usually incorporated in the system to reduce the noise level. The following points should be taken into consideration for the design of exhaust system of a big power plant.

1. The noise should be reduced to a tolerable degree.
2. It should be exhausted well above the ground level to reduce the air pollution at breathing level.
3. The pressure loss in the system should be reduced to minimum.
4. The vibrations of exhaust system must be isolated from the plant by use of flexible exhaust pipe.
5. A provision should be made to extract the heat from exhaust if the heating is required for fuel oil heating or building heating or process heating.

In many cases, the temperature of the exhaust gases under full load conditions may be of the order of 400°C. Nearly 40% of the heat in the fuel can be recovered from the hot jacket water and exhaust gases. The recovered heat from hot jacket water and exhaust gases can be used for heating oil which can increase the thermal efficiency to 80%. The heat from the exhaust can also be used for space heating of buildings and generating steam at low pressure which can be used for process heating. It is estimated that 2 kg of steam at 8 bar pressure can be generated per kW per hour, when the mass of exhaust gases can be taken as 10 kg/kWh.

Water Cooling System: The heat released by the burning of fuel in the engine cylinder is partially converted into work. The remainder part of the heat passes through the cylinder wall, piston, rings etc. and may cause damage to engine. According to general heat balance sheet of a Diesel engine, about 30% of the heat is lost to the cooling water. This, however, is necessary to maintain the temperatures of the piston, cylinder and other parts within the permissible range. If the engines are not properly cooled, the temperature existing inside engines would disintegrate the film of lubricating oil on the liners and 'wrapping' of valves and pistons takes place. In order to keep the temperature of the engine parts within the safe operating limits, adequate cooling is provided. The exit temperature of the cooling water must therefore be controlled. If it is too low, lubricating oil will not spread properly and wearing of piston and cylinder takes place. If it is too high, the lubricating oil burns and carbonizes thus depositing excessive carbon in the engine. The maximum exit temperature of the water is usually limited to 70°C. Constant cooling water flow rate rises the exit water temperature with the increase in load or vice versa when inlet water temperature is constant. A control on the flow of cooling water is therefore necessary according to the load conditions on the plant. It is thus essential to determine the weight of water required by knowing the inlet and outlet temperatures of the water, and the heat transferred to the water after it has absorbed heat from the cylinder walls. The maximum allowable difference between the inlet and outlet temperatures of cooling water is normally recommended to be 11^0C. As mentioned earlier, about 30% of the heat is lost to the cooling water. This 30% of heat in each kilogram of fuel multiplied by the consumption of fuel in kilograms per hour at that load plus the heat to be removed to a certain extent (about 10%) from the exhaust gases and lubricating oil. This is the heat Q_T which should be transferred to cooling water is given by:

$$Q_T = w_T (T_{inlet} - T_{outlet}) \qquad 9.19$$

The methods of circulation of water in the cooling system are generally divided into a single circuit cooling system and double circuit cooling system. The single circuit cooling system may be subjected to corrosion in the cylinder jackets because of the dissolved gases in the cooling water. The double circuit cooling system largely eliminates internal jacket corrosion. The maximum water outlet temperatures allowed are 49^0C for a single circuit cooling system and 60^0C for double circuit cooling systems. The cooling system consists of a water source, pump and cooling towers. The amount of heat determines the capacity of the pump required to circulate the water. The pump circulated water through cylinder and head jacket. The water takes away heat form the engine and itself becomes hot. The hot water is cooled by cooling towers and re-circulated for cooling in case of limited supply of water. Water must also be treated for hardness. Hard water will cause deposits at temperature of about 50°C. In addition, hard water will produce scale and continuous deposits of scale with time will constrict the pipes and reduce the heat transfer rate thus overheating the engine. Therefore, it is necessary to soften the water before entering into the system and to prevent the growth of algae which may reduce the heat transfer due to fouling. The cooling water is treated with 3 ppm Calgon™ to control the scaling in the different parts of the system and it is also chlorinated once per shift up to 6 ppm to prevent algae growth which would cause the rapid tube fouling. For inhibiting corrosion, 300 ppm of sodium chromate is also added. Generally, the quantity of cooling, water required is 35–60 liters per kW per hour.

Example 9.3: The installed capacity of a Diesel electric power plant is 400 kW with an annual plant capacity factor of 55%. Calculate the volume of cooling water per hour required for a power plant with fuel consumption of 1 kg for each 2.3 kWh generated. Assume that the calorific value of fuel is 10635 kcal per kg.

Given that:

Plant capacity factor: F_C = 55% or 0.55

Station capacity: P_C = 400 kW

The energy produced is calculated by using equation 4.6:

$$F_C = \frac{E_g}{P_C \times T}$$

Or

$$E_g = 0.55 \times 400 \times 8760 = 1927200 \text{ kWh}$$

Annual fuel consumption is therefore:

$$\frac{1927200}{2.3} = 837913.04 \text{ kg}$$

Fuel consumption per hour:

$$\frac{837913.04}{8760} = 95.65 \text{ kg}$$

The heat transferred to the cooling water is 30% of the heat input to the engine which is:

$$Q_T = 10635 \times 95.65 \times 0.3 = 305171.32 \text{ kcal per hour}$$

Using:

$$Q_T = w_T (T_{inlet} - T_{outlet})$$

Or

$$w_T = \frac{305171.32}{11} = 27742.84 \text{ kg per hour}$$

Knowing the density of water (1000 kg/m^3), the volume of water required per hour is:

$$\frac{2774284}{1000} = \mathbf{27.74\ m^3 / hour}$$

Lubrication System: Lubrication minimizes the wear of rubbing surfaces of the engine. The role played by the lubrication system in Diesel power plant is more important than any other plant because of very high pressures and small clearance in these engines. Main parts of a Diesel engine to be lubricated are crankshaft, wrist pin bearings, bearings and all other moving parts. The lubrication of piston and cylinder is little different as special lubricant is required for this purpose as the lubricant has to operate under conditions of high pressure and temperature. The life of the engine, the overall efficiency of the plant and possible continuous service of the plant are dependent on the effectiveness of the lubrication system. The forced-feed lubrication system is generally used to lubricate all the necessary parts of the engine. The general equipment which is used in lubrication system are; pump, oil cleaners, oil coolers, storage, sump tanks and safety devices. The lubrication oil is drawn from the lubricating oil tank by the pump and is passed through filter to remove impurities. The clean lubrication oil is delivered to the points which require lubrication. The oil coolers incorporated in the system keep the temperature of the oil low.

The friction losses of the engine will appear as the heating of the lubricating oil during its circulation through the engine. Generally, 2.5% of the fuel heat is given to the lubricating oil and it is necessary to remove this heat for proper functioning of the lubricant. This heat nearly amounts to 300 kJ/kWh. The lubricant oil is cooled in an oil cooler before supplying to the engine. The cooling is done through pump by using the water from the cooling tower.

Another important function of the lubrication system is to remove the impurities in the form of carbon particles, water and metal scrap carried by the oil during circulation. For this purpose, filters, centrifuges or chemical cleaning plants are used. The mechanical types of filters used are cloth bags, wood pads, paper pads and porous material pads. Many times, the oil from the engine is filtered by passing through the metal screen strainers and ultimate cleaning is accomplished by passing the oil through centrifugal cleaner. This is necessary in high capacity plant as the quantity of lubricating oil circulated per hour is very large for larger plants. The oil should be heated before passing through the cleaning system. This is necessary to increase the fluidity of the oil. Lubricating oil consumption depends on the design of Diesel engine. Typical oil consumption values for engines manufactured in 1970s were 0.46 gm/kWh. Those manufactured in the 1980s ranged between 0.33 to 0.48 gm/kWh. This figure has been improved and presently, modern Diesel engines require an average of about 0.08-0.22 gms/kWh of lubricating oil. The cost of the lubricating oil in the Diesel plant is thus considerable compared with other plants and as a rough estimation, the consumption is nearly 3 liters per 1000 kWh generated at full load conditions. Thus the lubricating oil consumption is nearly 1% of the fuel oil consumption.

Well refined mineral oil specially treated is required for Diesel engines. Engine lubricants consist of base oil (typically 75-83%), viscosity modifier (5-8%) and an additive package (12-18%) **[Boschert 2002]**. As the base oil alone cannot provide all of the lubricating oil functions required in modern engines, the additive package has evolved to play an increasingly important role in the oil formulation The American Petroleum Institute (API) classifies base stocks for engine lubricants are given in Table 9.1.

Table 9,1: API Base Oil Stock Classification (Source: DieselNet)

Group	Saturates		Sulphur		Viscosity Index	
	Min	Max	Min	Max	Min	Max
I	-	90%	0.03%	-	80	120
II	90%	-	-	0.03%	80	120
III	90%	-	-	0.03%	120	-

Starting System: This is an arrangement to rotate the engine initially, while starting, until firing starts and the unit runs with its own power. It is difficult to start even smallest Diesel engine by hand cranking as the compression pressures are extremely high. Starting methods are either electrical (used for small plants) or mechanical (used for large plants). In electrical method, a starter motor, which a DC series motor, powered by batteries, is used to crank the engine to the desired speed to start the 'running' process. Once the engine start running, the motor is disconnected from the battery by automatic means. In mechanical method generally, compressed air system or auxiliary gasoline engines are used for starting purposes. Compressed air system is commonly used in large Diesel power plants. During normal working of the plant, the power from the main shaft is used to drive the compressor which accumulates air into the accumulators. Once the accumulators indicate the rated pressure, the compressors are automatically disconnected from the power shaft. Mechanical method of starting system uses valve arrangement to admit pressurized air at about 20 bars into the cylinders, making them to act as 'reciprocating motors' to turn the engine shaft. Admitting fuel oil to the remaining engine cylinder helps the engine to start under its own power. For automatic starting system, the ordinary air starting equipment are arranged to open in the correct sequence and close when the engine starts running. The automatic starting system is also used to prime the lubricating oil system and to start the automatic flow of the cooling water.

Governing System: The governing system provides flexible control of the engine to match variations in load so that the speed is maintained almost constant at all loads. The governing of Diesel engine is performed by varying the quantity of fuel supplied to the engine. This is generally accomplished by using a method of constant stroke with variable suction or variable bypass to control and adjust the quantity fuel oil supply with changes in load. Most commonly centrifugal type governor is used to control the suction or bypass of the fuel.

9.7. Specifications and Selection of Alternator

The first step in installation of a Diesel electric generation system is to know the load demand of the given area or a building for which the generation system is to be installed. Once the load demand is known, the next step is to select generator(s) from the range of generators/alternators available commercially. It must be noted that the rotational speed of the commercially available alternators is an important criteria besides its power rating. The rotational speed n_S (synchronous speed in revolutions per second) is decided by the power frequency f and the number of poles p, which is given by the well-known expression:

$$n_S = \frac{2f}{p}$$

The rotational speed of the Diesel engine must match the synchronous speed of the alternator to provide output power at power frequency. In case the rotational speed of the Diesel engine does not match the synchronous speed of the alternator, a system of gears has to be incorporated at the expense of mechanical losses. The main specifications of the alternator are determined from the output equation of a three-phase alternator given as:

$$S = 3V_{ph}I_{ph} \ Volt\text{-}amp$$

$$S = 3 \times 10^{-3} V_{ph} I_{ph} \; kVA$$

Or

9.19

Where V_{ph} and I_{ph} are the phase voltage and phase current respectively. The expression for the phase current is given as:

$$I_{ph} = \frac{\pi d a_C}{6N} \qquad 9.20$$

Where d is the diameter of the stator and a_C are the number of ampere conductors per unit length of the stator periphery, which is generally taken as 300 to 430 per centimeters of the stator periphery. The phase voltage of an alternator is given by an expression:

$$V_{ph} = 4.44 k_d k_C f N \phi \; Volts \qquad 9.21$$

Where k_d and k_C are the distribution or breadth factor and coil span or pitch factor respectively, f is the frequency in Hz, N are the number of series turns per phase and ϕ is the flux per pole in Webers (Wb) and is given by:

$$\phi = B k_p l \qquad 9.22$$

Where B is the flux density in the air gap and is usually considered between 5.4×10^{-5} and 7.0×10^{-5} Wb/cm^2 k_p is the pole pitch and is: $\left(\frac{\pi d}{p}\right)$ and l is the effective length. Equation 9.22 can be expressed as:

$$\phi = B\left(\frac{\pi d}{p}\right) \times l \qquad 9.23$$

Substituting equation 9.23 in equation 9.21 and $f = \frac{n_S p}{2}$, we have:

$$V_{ph} = 4.44 k_d k_C \times \left(\frac{n_S p}{2}\right) \times NB \times \left(\frac{\pi d}{p}\right) \times l \qquad 9.24$$

Substituting equation 9.20 and 9.24 in the output equation 9.19, we obtain:

$$S = 3 \times 10^{-3} \left[4.44 k_d k_C \left(\frac{n_S p}{2}\right) NB \left(\frac{\pi d}{p}\right) \times l\right] \times \left(\frac{\pi d a_C}{6N}\right)$$

The product; $k_d k_C = 0.95$. Simplifying and re-arranging we have:

$$S = 10.44 \times 10^{-3} (a_C B n_S d^2 l)\ kVA \qquad 9.25$$

It must be remembered that the term $d^2 l$ in equation 9.25,is important and must be considered with the rotational speed. Alternators with rotating speed greater than or 1500 rpm, the diameter must be smaller at the expense of length to maintain $d^2 l$ constant. On the other hand alternators with low rpm, the diameter must be larger at the expense of length in order to accommodate greater number of poles for obtaining the required power frequency at low speeds.

9.8. Specifications of Diesel Engine

Once the choice and selection of alternator has been decided, the next step is to select a suitable Diesel engine. For small domestic power generation system, 2-stroke engines are generally used, for most medium and large-scale power generation schemes, 4-stroke Diesel engines are used. The main specification is the power rating of the engine in horsepower units (converted to kW), which must be higher than that of the alternator, depending on the electrical, mechanical and thermal efficiency of the system to account for losses.

The power rating of the engine is determined from bore (D) and length of stroke (L) of the engine cylinder and the number of cylinders. To mark an upper limit on the length of stroke and bore, it is essential that the maximum power output from a single cylinder must not exceed 75 kW. Thus the number of cylinders must be chosen in accordance with the total rating of the engine. This will determine the size of the engine. Since the rating of the engine is given in terms of the horsepower, equation 9.18 can be expressed in terms of the bore and stroke. Thus for a 4-stroke engine the metric horsepower from equation 9.18 are:

$$HP = \frac{p_m(\pi D^2/4)Ln}{2\times 4500}$$

$$HP = \frac{0.785 p_m D^2 Ln}{2\times 4500} \qquad 9.26$$

In equation 9.26, p_m is the mean effective pressure in kg/cm^2, which depends on the type of Diesel engine. Typical values of p_m are given in table 9.1. Equation 9.26 can also be expressed in terms of the ratio L/D, known as the stroke-to-bore ratio and is designated by k_b. The stroke to bore ratio for compression-ignition (Diesel engine) is usually taken between 1.2 and 1.4 and that for internal-combustion (petrol or gas engine) is taken between 0.9 and 1.3. Multiplying and dividing the right hand side of equation 9.26 by 100 so that ($L \times$ 100) in the numerator would mean length in centimeters and expressing in terms of stroke-to-bore ratio, equation 9.26 can be written on simplification as:

$$HP = 8.72\times 10^{-7}\, p_m D^3 k_b n \qquad 9.27$$

Equation 9.27 can be expressed in terms of mechanical power developed by engine cylinder P_{mech} in kW. Since 1 metric horsepower is equal to 0.735 kW, then:

$$P_{mech} = 6.41\times 10^{-7}\, p_m D^3 k_b n \text{ kW} \qquad 9.28$$

From which:

$$D = 110\left(\frac{P_{mech}}{p_m k_b n}\right)^{1/3} \quad 9.29$$

Table 9.1: Compression and Mean Effective Pressures

Engine Type	Compression pressure	Mean effective pressure
Air injection	32 to 35 kg/cm^2	5.25 to 6 kg/cm^2
Solid injection (low speed)	28 to 32 kg/cm^2	5.25 to 6.5 kg/cm^2
Solid injection (high speed)	32 to 46 kg/cm^2	5.5 to 7.5 kg/cm^2

Similarly for a 2-stroke engine, following the same procedure through equation 9.17, the bore (D) can be calculated by using:

$$D = 88\left(\frac{P_{mech}}{p_m k_b n}\right)^{1/3} \quad 9.30$$

Once the bore is determined, the length of the stroke can be obtained from knowing the stroke-to-bore ratio. Most engines for use with electrical generators, gasoline or Diesel, are designed to run continuously at about 70–80% of their maximum output. The manufacturer usually supplies a figure of specific fuel consumption (SFC) at certain specified load. A rough estimate is that a Diesel engine consumes about 1 gallon (4.45 liters) per hour for every 18 HP generated. Thus a 27 HP engine running at two-thirds capacity will generate 18 HP. Another way to calculate the amount of Diesel fuel used in 1 hour is to multiply the horsepower being used by 0.055. However, all outboard engines use more fuel than inboard engines per hour. Furthermore, 2-stroke engines consume more fuel than 4-stroke engine of the same rating. Individual fuel-consumption figures must be arrived at by careful measurement of fuel used over a measured time. It is fairly safe to assume, however, that older engines will consume 10–50% more fuel than newer engines of the same horsepower. Newer fuel-injected engines show a considerable improvement in fuel-consumption figures.

Example 9.4: Calculate the fuel consumption in liters per hour of a 20 kW Diesel generator set having a specific fuel consumption of 232 gm/kWh at 75% continuous rating.

Given that:

SFC = 232 gms/kWh at 75% load

Diesel generator set rating = 20 kW

Therefore continuous loading of the generator set is: 20 x 0.75 = 15 kW. The fuel consumption is therefore:

$$15 \times 232 = 3480 \text{ gms/h or } 3.48 \text{ kg/h}$$

The density of Diesel fuel is 0.832 kg per liter. Therefore Fuel consumption in liters per hour is:

$$\frac{3.48}{0.832} = \textbf{4.18 liters per hour.}$$

If a constant stroke-to-bore ratio is assumed, it follows that the value of mean effective pressure that can be tolerated will decrease with an increase in cylinder bore. Therefore, the cylinders of larger bore result in bulkier, heavier and costlier engines for a given output. There is also an upper limit to the number of cylinders to an engine. It follows that the engines of large capacity must have large bore cylinders. This is one of the reasons for rise in capital cost of the Diesel plant above 2.5 MW capacities. The lower cost requirements always favor the alternators with the minimum number of poles and that the maximum speed to be achieved is 3000 rpm or 3600 rpm. Therefore, increase in rotational speed is another way of packing more power into an engine. The dynamic forces on the engine increase proportional to the product of piston stroke and rotational speed. Therefore, the permissible operating speed decreases with an increase in engine size due to the limit set by the physical properties of the material available. Presently 500 rpm is regarded as an acceptable speed for base load generation.

The acceptable speeds are increased to 750 rpm and are further expected to increase to 1000 rpm in future as the research is directed to find out the materials to bear such heavy stresses. The operating speed increases with an increase in number of cylinders.

Example 9.5: The maximum load demand (including losses in distribution system) is estimated to be 550 kW with a load factor of 65%. It is desired to install a Diesel electric power station to meet the annual energy needs of the resort. The resort is completely closed for 60 days in a year. Work out the capacity and main dimensions of a Diesel engine and the alternator if the electrical efficiency is 92% and the thermal efficiency of 43%. If the calorific value of the Diesel fuel used is 10,635 kcal/kg and density is 0.83 kg/liter, estimate the fuel consumption and annual cost of fuel if the Diesel fuel cost Rs 100 per liter. Determine the plant capacity factor and cost of electrical energy if the capital cost on the generation scheme is Rs 10 million depreciated at 10% and the estimated annual operating and maintenance cost (excluding fuel cost) is Rs 2000 per kW of the installed capacity.

Given that:

Maximum load demand = 550 kW

Load factor: F_{LD} = 65% or 0.65

Electrical efficiency: η_{elect} = 92% or 0.92

Thermal efficiency: $\eta_{thermal}$ = 43% or 0.43

Calorific value (HHV): = 10,635 kcal/kg

Density of diesel fuel: = 0.83 kg/liter

Cost of fuel: = Rs 100 per liter

For a load demand of 550 kW (including losses) the generator set of rating 600 kW is chosen to account for any near future increase in demand and unforeseen acute emergencies. It is advisable to install two generator sets each of 300 kW rating. Let us consider a 16 pole, 50Hz generator, running at 375 rpm (6.25 rps). Considering a power factor of 0.8 lagging, the kVA rating of the generator will be:

$$S = \frac{300}{0.8} = \mathbf{375\ kVA}$$

The specifications of the alternator in terms of its main dimensions are worked out by using:

$$S = 10.44\times10^{-3}(a_C B n_S d^2 l)$$

Considering the flux density of 6.5 x 10^{-5} Wb/cm^2 and the number of ampere-conductors of 350, we have:

$$375 = 10.44\times10^{-3}(350\times6.5\times10^{-5}\times6.25\times d^2 l)$$

From which: $d^2 l = 2.5\times10^5$

Since d and l are in centimeters and since the generator is 16 poles rotating at 375 rpm, the length must be smaller than the diameter. The diameter can be calculated by using:

$$l = \frac{\pi d}{p} = \frac{3.14d}{16} = 0.196d$$

Therefore: $d^2(0.196d) = 2.5\times10^5$

Or $d^3 = 1.27\times10^6$

From which: $d =$ **103.33 cm**

The length of the stator is then:

$$l = 0.196(103.33) = \mathbf{20.27\ cm}$$

The Diesel engine will be a 4-stroke with rating a little higher than the generator. Since the load factor of the resort is 65% and it is advisable that the engine must run at 75% of full load continuously, the load factor of 65% would satisfy the continuous operating criteria. The rating of the engine will be calculated by knowing the electrical efficiency. Given that the electrical efficiency of 92%, the input required for the generator, which is to be supplied by the diesel engine will be:

$$P_{mech} = \frac{300}{0.92} = 326 \text{ kW or } 350 \text{ kW (rounded)}$$

Since the maximum power limit for each cylinder is 75 kW, therefore 350/75 = 4.66, a standard 6 cylinder engine is selected, with each cylinder rated at 350/6 = 58.33 kW, which seems reasonable. The specifications of the Diesel engine in terms of its main dimensions are worked out as follows:

Using:

$$D = 110\left(\frac{P_{mech}}{p_m k_b n}\right)^{1/3}$$

Considering a mean effective pressure of 6 kg/cm², the bore or cylinder diameter is calculated as:

$$D = 110 \times \left(\frac{58.33}{6 \times 1.4 \times 375}\right)^{1/3} = \mathbf{29.5\ cm}$$

The length of stroke L can be obtained from the stroke-to-bore ratio that is:

$$L = k_b \times D = 1.4 \times 27 = \mathbf{41.3\ cm}$$

The resort has to be closed for 60 days in a year. For a load factor of 65% and maximum demand of 550 kW, the annual energy generation will be:

$$E_g = F_{LD} \times P_m \times T = 0.65 \times 550 \times 7320 = \mathbf{2616900\ kWh}$$

The mechanical power in kW can be converted into equivalent heat in kcal by multiplying kW with 860 (1 kWh = 860 kcal or 1 kW = 860 kcal/h), which will give us the heat output per hour Q_0. Since the engine will be operating continuously at 75% of its maximum power capacity and is fuel injection type (with metered fuel), the 75% rating of 350 kW, which is 262 kW or 265 kW (rounded up) will be used in calculating the fuel consumption and annual cost of fuel. Given the thermal efficiency of the engine 43%, the heat input to the engine will be:

$$Q = \frac{Q_0}{\eta_{thermal}} = \frac{265 \times 860}{0.43} = 530000 \text{ kcal per hour}$$

Therefore the weight of Diesel oil used will be:

$$w = \frac{Q_{in}}{HHV} = \frac{530000}{10635} = 49.83 \text{ kg per hour}$$

Knowing the density of Diesel fuel, the fuel consumption per hour (say x) is:

$$x = \frac{w}{density} = \frac{49.83}{0.83} = $$ **60 liters per hour per engine**

Therefore cost of fuel will be: 100×60 = Rs 6000 per hour. Since the resort will be closed for 60 days in a year during which the plant will lie idle. The annual cost of fuel (ACF) for both the engines will be:

$$ACF = 2 \times 6000 \times (365-60) \times 24 = \textbf{Rs. 8,78,40,000}$$

Knowing the installed capacity P_C = 700 kW and the annual energy to be required, the plant capacity factor can be obtained by using equation 4.6:

$$F_C = \frac{E_g}{P_C \times T} = \frac{2616900}{700 \times 8760} = \textbf{0.426 or 42.6\%}$$

The cost of electrical energy is worked out as follows: The capital cost, one crore = Rs 10^7 when depreciated by 10% is Rs 10^6, which is the fixed part of the total cost. The operating and maintenance cost is estimated to be Rs 2000 of the installed capacity, which is: 2000 x 700 = 1400000. The total cost C_T will therefore be the sum of fixed part, the operation and maintenance cost and the cost of fuel, which will be:

$$C_T = 1000000 + 1400000 + 87840000 = \text{Rs } 90240000$$

Cost of electricity (y) will be:

$$y = \frac{C_T}{E_g} = \frac{90240000}{2616900} = \textbf{Rs 34.5 per kWh}$$

The high cost of electricity is due to the high cost of fuel. In practice comparison must be made between either buying electricity from utility company or if other options of producing electrical energy at cheaper rates are available. Much better option would be a hybrid system incorporating Diesel generation with solar or wind and utility grid.

9.9. Supercharging of Diesel Engines

It is a well-known fact that as the altitude above sea level increases, the atmospheric pressure reduces. A rough estimation is that for each 300 meters altitude, the pressure drops by 4%. The pressure p at an altitude h meters above sea level is given by:

$$p = p_0 \exp\left(-\frac{gMh}{RT_0}\right) \qquad 9.31$$

Where:

p_0 = Atmospheric pressure at sea level (101325 bars)

T_0 = Sea level standard temperature (288.15^{0}K)

g = Acceleration due to gravity (9.81 m^2 / s)

M = Molar mass of dry air (0.0289 kg / mol)

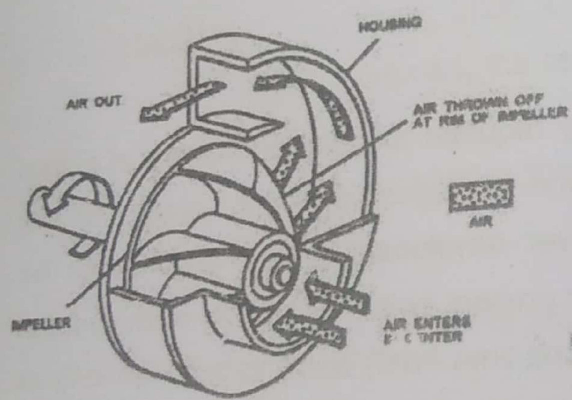
R = Universal gas constant (8.314 J / mol ^{0}K)

By substituting the known values of quantities, equation 9.31 can be expressed more concisely as:

$$p = p_0 \exp(-0.000118h) \qquad 9.32$$

An air-fuel ratio of 25:1 is usually required for the combustion of Diesel fuels. The power developed in the engine is proportional to the weight of fuel burnt in unit time. Therefore, the power developed by the engine can be increased by increasing the weight of air present in the cylinder at each cycle or by increasing the number of cycles per unit time (rpm) or using both. So long as the necessary amount of air can be provided in an engine cylinder of given size, theoretically there is no limit to the weight of fuel burnt in unit time and hence to the power which can be developed. To get more air-fuel mixture into the engine cylinder, an equipment called supercharger is used that can boosts engine power, sometimes up to 40%. It has been called a supercharger because it delivers a 'super' charge of air-fuel mixture to the engine. The working is illustrated in figure 9.3(a) and a photograph of a typical supercharger is shown in figure 9.3(b).

Supercharging is a process which helps to increase the suction pressure of the engine above atmospheric pressure. It must be remembered that the power output of the engine increases with an increase in the amount of air in the cylinder at the beginning of compression stroke because it allows more quantity of fuel to be burnt. Supercharging of Diesel engine is especially used when the power plant is located at an altitude above sea level because of low pressure and deficiency of oxygen. Supercharger consists of compressor of one, two or three stages, having intercoolers between stages. The compressor rotor has wheel with blades, much like the impeller of a centrifugal pump. When it rotates, it moves air by centrifugal force. The air between the rotor blades is pushed outward and through the outlet port of the supercharger. The air exits at relatively high pressure. The power to the supercharger is usually derived from the engine crank shaft through gears. The advantages of supercharged engines are listed in the following sub-sections:



(a)

(b)

Figure 9.3: Supercharger (a) Illustration (b) Photograph

Power Increase: By supercharging the engine, the engine output can be increased by 30-50% at the same engine speed.

Fuel Economy: The combustion in supercharged engine is better as it provides better mixing of the air and fuel than un-supercharged engine. The specific fuel consumption of a supercharged engine is therefore less than natural aspirated engine.

Efficiency: Both thermal and mechanical efficiency of a supercharged engine is better than natural aspirated engine at the same speed. This is because, the power increase due to supercharging increases faster than the rate of increase in friction losses.

Scavenging: The scavenging action is better in 2-stroke supercharged engines than naturally aspirated engines because the quantity of residual gases is reduced with the increase in supercharged pressure.

Knocking: Supercharge reduces the possibility of knocking in Diesel engines because the ignition delay period is reduced with an increased pressure resulting in smoother running of the engine. It has been found that 4-stroke engines are more easily adaptable to supercharging than 2-stroke engines. Due to number of advantages of supercharging mentioned above, modern Diesel engines used in Diesel electric plants are generally supercharged. By supercharging, the size of the engine is reduced for given output and consequently the space requirements and civil engineering works also. The superchargers which are considered for Diesel power plants are positive displacement type, centrifugal type and exhaust turbocharger. The selection depends upon its relative merits for a particular situation.

Example 9.6: Repeat example 9.5 for the specifications of Diesel engine and its fuel consumption if the same resort is to be located in a hill station at an altitude of 3000 meters above sea level.

Since the engine is to be operated at 3000 meters above sea level, this will require engine with higher than normal rating. The rating can be estimated if air pressure at 3000 meter altitude is known. Using equation 9.32, we have:

$$p = p_0 \exp(-0.000118h)$$

Or $$p = 101325\exp(-0.000118 \times 3000) = 70692.05 \text{ bars}$$

The pressure at 3000 meters altitude is therefore: $\frac{7069205}{101325} \times 100 \approx 70\%$ of the pressure at sea level. The engine capacity must be increased by (100 – 70) = 30% of that at sea level for 3000 meters altitude. Based on 30% pressure reduction, the rating of the engine will be: $350 \times 0.30 + 350 \approx 455$ kW. Since the maximum power limit for each cylinder is 75 kW, therefore 455/75 ≈ 6. A standard 6 cylinder engine (V-8 configuration) is selected, with each cylinder rated at 455/6 = 75.8 kW, which means the engine will be rated up to its maximum per cylinder. The specifications of the Diesel engine in terms of its main dimensions are worked out as follows:

Using: $$D = 110\left(\frac{P_{mech}}{p_m k_b n}\right)^{1/3}$$

Considering a mean effective pressure of 6 kg/cm^2, the bore is calculated as:

$$D = 110 \times \left(\frac{75.8}{6 \times 1.4 \times 375}\right)^{1/3} = \mathbf{32.12\ cm}$$

The length of stroke L can be obtained from the stroke to bore ratio that is:

$$L = k_b \times D = 1.4 \times 32.12 = \mathbf{45\ cm}$$

The mechanical power in kW can be converted into equivalent heat in kcal by multiplying kW with 860 (1 kWh = 860 kcal or 1 kW = 860 kcal/h), which will give us the heat output per hour Q_0. Since the engine will be operating continuously at 75% of its maximum power capacity and is fuel injection type (with metered fuel), the 75% rating of 496 kW, which is 341.25 kW or 340 kW (rounded) will be used in calculating the fuel consumption and annual cost of fuel. Keeping the thermal efficiency of the engine 43%, the heat input to the engine will be:

$$Q_{in} = \frac{Q_0}{\eta_{thermal}} = \frac{340 \times 860}{0.43} = 680000 \text{ kcal per hour}$$

Therefore the weight of Diesel oil used will be:

$$w = \frac{Q_{in}}{HHV} = \frac{680000}{10635} = 63.93 \text{ kg per hour}$$

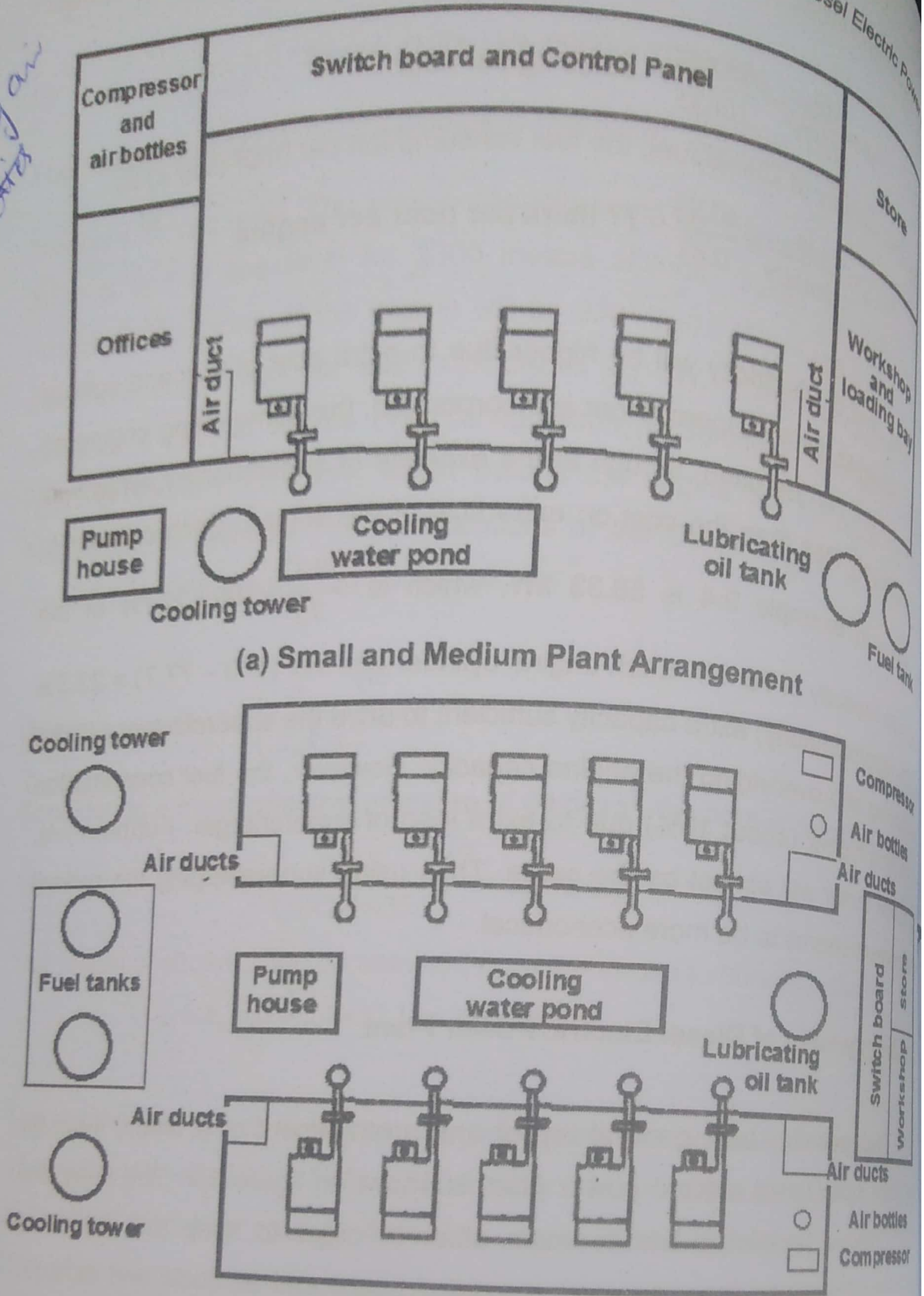
Knowing the density of Diesel fuel, the fuel consumption per hour (say x) is:

$$x = \frac{w}{density} = \frac{63.93}{0.83} = \textbf{77 liters per hour per engine}$$

The cost of electricity will be higher due to extra cost of fuel and cost of engine. However, when supercharger is incorporated, the same rating engine as in example 9.4 can be used, though at the expense of supercharger, which will be combatively less than the cost on extra size of the engine. Each cylinder of the engine in example 9.4 is 58.33 kW, which is $\frac{58.33}{75} \times 100 = 77.7\%$ of the maximum capacity of 75 kW. Each engine cylinder has still (100 – 77.7) = 22.3% or 22% (approximately) extra capacity sufficient to drive the supercharger without overloading and over-riding the engine capacity. However, the fuel consumption will be little higher (about 10%) due to extra load of supercharger. Furthermore, the space factor will almost be the same. Thus using supercharging the overall arrangement seems to be more economical.

9.10. Arrangement of Diesel Electric Power Plant

Two, possibly best general layout and arrangement of a small, medium and large size Diesel electric power plant is shown in figure 9.4. The units are usually placed parallel in-line to each other in order to keep the length of electrical connections for generators to control board and air ducts and exhaust pipes to a minimum. The generating units (Diesel engine–generator sets) are placed on large concrete slabs preferably reinforced. The foundation should be firm and sub-soil solid. The foundation should be firm and sub-soil solid. The air intake and filters and the exhaust mufflers should not be located in the engine room. Sufficient space must be provided around the various units for dismantling and repairing purposes. The fuel oil tanks are generally located outside the main buildings to avoid the fire hazards.



(a) Small and Medium Plant Arrangement

(b) Large Plant Arrangement

Figure 9.4: Two Possible Schematic Arrangements

The construction of buildings and engine layout are similar in many respects to the conventional thermal power plants, although on a much smaller scale. A steel frame with brick panels and asbestos sheet roof is quite satisfactory. A workshop must be situated at one end of engine house with rail or roadway running across it so that the crane can be used to unload directly from the wagons. Good natural lighting can be provided by including large vertical or horizontal windows in the side walls and rows of skylights in the engine house roof. The ventilation problem of engine house is not easy job particularly in hot climate. Generally, forced circulation with evaporative cooling or sometimes air-conditioning is used for cooling the engine room. The air ducts are placed in the basement wall at the alternator side and supply air to the alternator pits and to the operating floor for cooling the buildings. Figure 9.5 shows a photograph of typical Diesel electric units placed in a hall with control panel.

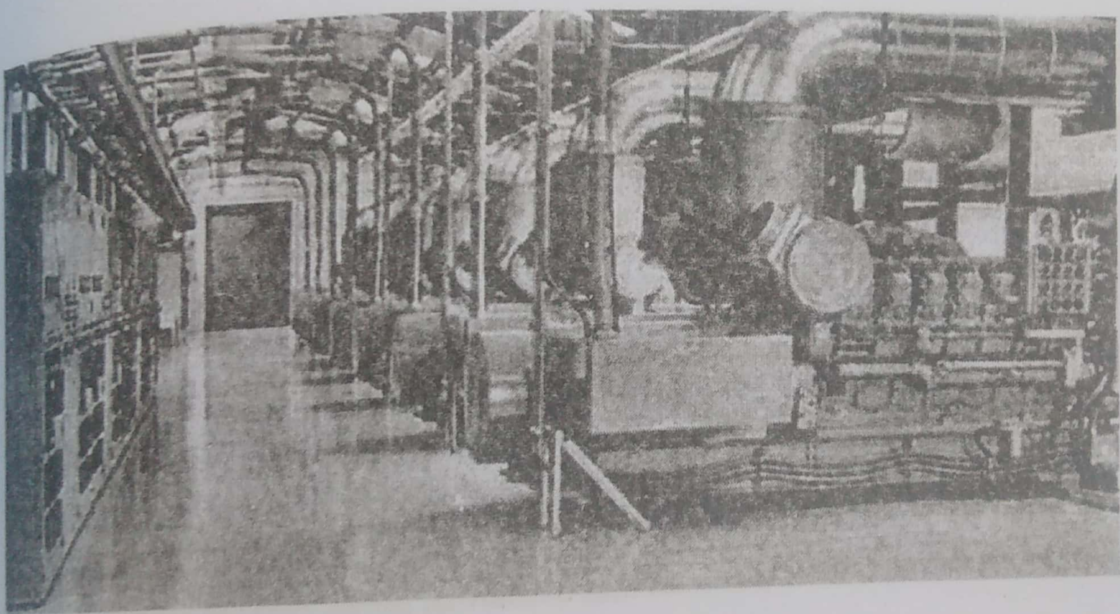


Figure 9.5: Power Generation Hall of a Diesel Plant

9.6. Dual Fuel Engines

In dual fuel engines, both gas and oil are used as fuels. The gas is used as main fuel and oil is used as a starter and helper for ignition. In the dual fuel engine, the air and gas are drawn in during suction stroke. During compression stroke the pressure of the mixture is increased. Near the end of the compression stroke, the oil is injected into the cylinder. The compression heat up and the oil and then gas mixture. The further working of the engine is similar Diesel engine. The air-gas ratio is comparatively higher in dual fuel en compared with ordinary gas engines. There is keen interest in the Diesel plants to use the dual fuel engines for better economy and proper u available gaseous fuel. Dual fuel engines may become an attractive metho electric power generation due to the wider availability of natural gas at lo prices. The use of dual fuel engines in electrical power generation would u gas as fuel at off-peak tariffs for the generation of electrical energy comparatively low prices. The overall effect of these trends would raise frontier of competition between the conventional thermal power plants and Dies plants into a higher level of installed capacity.

9.11. Advantages and Disadvantages of Diesel Electric Plants

Advantages:

1. Simple design and layout of plant.
2. Occupies less space and is compact.
3. Can be started quickly and picks up load in a short time.
4. Requires less water for cooling.
5. Thermal efficiency is better than thermal power plant of same size.
6. Overall cost is cheaper than that of thermal power plant of same size.
7. Requires less operating staff.
8. No stand-by losses.

Disadvantages:

1. High running charges due to costly price of Diesel.
2. Plant does not work efficiently under prolonged overload conditions.
3. Generates small amount of power.

4. Cost of lubrication very high.
5. Maintenance charges are generally high.