8

Gas Turbine Power Station

8.1. Overview

Gas-turbine electric power plants were initially created to take advantage of underground coal gasification processes. The first such power plant as the 'brown coal underground-gas electric power plant' in Tula Oblast in the former Soviet Union, was built in an area where there were deposits of high-ash and moist brown coal. Gas-turbine electric power plants are designed to meet peak-hour loads have a simplified thermal layout without provision for regeneration; they have an efficiency rate of about 20-25%. The cost of a standard kilowatt at such electric plants is about 50% of the cost of a standard kilowatt at a modern steam electric station. Gas turbine electric power plants were not widely developed in the past mainly because of some technical problems and that particles in the gases quickly wear down the vanes of the gas turbines. However, modern research has overcome the technical difficulties encountered in the past and presently gas turbine power generating schemes are attractive means of producing electricity. The use of gas turbine in power generation industry is more recent in the last few decades than its use in other fields as early as in 1875. The major progress has been achieved in three directions: increase in capacities of gas turbine units (50-100 MW), increase in efficiency to nearly 40% and drop in capital cost. Applications of gas turbines can be used for large-scale power generation. Examples are applications delivering 600 MW or more from a 400 MW gas turbine coupled to a 200 MW steam turbine in a co-generating installation. Such installations are not normally used for base load electricity generation, but for bringing power to remote sites such as oil and gas fields. During the 1950's and 1960's gas turbine electric power plants were built throughout the world. Their overall capacity exceeded 2000 MW by 1970. In the USA and Great Britain thermal units with a capacity of more than 500 MW are as a rule supplied with gas-turbine plants (25-35 MW capacity) to handle peak-hour loads. Automatic gas-turbine electric power plants employing aviation turbines in combinations of two to four turbine gas-units (each with a capacity of 10-20 MW) are also widely used. Gas-turbine electric power plants can be mounted on semi-trailer vans or railroad flatcars and used at new extraction sites, especially in oil fields (where the gas-turbine plants can work on the accompanying natural gas) or at construction sites (as temporary power plants). Low power gas turbine generating sets with capacities up to 5 MW can be accommodated in transportation containers to provide mobile emergency electricity supplies which can delivered by truck to the point of need. However, mobile gas-turbine power plants are rarely used, because their efficiency is relatively low and equipment costs is high as compared, for example to Diesel electric power stations. Gas-turbine electric power plants can also be used as reserve sources of power, switched on in case of an emergency in the energy system. Gas-turbine electric power plants are highly automated, which starts to operate and generate power automatically; Atomic gas-turbine power plants are being planned in the US. In these plants, high-temperature graphite-gas reactors will heat the operating gas (helium) to 800–1000°C.

8.2. The Gas Turbine System

Gas turbine, also combustion turbine engine that employ gas flow as the working medium, which transforms heat energy into mechanical energy. In these types of units, instead of heating steam to turn a turbine, hot gases from burning fossil fuels (particularly natural gas) are used to turn the turbine and generate electricity. Gas turbine and combustion engine plants are traditionally used primarily for peak loads, as it is possible to quickly and easily start and shut them. These plants have gained popularity due to advances in technology and the availability of natural gas. However, they are still traditionally slightly less efficient than large steam-driven power plants.

Hot gas is produced in the engine by the combustion of certain fuels. Fuel in gaseous or liquid-spray form is injected into this chamber, and combustion takes place there. The combustion products pass from the chamber through the nozzle to the turbine system. A simple-cycle gas turbine includes a compressor that pumps compressed the air into a combustion chamber. In a turbine, a row of fixed blades and a corresponding row of fixed blades attached to a rotor is called a stage. Large machines employ multi-stage axial-flow compressor and turbines. Stationary nozzle discharges jets of gas, which work against the blades of a turbine wheel that makes it to rotate at very high speeds. The impulse force of the jets on the turbine causes the shaft to turn. In shaft arrangements, in initial turbine stage (or stages) powers the compressor on one shaft while the later turbine stage (or stages) powers the external load on a separate shaft. The efficiency of the gas-turbine cycle is limited by the need for continuous operation at high temperatures in the combustion chamber and early turbine stages. A small, simple-cycle gas turbine may have a relatively low thermodynamic efficiency, comparable to a conventional gasoline engine. Advances in heat-resistant materials, protecting coatings, cooling arrangements have made possible large units with simple-cycle efficiencies of 34% or higher, approaching nearly 40%. The efficiency of gas-turbine cycle can be enhanced by the use of auxiliary equipment such as intercoolers, regenerators, and re-heaters. These devices are expensive, however, and economic considerations usually preclude their use. Many of the new natural gas fired power plants are known as combined-cycle plants, which will be discussed later in this chapter.

8.3. Thermodynamic Cycle of Gas Turbine System

The thermodynamic process used by the gas turbine is known as the Brayton cycle. The Brayton cycle, also called the Joule cycle, describes the thermodynamic power cycle associated with the compression and expansion of a gaseous working fluid. The system is referred to as an open cycle gas turbine system. As shown in figure 8.1, the gas turbine is comprised of three main components; a compressor, a combustor or combustion system and a turbine. The working fluid, air, is compressed in the compressor (adiabatic compression - no heat gain or loss), then mixed with fuel and burned by the combustor under constant pressure conditions in the combustion chamber (constant pressure heat addition). The resulting hot gas expands through the turbine to perform work (adiabatic expansion).

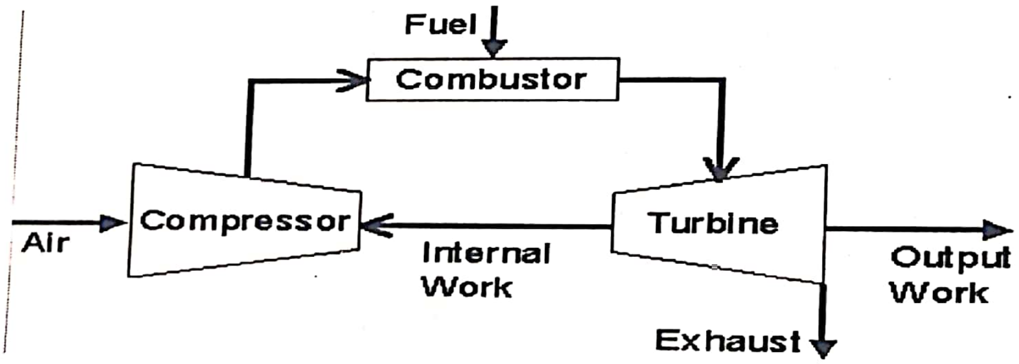

Figure 8.1: The Open Brayton Cycle Components

This heat–entropy diagram represents the ideal enthalpy and entropy relationship for the Brayton cycle and is shown in figure 8.2.

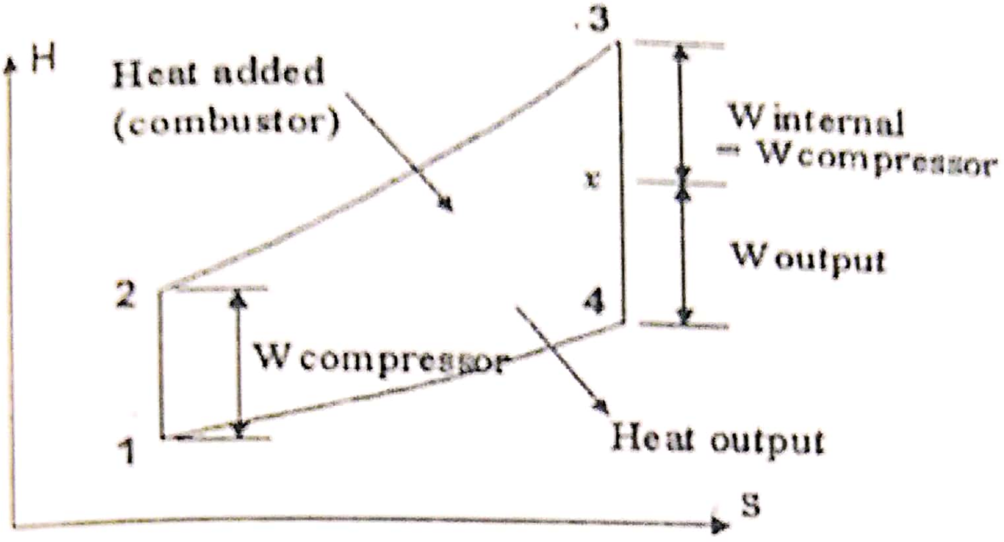

Figure 8.2: The Heat-Entropy Diagram of Brayton Cycle

As illustrated in figure 8.2 the thermodynamic cycle processes of Brayton cycle is described as follows: Air is compressed from point 1 to point 2. This increases the pressure as the volume of space occupied by the air is reduced. The air is then heated at constant pressure from 2 to 3. This heat is then added by injecting fuel into the combustor, which is then igniting it on a continuous basis. The hot compressed air at point 3 is then allowed to expand from point 3 to 4 thus reducing the pressure and temperature and increasing its volume. In the engine, this represents flow through the turbine to point x and then flow through the power turbine to point 4 to turn a turbine shaft. The process is summarized in table 8.1 and the pressure volume (p-V) diagram of the process is shown in figure 8.3.

Table 8.1: Summary of Brayton Cycle

Steps	Process	Heat and work done
1-2	Isentropic Compression	Q = 0
2-3	Isobaric Heat Addition	W = 0
3-4	Isentropic Expansion	Q = 0
4-5	Isobaric Heat Rejection	W = 0

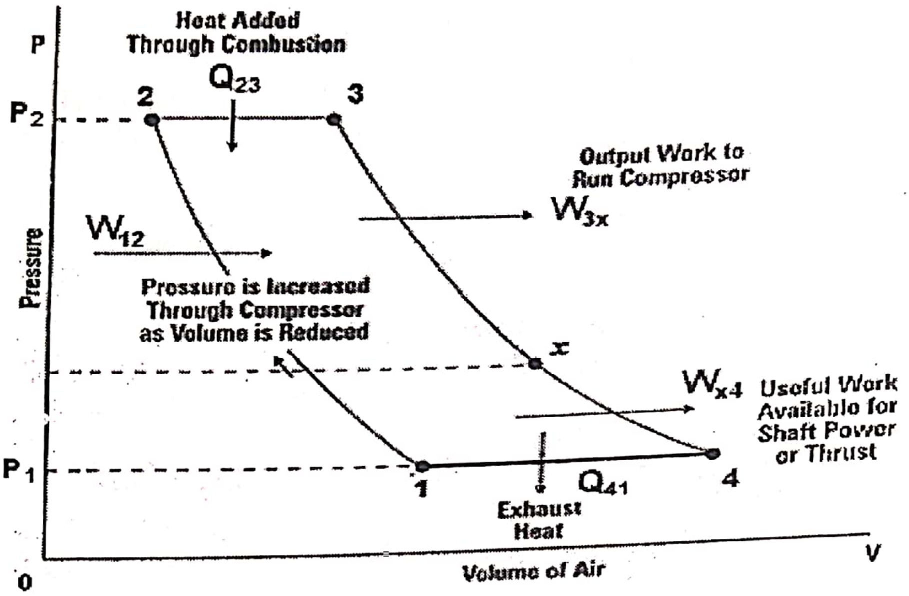

Figure 8.3: Pressure Volume Diagram

Much of the power produced in the turbine is used to run the compressor and the rest is available to run auxiliary equipment (such as generator) and do useful work. The system is referred to as an open system because the air is not reused so that the fourth step in the cycle, cooling the working fluid, is omitted. Like the Carnot cycle the Brayton cycle does not encompass a phase change and hence it has the potential for higher efficiencies. Analogous to the Carnot cycle in which the efficiency is maximized by increasing the temperature difference of the working fluid between the input and output of the machine, the Brayton cycle efficiency on the other hand is increased by increasing the pressure difference across the machine.

To determine the efficiency of the Brayton cycle, it is essential to know the amount of work each process contributes to the total internal energy. Tracing the path shown around the cycle from 1 to 4 and back to 1 as shown in figure 8.3, the first law of thermodynamics (writing the equation in terms of a unit mass), gives that the net change in internal energy ΔU is:

$$\Delta U = Q_2 + Q_1 - W = 0 \qquad 8.1$$

The net work done is equal to zero because the first law of thermodynamics states that energy is not destroyed nor created, and because in the Brayton cycle the final state function of the gas is the initial. This means that ΔU is zero in equation 8.1. The cycle thus returns the system to its starting state. The net work done from equation 8.1 is therefore:

$$W = Q_2 + Q_1 \tag{8.2}$$

Where Q_1 and Q_2 are defined as heat of the system, Q_1 is the heat received by the combustion and Q_2 is the heat released after expansion. It is also essential to evaluate the heat transferred in processes 2-3 and 4-1. Thus for a constant pressure, quasi-static process the heat exchange per unit mass is:

$$dh = C_p dT = dQ$$

Or $$[dQ]_{constant} = dh$$

It is also convenient to express the first law of thermodynamics in terms of enthalpy. The heat exchange can thus be expressed in terms of enthalpy differences between the relevant states. Treating the working fluid as a perfect gas with constant specific heats, for the heat addition Q_2 from the combustor:

$$Q_{23} = H_3 - H_2 = C_p(T_3 - T_2) \tag{8.3}$$

The heat-rejected Q_{12} is, similarly expressed as:

$$Q_{12} = H_1 - H_4 = C_p(T_1 - T_4) \tag{8.4}$$

The net work per unit mass ΔW is then given by:

$$\Delta W = Q_{12} + Q_{23} = C_p[(T_3 - T_2) + (T_1 - T_4)] \tag{8.5}$$

The thermal efficiency, which is the ratio of the net work done to the heat input of the Brayton cycle can now be expressed in terms of the temperatures:

$$\eta = \frac{C_p[(T_3 - T_2) - (T_4 - T_1)]}{C_p(T_3 - T_2)}$$

$$= 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)} \qquad 8.6$$

$$\eta = 1 - \frac{T_1[(T_4 / T_1) - 1]}{T_2[(T_3 / T_2) - 1]} \qquad 8.7$$

To proceed further, it is essential to examine the relationships between the different temperatures. We know that points 1 and 4 are on a constant pressure process as are points 2 and 3, therefore: $p_1 = p_4$ and $p_2 = p_3$. The other two limbs of the cycle are adiabatic and reversible, so that:

$$\frac{p_3}{p_4} = \frac{p_2}{p_1} = r_p \qquad 8.8$$

As both adiabatic processes take place between the same pressure ratios, the volume will be the same for both. Therefore:

$$p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$$

Where γ is the ratio of specific heat at constant pressure to the specific heat at constant volume and for various solids, liquids and gases is given in Appendix D, and is given by:

$$\gamma = \frac{C_p}{C_v}$$

$$\frac{p_2}{p_1} = \left(\frac{V_1}{V_2}\right)^{\gamma} = \left(\frac{V_4}{V_3}\right)^{\gamma} = (r_v)^{\gamma} \tag{8.9}$$

Also: $$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2}$$

Or $$\frac{p_2}{p_1} = \left(\frac{T_2}{T_1}\right)\frac{V_1}{V_2} \tag{8.10}$$

Comparing equation 8.9 and 8.10, we have:

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

or $$\frac{T_2}{T_1} = \left(\frac{V_1}{V_2}\right)^{\gamma-1} = (r_v)^{\gamma-1} \tag{8.11}$$

Where r_v is the volume ratio for the adiabatic process. The temperature ratio can also be expressed in terms of pressure ratio by again considering the gas laws: From which:

$$\frac{V_1}{V_2} = \left(\frac{p_2}{p_1}\right)\frac{T_1}{T_2} \qquad 8.11$$

Making the substitution from equation 8.9, we have:

$$\left(\frac{p_2}{p_1}\right)^{1/\gamma} = \left(\frac{p_2}{p_1}\right)\frac{T_1}{T_2}$$

or $$\frac{T_1}{T_2} = \left(\frac{p_2}{p_1}\right)^{\frac{1}{\gamma}-1} = (r_p)^{\frac{1}{\gamma}-1} \tag{8.12}$$

or $$\frac{p_2}{p_1} = \left(\frac{T_1}{T_2}\right)^{\frac{\gamma}{1-\gamma}} = r_p \qquad 8.13$$

Where r_p is the pressure ratio. From equation 8.8 and 8.13, it can be established that:

$$\left(\frac{T_4}{T_3}\right)^{\gamma/(1-\gamma)} = \left(\frac{T_1}{T_2}\right)^{\gamma/(1-\gamma)} \qquad 8.14$$

or $$\left(\frac{T_4}{T_3}\right) = \left(\frac{T_1}{T_2}\right) = (r_p)^{\frac{1}{\gamma}-1}$$

Next we obtain T_2 and T_3 in terms of T_1 and T_4 respectively, we have:

$$T_2 = T_1(r_p)^{1-\frac{1}{\gamma}}$$

And $$T_3 = T_4(r_p)^{1-\frac{1}{\gamma}}$$

In terms of compressor temperature ratio, and using the relation for an adiabatic reversible process we can write the efficiency in terms of the compressor (and cycle) pressure ratio, which is the parameter commonly used: The efficiency given in equation 8.6 can then be expressed in terms of pressure ratio as:

$$\eta - 1 - \frac{1}{(r_p)^{1-\frac{1}{\gamma}}} \qquad 8.15$$

In a similar manner from equation 8.11, we have:

$$T_2 = T_1(r_v)^{\gamma-1}$$

And $$T_3 = T_4(r_v)^{\gamma-1}$$

The efficiency from equation 8.6 in terms of volume ratio can then be expressed as:

$$\eta = 1 - \frac{1}{(r_v)^{\gamma - 1}} \qquad 8.16$$

Since: $\left(\frac{T_4}{T_3}\right) = \left(\frac{T_1}{T_2}\right)$, or, finally, $\left(\frac{T_4}{T_1}\right) = \left(\frac{T_3}{T_2}\right)$. Using this relation in the expression for thermal efficiency, equation 8.7 yields an expression for the thermal efficiency of a Brayton cycle:

$$\eta = 1 - \frac{T_1}{T_2} \qquad 8.17$$

Or

$$\eta = 1 - \frac{T_{atmosphere}}{T_{compressor}} \qquad 8.18$$

Example 8.1: A gas turbine expands gas from 1 MPa pressure and 600°C to 100 kPa pressure. The isentropic efficiency is 90%. The mass flow rate is 10.5 kg/s. Calculate the exit temperature and the power output. Assume C_p = 1005 J/kg ^{0}K and C_v = 718 J/kg ^{0}K.

Given that:

p_2 = 1 Mpa = 1000 kPa
p_1 = 100 kPa
T_3 = 600^{0}C or 873^{0}K
η = 0.90 or 90%

From the given values of specific heat at constant pressure and specific heat at constant volume, the value of γ can be obtained as:

$$\gamma = \frac{C_p}{C_v} = \frac{1005}{718} = 1.4$$

Refer to the p-V diagram of figure 8.3. The pressure ratio is obtained as:

$$r_p = \frac{p_2}{p_1} = \frac{1000}{100} = 10$$

Therefore: $T_3 = T_4 (r_p)^{1-\frac{1}{\gamma}}$

Or $T_4 = \dfrac{T_3}{(r_p)^{1-1/\gamma}} = \dfrac{873}{(10)^{0.28}}$ = 458.15^{0}K

The actual temperature T_4^a can be obtained from the expression of isentropic efficiency. The isentropic efficiency from the PV diagram of figure 8.3 is given the expression:

$$\eta_{isen} = \frac{(T_4^a - T_3)}{(T_4 - T_3)}$$

or $$0.90 = \frac{(T_4^a - 873)}{(458.15 - 873)}$$

From which:

$$T_4^a = 499.63^0\text{K}$$

The power output is then:

$$P = mC_p (T_3 - T_4^a)$$

or $P = 10.5 \times 1.005 \times (873 - 499.63) =$ **3940 kW**

Example 8.2: An oil-gas turbine installation at a power station consists of a compressor, a chamber into which oil is injected and in which combustion takes place at constant pressure, a set of nozzles and an impulse turbine coupled to a generator. The air is taken in at 100 kPa and at 27^{0}C, and compresses it to 415 kPa, with an adiabatic efficiency of 85%. Heat is then added by the combustion to raise the temperature to 572^{0}C. The combined efficiency of the nozzles and impulse turbine is 82%. The calorific value of oil used is 8607 kJ/kg. For an airflow of 1.36 kg/s, find: air/fuel ratio of the fuel, the net horsepower available at the turbine and electric power output if the electrical efficiency if 90%. Assume C_p = 1005 J/kg ^{0}K and C_v = 718 J/kg ^{0}K before entry into the nozzle and C_p = 1055 J/kg ^{0}K and C_v = 802 J/kg ^{0}K after entry into the nozzle.

Given that:

p_2 = 415 kPa
p_1 = 100 kPa
T_1 = 27^{0}C or 300^{0}K
T_3 = 572^{0}C or 845^{0}K
Adiabatic efficiency: η_a = 85% or 0.85

Turbine efficiency: $\eta_T = 82\%$ or 0.82

Generator efficiency: $\eta_e = 90\%$ or 0.9

Refer to the T-s diagram of figure 8.4, which is redrawn from figure 8.2.

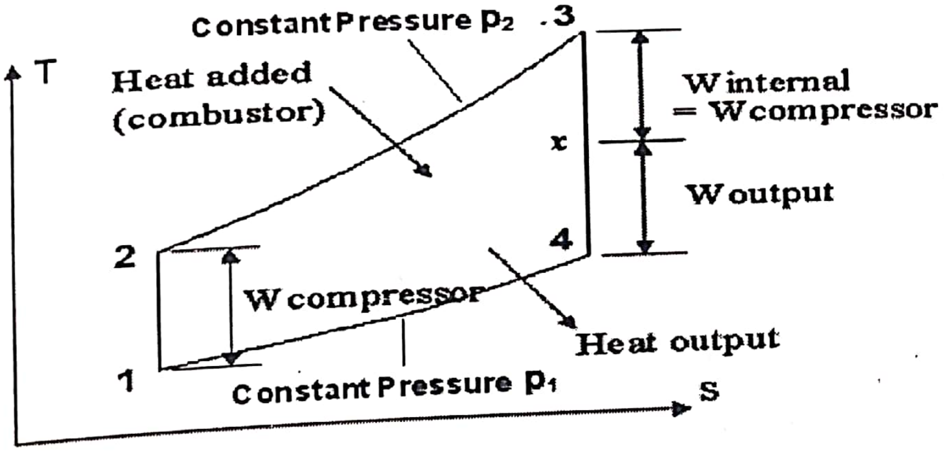

Figure 8.4

From the given values of specific heat at constant pressure and specific heat at constant volume, the value of γ can be obtained as:

$$\gamma = \frac{C_p}{C_v} = \frac{1005}{718} = 1.4$$

The pressure ratio is obtained as:

$$r_p = \frac{p_2}{p_1} = \frac{415}{100} = 4.15$$

From the T-s diagram of figure 8.4, we have:

$$\frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}}$$

or $$T_2 = T_1\left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}} = 300\times(4.15)^{0.28} = 446.86^0\text{K}$$

Therefore adiabatic work of compressor is:

$$W_{12} = mC_p(T_2 - T_1)$$

or $$W_{12} = 1.36 \times 1.005 \times (446.86 - 300) = 200.73 \text{ kJ/s}$$

Actual work of compressor is:

$$W_{12}^{a} = \eta_a \times W_{12} = 0.85 \times 200.73 = 170.62 \text{ kJ/s}$$

The actual final temperature of the air leaving the compressor from figure 8.4 is then:

$$\eta_a = \frac{T_2 - T_1}{T_2^{a} - T_1}$$

or $$0.85 = \frac{446.86 - 300}{T_2^{a} - 300}$$

From which: $T_2^a = 472.77^0\text{K}$

Heat supplied by the oil per second is then:

$$Q_{23} = mC_p(T_3 - T_2^{a}) = 1.36 \times 1.005 \times (845 - 472.77) = 508.76 \text{ kJ/s}$$

Therefore weight of the oil per second will be:

$$w = \frac{Q_{23}}{CV} = \frac{508.76}{41800} = 0.01217 \text{ kg/s}$$

Therefore the air fuel ratio will be:

$$Air/Fuel = \frac{1.36}{0.01217} = 111.75 \text{ or } \mathbf{112:1}$$

At the turbine the value of γ is obtained by considering the new value of C_p and C_v. Therefore: $\gamma = \frac{C_p}{C_v} = \frac{1055}{802} = 1.315$

$$\frac{T_3}{T_4} = \left(\frac{p_2}{p_1}\right)^{1-\frac{1}{\gamma}}$$

or $$\frac{845}{T_4} = (4.15)^{0.24}$$

or $T_4 = 600.56^0\text{K}$

The actual temperature at the turbine exit T_4^a will be:

$$\eta_T = \frac{T_3 - T_4^{a}}{T_3 - T_4}$$

or

$$0.82 = \frac{845 - T_4''}{845 - 600.56}$$

From which:

$$T_4'' = 644.56^0 K$$

At the turbine the weight of the total fuel mixture is:

$$m = 1.36 + 0.01217 = 1.37 \text{ kg/s}$$

The adiabatic work done by the turbine per second is then:

$$W_{34} = mC_p(T_3 - T_4)$$

or

$$W_{34} = 1.37 \times 1.055 \times (845 - 600.56) = 353.3 \text{ kJ/s}$$

Actual work done by the turbine is:

$$W_{34}^{a} = \eta_T \times W_{34} = 0.82 \times 353.37 = 289.7 \text{ kJ/s}$$

Net work done = Work done by the turbine – Work required by compressor

Therefore:

$$W_{net} = 289.7 - 170.62 = 119.08 \text{ kJ/s} = 119.08 \text{ kW}$$

The rating of the turbine is: (119.08/0.746) = **160 horsepower**. The electrical efficiency of the system is 90%. Therefore the electrical output from the plant is:

$$P = \eta_e \times W_{net} = 0.9 \times 119.08 = \mathbf{107.17 \text{ kW}}$$

8.4. Components of a Gas Turbine System

Gas turbines are one of the most efficient equipment for converting thermal energy from combustion of fuel to mechanical energy. Gas turbine functions in the same way as the internal combustion engine. It draws in air from the atmosphere and compresses it. The fuel is injected and ignited. The gases expand doing work and finally expelled outside through exhaust. The only difference is that instead of the reciprocating motion, gas turbine uses a rotary motion throughout. When the heat is given to the air by mixing and burning the fuel in the air and the gases coming out of the turbine are exhausted to the atmosphere, the cycle is known as open cycle system. If the heat to the working medium (air or any other suitable gas) is given without directly burning the fuel in the air and the same working medium is used again and again, the cycle is known as closed cycle system. The main components of the gas turbine system are shown in figure 8.4 and described in the following sections:

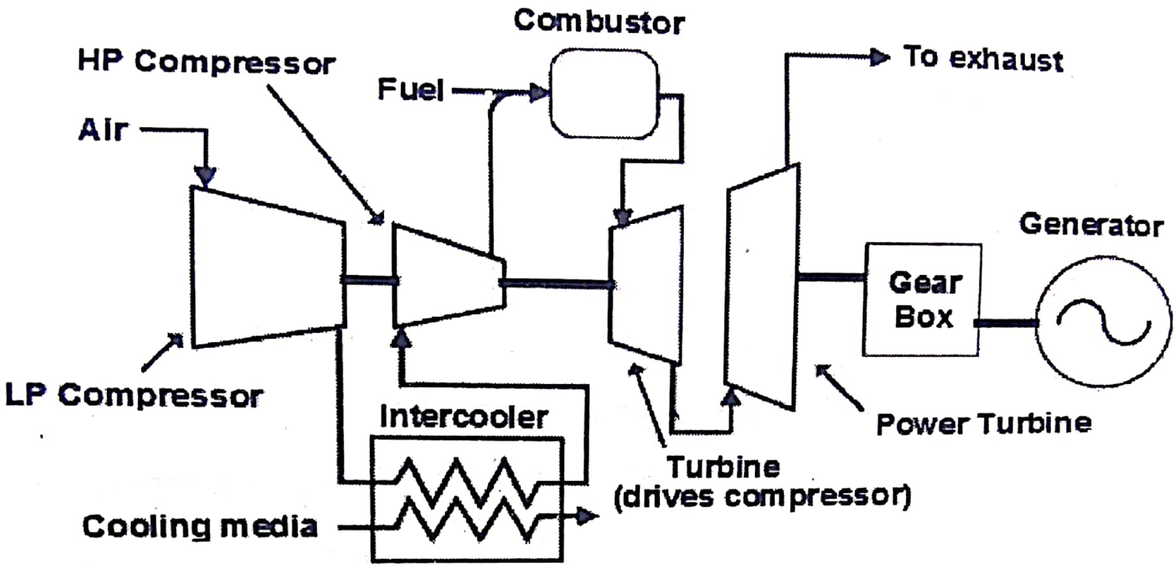

Figure 8.4: Gas Turbine Power Plant

8.4.1. Compressor System

The compressor system intake air at atmospheric pressure and produces air at high pressure at the outlet. The compressor is usually a rotary type, which consists of a number of rows of stationary guide vanes and moving blades mounted on a shaft. The arrangement is similar to a series of fans placed one after the other. Stationary guide vanes between each of the blade rows guide the airflow from one section to the next section. The pressurized air from the first row is further pressurized in the second row and so on. The compressor used in the plant is usually driven by a stage turbine. The shaft is connected and rotates along with the main gas turbine. Thus large percentage of power developed (66%) by the turbine is used to run the compressor. The power required to run the compressor can be reduced by compressing the air in two stages; that is in low pressure and high-pressure compressor and also by incorporating an intercooler between the two stages.

The compressor system thus comprise of a low pressure (LP) compressor, a high pressure (HP) compressor and an intercooler. The LP compressor draws in air form the atmosphere in suction mode. In this mode, the compressor draws the air at atmospheric pressure through a filter, which removes dust particles from the entering air. After suction of air the compressor compresses it to a suitable pressure and admits it into the HP compressor. The blades of the HP compressor thus push the air between stationary blades to raise its pressure in the range of 15 to 20 bars. Thus air is available at high pressure at the output of the compressor. Intercooler between LP and HP compressors is used to reduce work of the compressor and increase the efficiency. The energy required to compress air is proportional to the air temperature at inlet. Therefore if inter-cooling is carried out between the stages of compression the total work can be reduced.

8.4.2. Fuel System

The Fuel system prepares a clean fuel for burning in the combustor. One further advantage of gas turbines is their fuel flexibility. They can be adapted to use almost any flammable gas or light distillate petroleum products such as gasoline (petrol), Diesel and kerosene, which are available locally, though natural gas is the most commonly used fuel. Crude and other heavy oils and can also be used to fuel gas turbines if they are first heated in order to reduce their viscosity to a level suitable for burning in the turbine combustion chambers. For liquid fuels high-pressure pumping system, pump fuel to the pressure required for fine atomization of the fuel perfect for burning. Atomization can be accomplished with high-pressure air or steam, and is best suited for variable loads. Atomization can also be done by mechanical means (centrifugal force), which is better suited for steady loads and high capacities.

A fuel filter used in the fuel system prevents entry of any particles that may clog the burners. Natural gas when used directly from the well is scrubbed and cleaned prior to admission into the turbine. The combustion processes are endothermic, and result in pollutants of NO_x (nitrous oxides) and CO (carbon monoxide). NO_x emissions are reduced through control of the combustion process that is, either reducing the combustion temperature or lowering the air-fuel ratio. The production of carbon monoxide can be reduced by introducing excess air into the combustion chamber.

8.4.3. Combustion Chamber (Combustor)

The air at high pressure from the compressor is led to the combustion chamber via the regenerator. The air from the compressor is therefore referred to as the combustion air. The combustion chamber is an annular chamber where the fuel burns and is similar to the furnace of a boiler. In the combustion chamber, heat is added to the air by burning oil. The oil is injected through the burner into the chamber at high pressure in order to ensure atomization of oil and its thorough mixing with air. The result is that the chamber attains a very high temperature (about 1650^0C). The combustion gases are suitably cooled to between 700^0C and 820^0C and then delivered to gas turbine. There are different types of combustion systems (burners) for each type of fossil fuels. In the case of using natural gas as fuel only a proportion of the gas-air mixture (gas mix with air), which can be easily ignited by simple methods. Natural gas burners are therefore the simplest, since natural gas is the easiest fuel to burn. Oil burners prepare the oil by vaporization or gasification by heating it in the burner, or by atomization in the combustion-air stream. Many gas turbines have dual firing capabilities; a burner system and an ignition system with the necessary safety interlocks. Burners arranged circumferentially on the annular chamber controls the fuel entry to the chamber. The hot gases in the range of 1400^0C to 1500°C leave the chamber with high energy. The chamber and the subsequent sections are made of special alloys and designs that can withstand such high temperatures. In order to increase the thermal efficiency, hot air from regenerator is also allowed to flow to the combustion chamber. Fuel (natural gas or coal gas or kerosene or gasoline) is injected into the combustion chamber and burns in the stream of hot air. A control valve regulates the amount of fuel to be burned. The products of combustion, comprising a mixture of gases as high temperature and pressure are then passed to the turbine.

8.4.4. The Turbine

The turbine does the main work of energy conversion. Figure 8.5 is a photograph of a typical gas turbine. The turbine consists of multiple rows of blades keyed to the shaft. Stationary guide vanes direct the gases to the next set of blades. The next set of moving blades acts as an air compressor mounted on the same shaft. The air turbine (compressor) draws in air, compresses it and feeds it at high pressure into the combustion chamber increasing the intensity of the burning flame. It is a positive feedback mechanism. That is as the gas turbine speeds up, it also causes the compressor to speed up forcing more air through the combustion chamber which in turn increases the burn rate of the fuel, sending more high pressure hot gases into the gas turbine thus further increasing its speed. Uncontrolled runaway is prevented by controls on the fuel supply line, which limit the amount of fuel being fed to the turbine, thus limiting its speed.

The hot gases in the range of 1400^0C to 1500°C leave the chamber with high energy. The combustion gases are suitably cooled to 700^0C to 820^0C and then delivered to gas turbine. The kinetic energy of the hot gases impacting on the blades rotates the blades and thus the shaft. The blades and vanes are made of special alloys and designs that can withstand the very high temperatures. The exhaust gases then exit to exhaust system through the diffuser (not shown in figure 8.4). The gas temperature leaving the turbine is in the range of 500^0C to 550°C. Products of combustion are expanded in high-pressure turbine and then in low-pressure turbine. The part of the work developed by the gases passing through the turbines is used to run the compressor and the remaining (about 34%) is used to generate electric power.

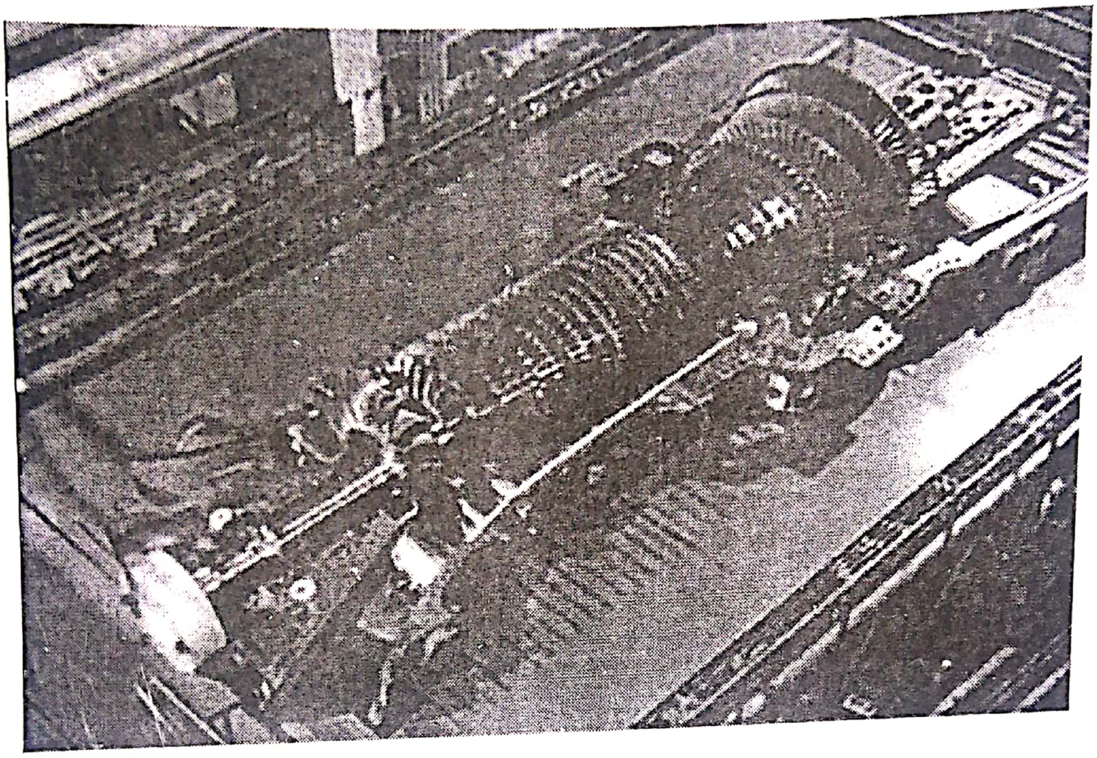

Figure 8.5: Photograph of a Gas Turbine

The products of combustion consisting of a mixture of gases at high temperature and pressure are passed to the gas turbine. These gases in passing over the turbine blades expand and thus do the mechanical work. The temperature of the exhaust gases from the turbine is about 480^{0}C. To minimize the size and weight of the turbine for a given output power, the output per unit weight of airflow should be maximized. This is accomplished by maximizing the air flow through the turbine which in turn depends on maximizing the pressure ratio between the air inlet and exhaust outlet. The main factor governing this is the pressure ratio across the compressor, which can be as high as 40:1 for modern gas turbines. In simple cycle applications, pressure ratio increases transforms into efficiency gains at a given firing temperature. However, there is a limit since increasing the pressure ratio means that more energy will be consumed by the compressor and a compromise is therefore necessary. Gas turbines can be used for large-scale power generation. Examples are applications delivering 600 MW or more from a 400 MW gas turbine coupled to a 200 MW steam turbine in a co-generating installation. Micro-turbines are scaled down versions of large gas turbines. As their name suggests, these generating units are very small, and typically have a relatively small electric output. These types of distributed generation systems have the capacity to produce from 25 to 500 kW of electricity, and are best suited for residential or small-scale commercial and industrial units. Advantages of micro-turbines include a very compact size, a small number of moving parts, light-weight, low-cost, and increased efficiency. Using new waste heat recovery techniques, micro-turbines can achieve energy efficiencies of up to 80%.

8.4.5. Reheating Combustion Chamber

The output of the plant and the efficiency can be further improved by providing a reheating combustion chamber between high pressure and low-pressure turbines. In the simple open cycle system the heat of the turbine exhaust gases goes as waste. To make use of this heat a regenerator is incorporated. A regenerator (not shown in figure 8.4) is a device, which recovers heat from the exhaust gases of the turbine. The exhaust gases are thus passed through the regenerator before being expelled to the atmosphere. A regenerator consists of a network of tubes contained in a shell. The compressed air from the compressor passes through the tubes on its way to the combustion chamber. In the regenerator the heat of the hot exhaust gases from the turbine is used to preheat the air entering the combustion chamber. In this way compressor is heated by the hot exhaust gases. The addition to the regenerator, intercooler and reheating combustion chamber increases the overall efficiency of the plant. The compressor uses more than 50% of the energy converted; with only around 35% of the energy input is available for electric power generation in the generator. The rest of the energy is lost as heat of the exhaust gases to the atmosphere. Three parameters that affect the performance of a gas turbine are:

1. The pressure of the air leaving the compressor.
2. The temperature of hot gases leaving the combustion chamber.
3. The temperature of the exhaust gases leaving the turbine.

8.4.6. Generator

The gas turbine shaft connects to the generator (alternator) to produce electric power. This is similar to generators used in conventional thermal power plants. The generator converts the mechanical energy of the turbine into electrical energy. The output of the generator is given to the bus bars through transformers, isolators and circuit breakers. In electricity generating applications the turbine is used to drive a generator which provides the electrical power output but because the turbine normally operates at very high rotational speeds of 12000 rpm or more it must be connected to the generator through a high ratio reduction gear since the generators run at speeds, typically of 1000 rpm, 1500 rpm and 3000 rpm to produce power at frequency of 50 Hz (power frequency used in Pakistan) of the electricity grid.

8.4.7. Starting Motor

Before starting the turbine, compressor has to be started. For this purpose, a DC series motor mounted on the same or an auxiliary shaft that transmit motion to the turbine, is used as a starter motor. The motor is energized by the batteries for initial start-up. This is similar to the starter motor of an automobile. Starting system provides the initial momentum for the gas turbine to reach the operating speed. Once the unit starts, a part of the mechanical power of the turbine drives the compressor and there is no further need of the starter motor. The gas turbine in a power plant typically runs at 3000 rpm for the 50 Hz system and 3600 rpm for the 60 Hz systems. During starting the speed has to reach at least 60% for the turbine to work on its on inertia. The simple method is to have a starter motor with a torque converter to bring the heavy mass of the turbine to the required speed. For large turbines this means a big capacity motor. Modern trend is to use the generator itself as the starter motor with suitable electrical system. In situations where there is no other start up power available, like a ship or an offshore platform or a remote location, a small Diesel or gas engine is used.

8.5. Working

The compressor, which draws air into the engine, pressurizes it, and feeds it to the combustion chamber at speeds of several hundreds revolutions per minute. The combustion system typically made up of a ring of fuel injectors that inject a steady stream of fuel into combustion chambers where it mixes with the air. The mixture is burned at temperatures of more than 1100^{0}C. The combustion produces a high temperature, high pressure gas stream that enters and expands through the turbine section. The turbine, which is an intricate array of alternate stationary and rotating aerofoil-section type set of blades, is set into rotation. The hot combustion gas expands through the turbine thus doing the necessary work. The turbine is mechanically coupled to a generator, which spins to produce electrical energy.

Gas turbine engines derive their power from burning fuel in a combustion chamber and using the fast flowing combustion gases to drive a turbine in much the same way as the high-pressure steam drives a steam turbine. One major difference, however, is that the gas turbine has a second turbine acting as an air compressor mounted on the same shaft. The 'air turbine' (compressor) draws in air, compresses it and feeds it at high pressure into the combustion chamber increasing the intensity of the burning flame. A simple cycle gas turbine can achieve energy conversion efficiencies ranging between 20% and 35%. Another way to boost efficiency is to install a recuperator or heat recovery steam generator (HRSG) unit to recover energy from the turbine's exhaust. HSRG consists of four major components; the economizer, evaporator, superheater and water pre-heater. The different components can be put together to meet the operating requirements of the unit. An HRSG captures waste heat in the turbine exhaust system to preheat the compressor discharge air before it enters the combustion chamber. Heat recovery steam generators, also formerly known as waste heat boilers or waste heat generators, use waste heat in the hot flue gases to produce steam which is then used to power a thermal power plant. High-pressure steam from the boiler can be used to generate additional electric power with steam turbines, a configuration called a combined cycle.

8.6. Combined Cycle

The first combined cycle plant with a capacity of 16 MW was commissioned in 1964 at Leningrad in the former Soviet Union with an existing 30 MW steam turbine. Gas turbine stations are generally expensive to operate independently; they are therefore designed and constructed in a combined-cycle configuration together with steam power station. Many of the modern natural gas fired power plants are combined-cycle units, incorporating waste heat recovery system. In these types of generating facilities, there is both a gas turbine and a steam unit, all in one. The gas turbine operates in much the same way as a normal gas turbine, using the hot gases released from burning natural gas to turn a turbine and generate electricity. In combined-cycle plants, the waste heat from the gas-turbine process is directed toward generating steam, which is then used to generate electricity much like a conventional thermal unit. In combined cycle turbines, it is thus possible to recover energy from the waste heat of simple cycle systems by using the exhaust gases in a hybrid system to raise steam to drive a steam turbine electricity generating set. Combined cycle systems are designed for maximum efficiency in which the hot exhaust gases from the gas turbine are used to raise steam to power a steam turbine with both turbines being connected separately to electricity generators. In such cases the exhaust temperature may be reduced to as low as 140°C enabling efficiencies of up to 60% to be achieved in combined cycle systems. Figure 8.6 shows a schematic diagram of a typical combined cycle power generating system.

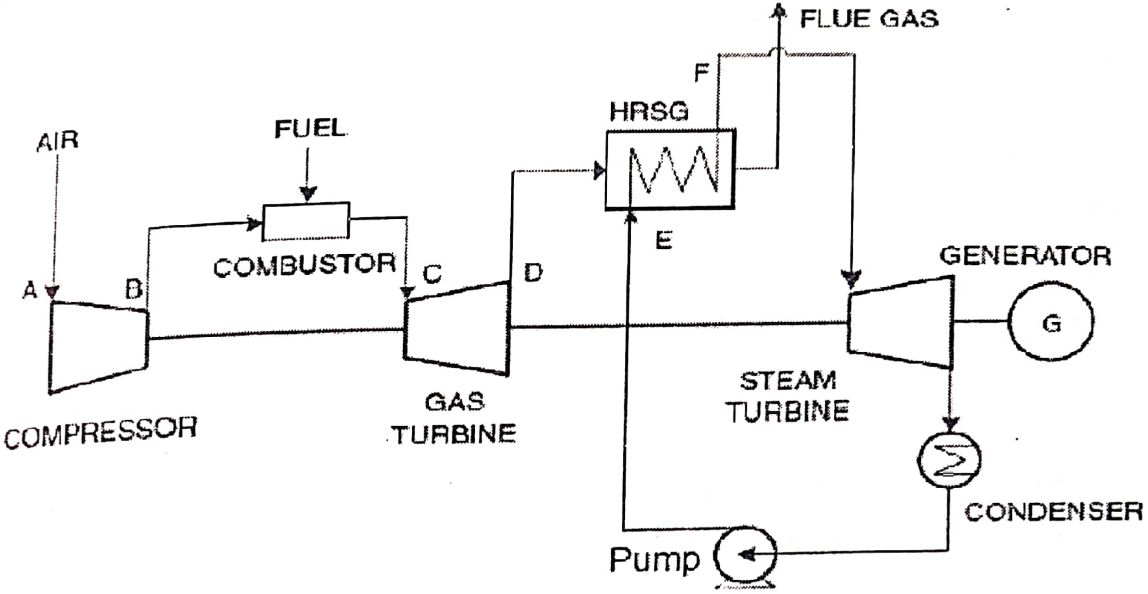

Figure 8.6: Schematic Diagram of a Combined Cycle System

In combined cycle plants, fuel and air are supplied to a combustion chamber under pressure; the products of combustion and heated air are sent to a gas turbine. After passing through the first stage of the turbine, the products of combustion are admitted to an intermediate combustion chamber, where a portion of the fuel is burnt with the excess oxygen (air) present in the gases. The combustion products leave the intermediate combustion chamber and enter the final stage of the turbine, where their continued expansion and cooling take place. The exhaust gases may be used to heat water or to manufacture low-pressure steam in a steam generator. Air is supplied to the combustion chamber by a compressor mounted on the same shaft as the turbine. In combined-cycle applications, pressure ratio increases have a less pronounced effect on the efficiency since most of the improvement comes from increases in the Carnot thermal efficiency resulting from increases in the firing temperature. The combined output is approximately 50% greater than that of the gas turbine alone. Heavy-duty gas turbines in both simple and combined cycles have become important for large-scale generation of electricity. Unit rating in excess of 200 MW are available. The combined cycle output can exceed 300 MW. The usual fuels used in gas turbine are natural gas and liquids such as kerosene and Diesel oil. Coal can be used after conversion to gas in a separate gasifier.

Combined steam and gas turbine electric power plants have a bright future. The technical design of gas-turbine plants is noted for simplicity; the need for auxiliary equipment and pipelines is minimal. The combined steam and gas turbine plant normally works on the cycle of a steam turbine plant, but to meet peak hour demands it is switched over to the cycle of a steam and gas plant. In this way high initial operating temperatures are attained, whereas little heat is lost in the exhaust. Thus efficiency is high, and capital expenditures are somewhat reduced. The use of combined cycle system in power generation industry is more recent in the last few decades than its use in other fields in the early days. As mentioned earlier, the major progress has been achieved in three directions: increase in capacities of gas turbine units (50-100 MW), increase in efficiency (up to 40%) and drop in capital cost.

8.7. Advantages of Gas Turbine Power Plant

1. Natural gas is very suitable fuel and where it is readily and cheaply available.
2. Gas turbine plant is smaller in size and weight compared to an equivalent steam power plant. For smaller capacities the size of the gas turbine power plant is appreciably greater than a high-speed Diesel engine plant; but for larger capacities it is smaller in size than comparable Diesel plant. If size and weight are main considerations such as in ships, aircraft engines and locomotives, gas turbines are more suitable.
3. The initial cost is lower than an equivalent steam plant.
4. It requires less water as compared to a steam plant.

5. It can be started quickly, and can be put on load in a very short time.
6. Maintenance cost is low.
7. It does not require heavy foundations and buildings.
8. Any poor quality and wide variety of fuels from natural gas to residual oil or powered coal can be used.
9. The running speed of the turbine (40,000 to 100,000 rpm) is considerably large compared with Diesel engine (1000 to 2000 rpm).
10. The exhaust of the gas turbine is relatively free from smoke.

8.8. Disadvantage Gas turbine power plant

1. Major part of the work (66%) developed in the turbine is used to drive the compressor. Therefore net output of the plant is low.

2. It requires special metals and alloys for different components because the operating temperature (2000^{0}C) and speed (100,000 rpm) are very high.

3. Part load efficiency is poor as compared to others, such as Diesel plant.