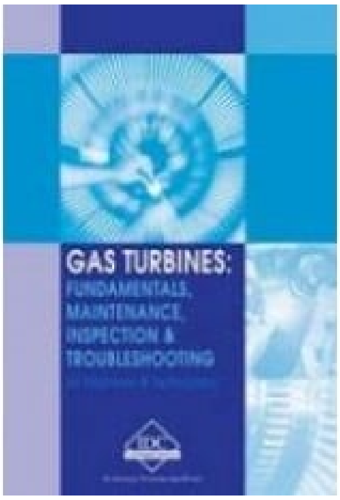
GT-E- Gas Turbines Fundamentals, Maintenance, Inspection and Troubleshooting



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Short Description

This manual gives a solid review of gas turbines with a focus on fundamental thermodynamics; gas turbine components; materials of construction; bearing, seals and lubrication systems; fuels and fuel supply systems; combustion air filters; control systems and instrumentation and operations and maintenance.

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First Chapter

Gas Turbines: Fundamentals, Maintenance & Troubleshooting - General Overview

1 General Overview of Gas Turbines

1.1 Introduction

Gas turbine engines are generally classified based on the type and nature of application, size and location. This chapter contains a general overview of the different types of gas turbines in use, and also a brief introduction to the various components comprising the gas turbine engine in addition to discussing the concept of heat recovery in combined cycle gas turbine plants. Gas turbines in general are broadly classified into five categories. They are:

- Frame type heavy-duty
- Industrial type
- Aircraft derivative
- Small gas turbines
- Micro-turbines

These categories of turbines are discussed in detail from the point of view of their design, construction, principle of working and application.

1.2 Frame type heavy-duty gas turbines

Frame type heavy-duty gas turbines are high-efficiency machines finding widespread application as prime movers in large power generation units. A majority of modern day heavy duty gas turbines work on the combined gas turbine cycle, although earlier gas turbines of this type were designed mainly as an extension of steam turbines. With the success encountered in achieving higher firing temperatures in the range of 1426°C (2600°F), the efficiency levels of these categories of turbines have been found to reach as much as 50%. A sectional view of a typical heavy duty gas turbine is shown in Figure 1.1.

Figure 1.1

Sectional view of a frame type gas turbine

Since space and weight restrictions are not considered that important in the design of these turbines, they are large with distinct features like heavy wall casings, large diameter combustors, thick-sectioned blades and large frontal areas. These turbines largely employ multistage axial-flow compressors and turbines, with multiple can-annular combustors connected to each other by crossover tubes. The cross-over tubes achieve flame propagation from one chamber to the other and pressure equalization between each chamber. A common example of this type is the GE heavy duty large gas turbine. However not all frame type turbines employ can-annular combustors. While the older Siemens V type heavy duty turbines employed silo type combustors, the newer ones use annular combustors with Hybrid Burner Ring. Certain designs also employ annular combustors with sequential firing. Examples being Alstom GT 24, 26.

The multistage operation of the compressors is carried out in stages, varying between 15 and 17, in order to achieve high overall pressure ratios in the range between 16:1 and 25:1. As the pressure increase is carried out in many stages, there is a small pressure rise in each stage and therefore the operation is highly stable. The compressor along with the generator is driven by the expander section usually consisting of a 2-4 stage axial flow turbine. The compressor, turbine and combustor types are discussed in the chapters to follow.

Although these units produce large noise levels, they are nowhere as high as that produced in aircraft derivative turbines. Their large frontal areas reduce the air inlet velocity and thereby air noise. The advantages with these turbines are their long life, high operating reliability, high availability and high overall efficiency.

As mentioned earlier, the high efficiency levels achieved in these turbine types are partly due to the high turbine inlet temperatures of around 1371°C (2500°F). Research is continuously on to push this temperature up further to around 1649°C (3000°F), which would make these turbines even more efficient.

1.3 Industrial type gas turbines

Industrial Type gas turbines are medium range gas turbines and are quite similar in design to the heavy duty gas turbines, but with reduced power outputs. They are largely used in petrochemical plants and operate both on simple and combined cycles. A sectional view of a medium size industrial type gas turbine is shown in Figure 1.2.

Figure 1.2

Sectional view of a medium size industrial type gas turbine

These turbines usually employ multi-stage axial compressors that result in pressure ratios in the range of 5:1 to 15:1. Can-annular type or silo combustors are normally used in these turbines. These types are explained in detail in subsequent chapters.

The expander section of these turbines consists of a gas generator employing a 2 or 3 stage axial turbine. The first stage nozzle guide vanes and blades will be air cooled. The power turbine will comprise a one or two stage axial flow turbine. One major disadvantage with industrial turbines is that they require relatively long warm up periods and perform best only when operated constantly at base load.

The majority of industrial applications can be broadly categorized based on economic factors as:

- Applications using aero-derivative gas turbines used as industrial type gas turbines. The running hours are relatively low, thereby rendering thermal efficiency unimportant. They are used mainly in standby and emergency installations. This area has witnessed significant developments in the recent past with the emergence of the aircraft derivative gas turbines as industrial units mainly on account of their fast startup, high power to weight ratio giving large power outputs for short durations and low specific cost.
- Base load applications involving non aero-derivative industrial gas turbines, where fuel cost forms a negligible part of the overall operational cost thereby rendering thermal efficiency unimportant. This is particularly applicable to oil producing regions of the world where natural gas or crude oil is used as fuel. The choice with regard to the selection of a gas turbine here rests on its ability to burn the local fuel and its operational efficiency. Non aero-derivative gas turbines are normally designed for base load applications because of their higher reliability.
- Applications in which the exhaust heat of a low efficiency engine is utilized to increase the overall thermal efficiency. In the COGEN application, the gas turbine provides a large heat source, with electricity generation being a secondary objective. The economic viability of using these turbines depends upon the ratio of the turbine fuel cost to the cost of other available heating fuels.

Efforts at designing high efficiency turbines of this type have proved successful as demonstrated by the achieving of around 38% efficiency on the latest regenerative gas turbines which have largely replaced the earlier turbines working on the simple cycle. The regenerators, whose working principle will be discussed later, utilize the heat produced by exhaust gases to improve the turbine efficiency. Being split shaft designed, these turbines exhibit high efficiency in part load operations.

1.4 Aircraft derivative gas turbines

Aircraft derivative turbines are largely employed in the power and petrochemical industries. For power generation purposes, these turbines are used in the combined cycle mode, while in the case of the petrochemical sector, they are usually used on off-shore platforms for gas-reinjection. They are also used as power plants on account of their compact design and ease of repair. These turbines also find wide applications as variable speed mechanical drives. These turbines have one enormous advantage when compared with most heavy duty and industrial turbines in that they readily perform peak duty operations, starting up and shutting down at frequent intervals. This is a very important feature. The fact that they can be quickly removed and replaced in the event of failure, or during overhauls, makes them an attractive proposition in a wide range of applications. A sectional view of an aircraft derivative gas turbine engine is shown in Figure 1.3.

Figure 1.3

Sectional view of an aircraft derivative gas turbine engine

The aero-derivative turbines consist of two basic components, the aircraft-derivative gas generator and a power turbine. The gas generator is in most cases an aircraft derivative engine modified to burn industrial fuels and is used to produce energy. The engine may be subjected to various modifications in order to increase their suitability for use in a ground based environment. As indicated in Figure 1.3, axial flow compressors provided in these turbines generally comprise of two sections, a low pressure and a high pressure compressor which are in turn respectively driven by a low pressure and high pressure turbine.

As the name suggests, the aircraft derivative turbines are those turbine types which originate from aircraft engines that have in turn been modified for adoption in power generation units. This is usually accomplished by removing the by-pass fans in aircraft engines and adding a power turbine at their exhaust. This modification results in efficiency levels ranging between 35-45%. One important point to be noted is that the power turbine in aero-derivative gas turbines is a separate entity which is not mechanically coupled, the only connection being via an aerodynamic coupling. This power turbine operates at speeds independent of the gas generator turbine and is in most cases is supplied by a different manufacturer.

The installation costs incurred on these gas turbines is considerably less because of their compact size and reduced weight. The aero-derivative part of these turbines can be easily replaced. This is very advantageous especially during times of overhaul and maintenance. Since the auxiliary and monitoring systems in these turbines are not complex, remote controlling and monitoring of the turbine operations is possible. Also, since the power turbine temperatures in these units are lower, they do not normally encounter the sort of problems that are usually associated with aero engines.

1.5 Comparison between aircraft-derivative and industrial heavy-duty turbines

1. Aircraft-derivative gas turbines have favorable installation costs, higher power to weight ratio and lower specific costs when compared with industrial heavy duty turbines.
2. Aircraft-derivative turbines give larger power outputs than industrial turbines for short time durations.
3. The starter power and torque requirement for industrial turbines is greater when compared with the aero-derivative type.
4. Aero-derivative types have faster startup as compared to the industrial type.
5. Industrial heavy duty gas turbines have higher operational reliability and efficiency than aero-derivative gas turbines.
6. Aero-derivative types have higher noise levels as compared to industrial turbines.
7. Aero-derivative turbines can perform peak duty operations and can startup and shutdown at frequent intervals, whereas the industrial turbines give optimum performance only at constant base load operation.
8. Industrial heavy duty type turbines are suitable for constant speed applications such as generator drives and pump/compressor drives whereas the speed flexibility of the aero-derivative type makes it possible for it to meet or exceed load-speed requirements of all types of driven equipment including variable speed drives.
9. Industrial turbines have longer life and are more rugged in design and construction when compared with the aircraft- derivative type.

10. Industrial type turbines are more suitable for use in continuous duty applications where there is a large power requirement demanding longer endurance life and having no size restriction.
11. The auxiliary and monitoring systems in aero-derivative turbines are not as complex as in industrial heavy duty turbines and therefore remote monitoring and control is relatively easy.
12. Maintenance and overhaul is easier in aircraft-derivative turbines as compared to the industrial type.
13. Lower inlet temperature conditions in aircraft-derivative turbines result in fewer problems when compared with industrial turbines.

1.6 Small and micro gas turbines

Small gas turbines usually generate less than 5 MW of power. Their design is normally modeled on larger industrial turbines and in the simplest form, consists of a single stage centrifugal compressor with a single silo combustor and a radial-inflow turbine. They are rugged and simple in construction and this ensures long periods of trouble free operation in most cases. Although the efficiency levels of these turbines are much lower on account of the reduced efficiency levels of their components and limitations with regard to the turbine inlet temperature, it is possible to obtain higher thermal efficiencies of these turbines by utilizing the exhaust gas heat.

Figure 1.4a shows a small turbine unit with a centrifugal compressor and a radial inflow turbine.

The compressed air from the compressor flows into the silo combustion chamber from where a portion enters the combustor head, to mix with the fuel for combustion, while the remaining air passes through the combustor walls to mix with the hot gases. An even temperature distribution is attained in the hot gases by efficient atomization of fuel and controlled mixing. The hot gases are allowed to expand in the turbine, to impart rotational energy used for driving the external load and other auxiliary systems.

Small turbines can also be derived from aircraft. These are similar to the aircraft derivative turbines already discussed and with the same principles of design and operation, but smaller in size.

Another example shown below (Figure 1.4b) is that of a small aircaft gas turbine engine with both an axial and centrifugal compressor.

Figure 1.4a

Sectional view of a small land based turbine unit with a centrifugal compressor and a radial inflow turbine

Figure 1.4b

View of a small gas turbine with a final stage centrifugal compressor.

1.6.1 Micro turbines

These turbines are so called because of the fact that they generate very little power, usually 350 kW and less and are comparatively small in size. They find application in base load and co-generative (COGEN) units and are powered either by natural gas or diesel fuel.

The micro turbines usually consist of radial flow turbines and compressors and are in most cases provided with regenerators to obtain high thermal efficiencies. Their relative advantages in the form of compactness, low manufacturing cost, and quietness in operation, quick start-ups and minimal emissions make them ideal candidates for industrial applications of the future (in the form of distributed power systems).

1.7 Aircraft gas turbines

Aircraft gas turbines are designed for greater performance, reliability and flexibility in operation and use the most sophisticated and modern technology that has evolved over the years. Thrust to weight ratio is the most critical aspect in the design of these gas turbines and considerable success has been achieved in recent times with the development of high-aspect ratio blades and maximum work output per unit mass flow. Although different types of gas turbine engines are used for propelling aircraft, they are basically categorized as:

- Turbojet

- Turbofan and
- Turboprop engines

The turbojet engine consists of a gas generator section and a thrust section. In the gas generator section, the high pressure, high temperature gas is produced, while in the thrust section, engine thrust is provided by a nozzle. The propulsion efficiency in these engines is quite low on account of the high velocity of the exiting gases. Jet engines have been in the forefront in achieving higher firing temperatures and pressure ratios in the range of 1371°C to 1649°C (2500°F to 3000°F) and 40: 1 respectively.

To achieve higher propulsion efficiencies additional air must be compressed. More power has to be extracted in the turbine, without increasing the work done to drive the compressor. This results in no increase in the amount of fuel supplied to the engine. This is essentially the working principle in turbofan engines, where the propulsion efficiency is increased by reducing the overall exit velocity.

The turbofan engine is therefore a modified turbojet engine where the first compressor stages are replaced by fans. The added turbine capability needed to drive the fan and the compressor is largely dependent on the fan pressure ratio and the amount of air bypassing the turbojet. The specific fuel consumption in these engines is lower on account that this added thrust does not require any increase in fuel flow.

In a turboprop engine, the propulsion is achieved by a combination of an external propeller and the thrust obtained by the exit of the exhaust gases from the turbine. This is also essentially a modification of the turbojet engine, in which an additional turbine is provided to drive the propeller, through a reducing gear mechanism. This engine therefore combines the advantages of both the turbojet and the propeller in order to achieve higher propulsion efficiency.

1.8 Gas turbine components

1.8.1 Introduction

A gas turbine unit consists of various components like the compressor for delivering pressurized air to the combustion chamber or combustors where the actual combustion occurs, the expander section comprising the turbine where the exhaust gases are expanded to do work, the regenerators which utilize the heat generated by the exhaust gases to improve turbine efficiency, exhaust nozzles, igniters and fuel atomizers. A brief introduction to the important turbine components is given below; to be followed by a detailed discussion in subsequent chapters.

1.8.2 Compressors

A compressor is a device which pressurizes a gas. It is a critical component of the gas turbine plant since it consumes a large percentage of the turbine energy and plays a significant role in determining the overall performance and efficiency of the unit. Compressors are categorized, by their principle of operation and the mass flow and pressure requirements.

Positive displacement compressors

Positive displacement compressors are not continuous flow devices and are therefore not used for compressing the air in gas turbines. They are normally used for high pressure and low flow applications.

Centrifugal compressors

Centrifugal compressors are continuous flow devices and are therefore widely used in gas turbine applications requiring medium pressure and flow. They possess the relative advantages of smooth operation, higher tolerance to process fluctuations and higher operational reliability.

A majority of the centrifugal compressors in use (such as those in small turbines), produce pressure ratios in the range of 1.2:1 to 4.5:1 in a single stage. A typical centrifugal compressor stage consists of an impeller or rotor and a diffuser. At the entrance to the impeller is the inducer where the fluid enters. The inducer inlet is sometimes provided with inlet guide vanes for imparting circumferential velocity to the fluid. The fluid is then forced through the impeller by the rotating blades and the resulting action ensures that the velocity of the fluid is partially converted into pressure energy. The fluid is then directed towards the diffuser which consists of vanes designed tangential to the impeller and it is here that most of the velocity of the fluid is converted to pressure energy by the diverging vane passages. The fluid coming out of the diffuser exit enters a scroll or collector.

Some of the advantages of centrifugal compressors are:

- They are very durable

- They are less prone to damage by foreign objects
- They are cheaper to manufacture and have low maintenance requirements
- They are less sensitive to fouling

Some of the disadvantages of these compressors are:

- They have very large diameters when compared to other compressors
- With reduction in size, they become less efficient
- They experience loss in efficiency with increase in pressure ratio
- Pressure ratios in these compressors rarely exceed 4.5: 1

Axial-flow compressors

Axial flow compressors are also continuous flow devices and are therefore extensively used in gas turbines for high flow applications. These are invariably multi-stage devices achieving pressure ratios as high as 40: 1, through a series of small increases in each stage, resulting in very high efficiency levels.

The working fluid in axial flow compressors is compressed by initially accelerating the fluid in a row of rotating blades and then diffusing it with a row of stationary blades (stators). Thereby converting the velocity increase obtained by the action of the rotating blades to a pressure increase. A stage therefore comprises a rotor and a stator. These compressors usually incorporate an additional row of stator blades called inlet guide vanes that makes the fluid enter the first stage rotors at the desired angle. The IGVs are sometimes adjustable to match mass flow to power required from the engine.

The advantages with using these compressors are:

- They are most suitable for multi-staging operations
- They give higher efficiencies at high pressure ratios
- Higher mass flow with smaller frontal areas.

Some of the disadvantages associated with axial flow compressors are:

- Their efficiency decreases with reduction in engine size on account of the high percentage of blade-tip leakage in smaller compressors.
- Narrow range of stable operation between surging and choking limits makes part load operations difficult.

1.8.3 Combustors

Air leaving the compressor enters the combustor through the diffuser zone. The diffuser zone acts as a transition zone between the compressor discharge and the combustor inlet. Here the compressor discharge air is diffused such that its velocity reduces. This is done in order to minimize pressure loss which in turn is a function of the squared velocity.

A combustor in a gas turbine is where the actual combustion takes place. There is an almost complete burning of the fuel in combination with 1/3rd or less of the compressor discharge air. These high temperature exhaust gases are then completely mixed with the remaining air to arrive at a suitable turbine inlet temperature.

Design of a good combustor should achieve the following:

- Ensure stable and efficient operation over a wide operating range
- Ensure uniform temperature distribution for greater efficiency in operation
- A near complete release of chemical energy in the space provided for efficient combustion
- Pressure drop across the combustor should be minimal
- High combustion efficiency giving greater reliability in operation and low emission levels

All combustion chambers irrespective of their design features consist of three distinct zones as shown in Figure 1.5.

Figure 1.5

A typical combustor can with straight through flow

These three zones are:

- A recirculation zone where the fuel is partially burnt and evaporated, in order to prepare it for full combustion in the burning zone. This zone of the combustor where the fuel is injected and ignition occurs. The fuel injection should be done in such a manner that a uniform distribution of the fuel-air mixture takes place. The air velocity in this zone should be kept below the flame velocity, to ensure that the flame is not carried out of the combustor. The fuel should be injected in a highly atomized condition at high velocity to ensure complete and efficient combustion.

- A burning zone where the fuel is completely burnt to form products of combustion and
- A dilution zone where the products of combustion in the form of the hot burnt gases are mixed with the morning air, in order to attain a suitable turbine inlet temperature.

Normally combustion temperatures range from 1871°C to 1927°C (3400°F to 3500°F). The combustor efficiency is largely determined by the effectiveness and completeness of the combustion procedure, the pressure decrease across the chamber and the uniform distribution of outlet temperature.

Types of combustor arrangements

Combustion chambers can be arranged as follows:

Can type combustion chambers

A sectional view of a simple can type combustor arrangement is shown in Figure 1.6.

Figure 1.6

Can type combustion chambers

The can type combustors extensively used in various industrial applications are made up of a number of small diameter units. They are called cans with their individual liners and casing. They are arranged concentrically about the turbine axis. These combustors are reliable and give high combustion efficiencies. They are also easy to maintain, as the individual cans may be separately inspected, removed or replaced. They also possess excellent structural strength without excessive weight and can be operated for long periods without maintenance.

One of the major disadvantages associated with these combustion chambers are their unusually large size due to the inefficient use of cross-sectional area by the individual can. There is also a tendency in these combustors for hot spot formation, because of inadequate mixing of dilution air with the burnt gases. Additionally, the use of separate small chambers with their narrow inlet and exit ducts, results in appreciable pressure loss in the chambers.

Annular type combustion chambers

The annular type combustion chamber is theoretically the most suitable combustor from the point of view of simplicity in design, space saving and reduced pressure losses. They are extensively used in aircraft applications, where small frontal area is important. Figure 1.7 shows the arrangement in an annular type combustion chamber.

Figure 1.7

Annular combustion chamber

The annular combustion chamber in its simplest form is essentially a single chamber made up of concentric cylinders mounted co-axially about the engine axis. The outside radius of this combustor is the same as the compressor casing and overall design is such that, the available space is used effectively.

These combustors are used extensively in high temperature applications on account of the fact that their smaller surface areas require less cooling air. They also provide a near uniform gas mixture at the turbine nozzle inlet with very low pressure drop and therefore give high overall efficiencies.

The major disadvantage with this combustor (from the maintenance point of view) is that the entire combustion chamber must be removed for inspection and repairs. These combustion chambers also have warping tendencies and are structurally weaker.

Can-annular type combustion chambers

The can annular type combustion chamber is an improvement on the can type and is used in a number of gas turbine engines. This combustor consists of individual cans placed inside a cylindrical chamber. The cans are usually joined by flame tubes which are used to propagate the flame. The sectional view of a can-annular type combustor arrangement is shown in Figure 1.8.

Figure 1.8

Can-annular type of arrangement

The advantage with this combustor is that it makes good use of the available space, unlike the can type. Additionally a good amount of control can be exercised over the flow of fuel and air, because the individual cylinders receive air through a common annular housing. The can-annular type combustors possess greater structural stability, give less pressure loss and utilize the cross-sectional area better, when compared with the can type. The temperature distribution at the turbine nozzle inlet is even and this reduces the possibility of formation of hot spots. The design and arrangement of these combustion chambers, like the can type, facilitates easy maintenance. Most importantly, the combustion process is also even, as each can has its own nozzle and separate small combustion zone.

This combustion chamber is not suitable for use in high temperature applications because of the reduced availability of air for cooling.

‘Silo’ type cylindrical combustors are widely used by industrial engines. There may be more than one per engine. They are internally lined with metallic tiles. They can be vertically or horizontally mounted.

Silo type combustion chambers

Silo type cylindrical combustors are widely used by industrial engines. There may be more than one per engine. They are internally lined with metallic tiles. They can be vertically or horizontally mounted.

1.8.4 Regenerators

Regenerators are usually employed in gas turbines to increase the cycle efficiency. They utilize the heat generated by the exhaust gases, which is otherwise wasted by transferring it to the combustor incoming air, resulting in reduced fuel consumption.

A **schematic** of a typical regenerator unit used in gas turbines is shown in Figure 1.9 below. Air entering the regenerator air inlet absorbs heat from the hot exhaust gases before leaving via the air outlet to enter the combustor. By utilizing the concept of regeneration in gas turbines, a reduction in fuel consumed to the tune of almost 30 % can be achieved. The example shown in Figure 1.9 is widely used in industrial applications.

Figure 1.9

Plate fin type regenerator

1.8.5 Turbines

The expander section of gas turbines can be one of two basic types. They are:

- The axial-flow turbine and
- The radial-inflow turbine

Of these two turbine types, axial-flow turbines are the most efficient.

Radial-inflow turbine

The radial-inflow turbine is basically a centrifugal compressor with reversed flow and opposite direction of rotation. There are two types of radial-inflow turbines:

- The Cantilever type and
- The Mixed-flow type.

The cantilever type is similar in design to the axial-flow turbine, but with radial blading. This type is not very popular because of the difficulties associated with its design and manufacturing.

The mixed-flow radial turbine is the most widely used and is identical in design to a centrifugal compressor, except for the fact that the components in this turbine serve a different purpose.

This turbine consists of an impeller or rotor around which nozzle blades are fitted. These blades direct the fluid flow inwards. Acceleration in flow takes place when the fluid flows through these blades. The exit section of the blading is known as the exducer. The exducer is curved in order to remove some of the tangential velocity force at the outlet. The outlet diffuser provided in the turbine, converts the high velocity fluid flow from the exducer into static pressure energy.

Like radial flow compressors, the work produced by a single stage in a radial-flow turbine is equivalent to that of two or more stages in an axial turbine. Its lower initial costs are an added advantage. Widespread use of these turbines is made in turbochargers of internal combustion engines, as an expander in environmental control systems and as standby generating units.

Axial-flow turbine

Axial-flow turbines are the most widely used in gas turbine units. They are highly efficient in most operational ranges. The flow in these turbines is in the axial direction, both at the entrance and exit sections. Like their compressor counterparts, they usually consist of more than one stage. There are two types of axial-flow turbines:

- The Impulse and
- The Reaction

In the Impulse type axial-flow turbine, the fluid enters the rotor at very high velocity, because the entire enthalpy drop takes place in the nozzle, whereas in the case of reaction turbines, the enthalpy drop is divided between the nozzle and the rotor.

The various concepts associated with the design, function and operating principles of the components described above, are discussed in detail under ‘Gas Turbine Components’.

Heat recovery steam generators (HRSG)

One method of heat recovery in gas turbines utilizes the turbine exhaust gases for generating steam in power plants operating on the combined cycle. This is a combination of the gas turbine and a steam turbine. This combined cycle finds extensive application in modern power plants because of the following advantages:

- **High thermal efficiencies at smaller unit sizes.**

Reduction in cooling requirements because cooling is required to be carried out only on the steam turbine portion of the cycle. The plant can be extended in stages, meaning an initial simple cycle gas turbine plant can be upgraded at a later stage by the addition of a steam turbine, to form the combined cycle power plant.

- **High operational stability and performance at different ranges of operation.**

The gas turbine in a combined cycle plant exhausts into the Heat Recovery Steam Generator (HRSG). The HRSG transfers the heat energy to water to produce steam.

- There are various configurations of HRSG units. These are:

- The unfired HRSG unit, where no additional energy is added to the gas turbine exhaust gases between the gas turbine exit and the inlet to the HRSG.

    - and
- The supplementary fired HRSG unit, where additional fuel is supplied between the gas turbine exhaust and the HRSG boiler.

Figure 1.10 shows a typical combined cycle plant with an unfired heat recovery steam generator.

Figure 1.10

Heat recovery without supplementary firing

The HRSG unit usually consists of a de-aerator, a pre-heater or economizer, an evaporator and a superheater, which may be of the single-stage or multi-stage type. The function of the de-aerator is to remove the gases from the water or steam. Without de-aeration, the oxygen content in the water or steam can cause severe corrosion related problems. The de-aerator is quite simple in design and is nothing but a heater onto which the condensate is sprayed and heated, in order to release the gases that are absorbed by water or steam.

The economizer in the HRSG heats the water to a temperature close to its saturation point. Care should be taken to ensure proper design of the economizer so that it doesn’t generate steam which can lead to blocking the flow. This may be prevented by keeping the water at the outlet in a slightly sub-saturated state. Steam formation in the economizer can also be prevented, by maintaining high pressure with the help of a feed water control valve installed downstream of the economizer. The difference between the water temperature at the economizer exit and the saturation temperature is called approach temperature and is maintained as small as possible in the range between –12°C and –6°C. The water exits from the economizer in the form of a saturated liquid. The minimum temperature difference which occurs at this point between the gas stream and the water stream is known as the pinch point which is usually in the range between –1.1°C and 10°C. Lower pinch points result in greater heat recovery i.e. the amount of energy transferred from the exhaust gases to the water can be increased by bringing down the pinch point temperature. This requires larger heat exchanger surface areas for which cost factors come into play. Excessively lower values of pinch points can also mean insufficient steam generation, especially if the exhaust gas is low in energy.

In the evaporator, conversion of water from the saturated liquid state to the saturated vapor state takes place. This saturated vapor is finally superheated in the superheater before entry into the steam turbine section.

In a combined cycle plant, about 60% of the power requirement is met by the gas turbine, while around 40% is met by the steam turbine. The thermal efficiencies of the combined cycles with heat recovery can be as high as 60%, although the individual thermal efficiencies of the gas and steam turbine units are between 30–40%. The improved efficiency levels attained by the introduction of the concept of heat recovery in combined cycles are obvious.

As discussed earlier, combined cycle plants with supplementary firing have additional heat supplied between the gas turbine exhaust and the HRSG inlet as shown in Figure 1.11**.**

Figure 1.11

Heat recovery with supplementary firing

The typical HRSG inlet temperatures in these units are usually in the range of 427°C–815°C (800-1500°F).

Supplementary firing enables the system to track demand i.e. produce more steam as the load swings upwards. This is not possible in unfired combined cycle units.

The other advantage with supplementary fired units is that the gas turbine can be made to handle base load requirements, while the higher load swings are taken care of by the supplementary firing. This also results in higher HRSG inlet temperatures allowing for a significant reduction in heat transfer area and thereby the cost. The other advantages of supplementary firing in combined cycle plants are

- It results in an increase in the total combined output of the cycle
- It helps control the HRSG inlet temperature which in turn influences the

gas temperature and air flow rate at the gas turbine exit

Adequate care should be taken in the design and construction of combined cycle supplementary fired systems, (like using special alloy material for the evaporator and the superheater) in order to withstand higher temperatures, ensuring sufficient length of the inlet duct for complete combustion, avoiding direct flame contact on the heat transfer surfaces and increasing the insulation thickness on the duct section.

In natural circulation HRSGs, the circulation of the steam-water mixture through the evaporator is due to convection.

Forced circulation HRSGs use a re-circulating pump for circulating the steam-water mixture through the evaporator tubes. This forced method of circulation allows the use of smaller sized tubes with increased heat transfer coefficients although a pump for this purpose will increase the load of auxiliaries.

While natural circulation HRSGs are normally of the horizontal flow type, forced circulation HRSG’s normally have a vertical exhaust flow arrangement. This may not always be the case and may vary according to manufacturer specification and design.

Drum Type HRSG and Once Through Steam Generator (OTSG)

The most commonly used heat recovery system in combined cycle plants is the drum type HRSG with forced circulation. These are vertical type heat recovery generators having vertical gas flow with the drums being supported by steel structures provided in the unit. Drum type HRSG’s can be of both the natural or forced circulation type.

The Once through Steam Generator or OTSG is another type of HRSG that is finding increasing acceptance in combined cycle plants. These units have the advantage of simple design, can be installed in a much shorter time and are cost effective. They basically differ from the other HRSGs in that they do not have defined economizer, evaporator and super-heated sections. Also the drums and the circulation pumps are totally dispensed with. The OTSG instead simply consists of a tube where the water enters from one end, absorbs heat during the course of flow through the tube and exits as steam from the other end. OTSGs are often applied for supercritical steam conditions.

The multi-pressure steam generator is the other HRSG variant which is being increasingly used. The restriction in the amount of heat recovered in single pressure steam generators on account of their inability to reduce the exhaust gas temperature below the steam saturation temperature, is a serious impediment which can be overcome by using multi-pressure steam generators. Here steam is supplied to the steam turbines at different pressures resulting in greater thermal efficiencies and better heat energy utilization of the exhaust gases.

Combined cycle for power generation

By virtue of their high efficiency levels of around 55%, combined cycle plants are the obvious choice for power applications. They exhibit rapid starting and acceleration characteristics and thereby allow full power output to be reached quickly and can be used for both base and peaking loads. In fact, new gas turbines in the combined cycle mode are being selected in preference to steam turbines as base load providers of electric power.

As already discussed, combined cycles range from the simple single-pressure cycle where the steam is generated at only one pressure to multi-pressure cycles where steam is generated at different levels. One important consideration in a combined cycle power generation plant is whether the unit is to be a separate system or is to be connected to a larger existing system. While a separate system will maintain its own frequency control, the latter will have the frequency controlled by the main system.

In the combined cycle power plant used for power generation, the gas turbine is to be operated at constant speed since any variations in speed could cause major problems. The load here is controlled by modulating the fuel input which is in turn a function of the turbine firing temperature and inlet guide vane position. The gas turbine exhaust temperature must be held relatively high because the effectiveness of heat recovery is dependent on maintaining this temperature.

Combined cycle power generation plants can be either of the single or the two-shaft configuration. In the single-shaft arrangement, the steam turbine, gas turbine and the generator are provided on a single shaft, while in the case of the two-shaft arrangement, the steam and gas turbines have separate shafts. Nowadays, all large base load combined cycle power plants are of the single-shaft configuration. Gas turbines in combined cycle power plants can also be categorized as hot or cold end drive application types.