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The Working Principle of a Turbine "Case Study: GE Frame 9E Gas Turbine"

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Case Study

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ABSTRACT

Gas Turbine is one of the machines that use the thermodynamic principle converting fuel energy to mechanical energy. It is an internal combustion engine. Also, designed to accelerate a stream of gas, which is used to produce a reactive thrust to propel an object or to produce mechanical power that turns a load. It functions in the same way as the internal combustion engine. It sucks in air from the atmosphere, and compress it. The fuel (gas) is injected and ignited (spark plug). The gases expand doing work and finally exhausts outside. Instead of reciprocating motion, the gas turbine uses a rotary motion throughout, and that is the only difference.

Keywords: Turbine; fuel (gas); principle; combustion; exhaust.

1. INTRODUCTION

Gas turbine engines were first invented to power aircraft and were adopted to propel ship until it was introduced in power generation.

However, the gas turbine does not generate electricity, they are used to drive electrical generators, and hence generators that are driven by gas turbine are called gas turbine generators [1-6]. The gas turbine provides the mechanical

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rotation required to create an interaction between metallic conductors and magnetic flux which produces emf. Emf is produced when metallic conduction cuts across magnetic flux or vis-visa, the turbine provides the motion for the flux (conduction) interaction [7-12].

There is an abundant deposit of oil and gas for gas plant usage in Nigeria. Investigation shows that gas is abundant in the Niger-Delta region of Nigeria.

A gas turbine, also called a combustion turbine, is a type of internal combustion engine that has an upstream rotating compressor coupled to a downstream turbine, and a combustion chamber in between. The major compartments of a gas turbine are Compressor, the combustor, and the turbine. As shown in Fig. 1. This work shows that the basic operation of the gas turbine is similar to that of the steam power plant except that air is used instead of water. Gas turbine operates by continuous drawing in fresh air into the compressor [13-18]. The air is then compressed to high pressure in the compressor and discharge into the combustion. Here, the air is mixed with gas and burns continuous once ignited to increase its energy level at constant pressure. The high pressure and temperature combustor product enter an expansion turbine that converts the gas thermal energy into the mechanical energy of a rotating shaft, which in turn drives the generator rotor [19-25]. The resulting low pressure and low-temperature gases are discharged to the atmosphere at constant pressure after expanding through the turbine.

2. MAJOR COMPARTMENT AND METHODS

The major Turbine Compartment are; Accessory Compartment, Compressor Compartment, Turbine Compartment. (Combustion and Turbine Section), Exhaust Compartment.

The starting (cranking) motor, engaging the torque converter and rotating the turbine shaft. But until the turbine “catches" or "start", it's only cranking or turning over. The cranking and the turning over are the mechanical rotation of the engine before it catches or starts. When the gas turbine is s started from a diesel engine, such a turbine could be said to have a facility called black start (i.e. No external source of current is needed in starting such machine). Such a machine is important when there is a total grid power collapse. The initial speed is given by the starting means, and this starting means carries the machine to sustainable speed before cutting off (breakaway) at about 75% speed. There is no shaft to shaft contact, hydraulics is used to transmit the rotational force of the starting means to that of the turbine shaft. The principle of hydraulics is used to convert the energy from the starting means to a higher one which can now move the shaft of the turbine. As shown in Fig. 2. It is flexibly coupled by hydraulic and therefore transmits energy through the fluid without flange to flange coupling.

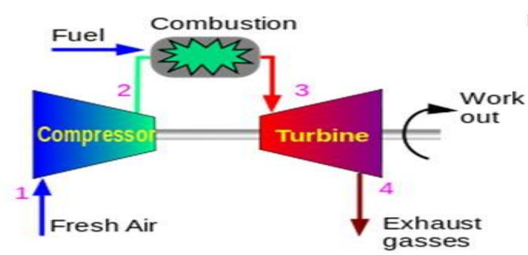

Fig. 1. Simple-cycle, single shaft gas turbine

The accessory Gear Box [Fig. 3] connects the shaft of the Torque Converter to the turbine. There is an over- speed bolt fixed within the accessory gearbox for machine/mechanical over-speed protection.

The gas turbine compressor is an axil flow type centrifugal compressor that efficiently compresses a large volume of air. It consists of many individual stages, operating in series. The number of stages depends on the design and unit capacity e.g. GE frame 9 machines have a 17 stages compressor. The compressor sucks in air from the atmosphere, at atmospheric pressure and compresses it to pressure in the rage of 15 to 20 bars. Each stage consists of a rotating row of blades that increases the velocity of the incoming air followed by a stationary row of blades that converts the kinetic energy of the air to increased pressure. At the compressor inlet, there is a row of stationary blades known as the inlet guide vanes (IGV) that controls the amount of incoming air into the first rotating stage of the compressor in a smooth fashion. The flow angle of the IGVs can be varied in control of the volume of air being drawn into the compressor. Such IGVs are called variable inlet guide vanes. The compressed air also serves as a source of cooling and sealing air for the turbine nozzles, wheels, transition pieces, bearing and other portions of the hot gas path that needs cooling.

Fig. 2. Torque converter

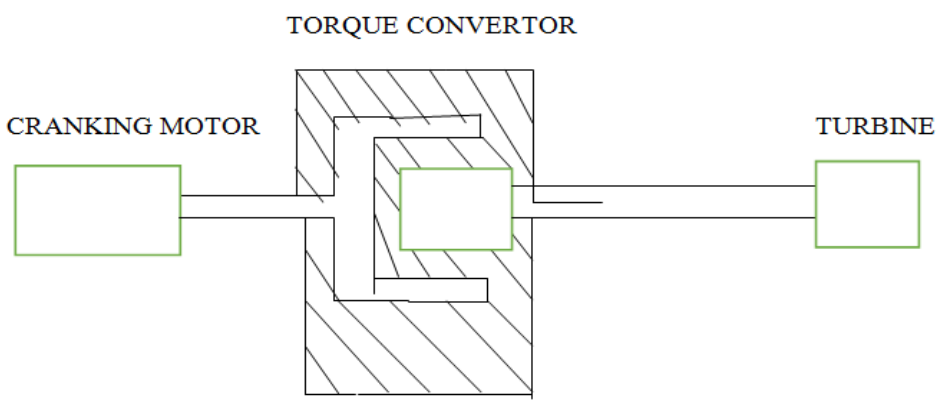

Fig. 3. Torque converter (schematic)

Fig. 4. Accessory gear box

2.1 Inlet Guide Vane (IGV)

To prevent surging of the compressor and for smooth-acceleration, variable inlet guide vanes are provided and are located at the end of the inlet side casing. During start-up period, blade opening is reduce to 25.8 degree, and then the blade opening is controlled by pre-determined characteristics only after the adjusted turbine rotating speed compensation by ambient temperature becomes more than 74.3%. After rotated (100%) speed, it is controlled in accordance with the load within the opening of 60.8 ~80.1 degree.

Movement of this inlet guide vane is actuated by a hydraulic cylinder connected to the inlet guide vanes control ring that turns the individual pinion gear mounted on the end of each blade.

2.2 Combustion Section

The combustion consist of the followings:

1. Combustion chamber.
2. Fuel nozzle.
3. Spark plugs.
4. Ultraviolet flame detectors (instrument device)
5. Thermocouple (instrument device)
6. Liner assembly and cap
7. Cross fire tubes.
8. Retainer clip.

The combustion system consists of fourteen (14) liners into which fuel is injected and burns with a portion of the compressed air. The excess air is used to cool the products of combustion to temperature level useable by the turbine. The individual liners are connected to the turbine section by transition pieces.

Fuel is injected into each linear by fuel nozzles that atomize the fuel for proper burning. The fuel is ignited initially by electric spark plugs (igniters). Once the fire is started, the combustion process is self-sustaining as long as fuel and air are available.

The pressure created by the combustion then forces or pushes the spark-plug from the combustion zone.

2.2.1 Combustion chamber

Discharged air from the compressor enters ring-shaped space which is formed by the rear part of end side casing and the front part of the turbine casing. At this point, the air flow is changed to reverse direction and go into the combustion liners. Inlet air to the combustion chamber supplies the necessary oxygen and also cools down the linear and outer cylinder.

Certain amount of inlet air goes into the liner cap, and then cools down the liner cap and fuel nozzle. Air goes through the ring-shaped space between the Linear and outer cylinder cool down the outer wall of the liner and inner wall of the outer cylinder, also go inside the liner through the liner hole and slot cooling hole, thereby cool down the liner inner wall, the mix with fuel as Combustion air.

Fig. 5. Compressor rotor and blades

Fig. 6. Inlent guide vane

Fig. 7. Combustion rotor

Most of all amount of combustion air is gone inside through the liner hole. The hot gases in the range of 1400 to 1500ºc leave the chamber with high energy level.

2.2.2 Spark plugs

Combustion is initiated by means of spark discharge from two spark plugs which are bolted to flanges on the combustion cans and centred within the liner and flow sleeve in adjacent combustion chambers. These spark plugs receive their energy from ignition transformers. At the time of firing, a spark at one or both of these plugs ignites the fuel (air) mixture in a chamber, the remaining chambers are ignited by crossfire through the tubes that interconnect the reaction zones of the remaining chambers.

Fig. 8. Spark plugs

Flame monitoring is realized by flame detectors which are installed in 2 and 3 or 7 and 8.

2.2.3 Fuel nozzle

Gas fuel entered into the combustion chamber through the fuel nozzles which are installed on outer cylinder cover of each combustion chamber and are penetrated to the inside of liner cap. This nozzle creates a highly atomized, accurately shaped spray of fuel for rapid mixing and combustion with the primary airstream under varying conditions of fuel and airflow. Most engines use either the single (simplex) or the dual (duplex) nozzle.

2.2.4 Crossfire tubes

All combustion chamber are interconnected by the means of crossfire tubes. These tubes enable flame to propagate from chamber to chamber. The outer chamber is connected with an outer crossfire tube and the combustion liner primary zones are connected the inner crossfire tubes.

2.2.5 Retainer clip

A retainer clip can be referred to as the anti-rotation function. All the liners are connected with the help of cross-fire tubes, this tube helps to transfer fisre/flame from one liner to another.

The retainer clip help to keep the cross-fire tube firm (constant) i.e. it's does not give room for the cross-fire tubes to shift from their position (primary zones).

2.2.6 Flow sleeve

Flow sleeve guides cooling and combustion air to the liners. Also supports liners and crossfire tubes.

2.2.7 Combustion liners

Liners are the materials used to direct the combustion product from the combustion section down-stream to the turbine region. During operation, the combustion liners become quite hot. Therefore, cooling air is provided to cool the combustion liner.

The combustion use external ridges and conventional cooling slots for cooling. Interior surface of the liner and the cap are thermal barrier coated to reduce metal temperatures and thermal gradients.

The cap has five premixer tubes that engage each of the five fuel nozzle. It is cooled by combustion of film cooling and impingement cooling and has thermal barrier coating on the inner surfaces. Some gas turbine has one fuel nozzle attached to each can as specifically designed, e.g. GE frame 9 machine and Hitachi H25 machine. Air enters the combustor through a variety of holes in the liner and cap and swirlers which are typically a part of the fuel nozzle.

Depending on the injection location, air is utilised for the actual combustion process, for cooling, or as dilution to tailor the exhaust gas profile.

Fig. 9. Fuel nozzles

Fig. 10. Crossfire-tube

2.2.8 Transition piece (TP)

The Transition Piece having a body of tubular shape, it is an inlet to receive and guides hot gases from liners into the first stage turbine nozzle.

2.2.9 Ultraviolent flame detectors

The control system continuously monitors for presence or absence of flame using flame detectors installed in two combustors.

2.3 Turbine Section

The turbine consist of Three (3) stages: each stage is comprised of a stationary row of nozzles where the high energy gases are increased in velocity and directed towards a rotating row of buckets attached to a turbine shaft. The high-velocity gases pushed against the buckets converting their kinetic energy to rotating motion of the turbine shaft.

The energy from the combustion system available to drive the turbine is change by varying the amount of fuel injected into the combustion liners.

The turbine section is the area where energy, in the form of high temperature pressurized gas produced by the compressor and the combustion section, is converted to mechanical energy. Gas turbine hardware includes the following:

1. Turbine rotor
2. Turbine casing
3. Exhaust frame
4. Exhaust diffuser
5. Nozzles
6. Shrouds

2.3.1 Turbine buckets

The turbine bucket forms the turbine rotor which is in 3-stages forming the three-stage turbine wheel.

The turbine bucket increase in size from the first to the third-stage, because of the pressure reduction from the energy conversion in each stage, an increased annulus area is required to accommodate the gas flow. Thus necessitating increasing the size of the buckets. The first-stage buckets are the first rotating surfaces encountered by the extremely hot gases leaving the first-stage nozzle. Each first-stage bucket contains a series of longitudinal air passages for the bucket cooling. Air is introduced into each first-stage bucket through a plenum at the base of the bucket dovetail. It flows through cooling holes extending the length of the bucket and exits at the recessed bucket tip. The holes are spaced and sized to obtain optimum cooling of the air-foil with minimum compressor extraction air. Like the first-stage buckets.

Like the first-stage buckets, the second-stage buckets are cooled by span-wise air passages running the length of the air-foil. Since the lower temperatures surrounding the bucket shanks do not require shank cooling, the second-stage

Cooling holes are fed by a plenum cast into the bucket shank. Spanwise holes provide cooling air to the air-foil at a higher pressure than shank holes. This increases the cooling effectiveness in the air-foil with a minimum penalty to the thermodynamic cycle. The third-stage buckets are not internally air-cooled. The tips of the buckets are enclosed by a shroud which is a part of the tip seal. These Shrouds interlock from bucket to bucket to provide vibration damping.

2.3.2 Turbine shrouds

Unlike the compressor blading, the turbine bucket tips do not run directly against an integral machined surface of the casing but against annular curved segment called turbine shrouds.

Fig. 11. Retainer clip

Fig. 12. Flow sleeve

Fig. 13. Combustion liner

Functions of the shroud blocks

1. The shrouds' primary function is to provide a cylindrical surface for minimizing bucket tip clearance leakage.
2. The turbine shrouds' secondary function is to provide a high thermal resistance between the hot gases (1200F) and the comparatively cold shell (600F).
3. The third function of the shroud is to support the nozzles.

The turbine shrouds' secondary function is to provide a high thermal resistance between the hot gases and the comparatively cool shell. In doing this, shell cooling load is drastically reduced, the shell diameter is controlled, the shell roundness is maintained, and important turbine clearances are assured.

The shrouds segments are maintained in the circumferential position by radial pins from the shell. Joints between shroud segments are sealed by interconnecting tongues and grooves.

Fig. 14. The transition piece

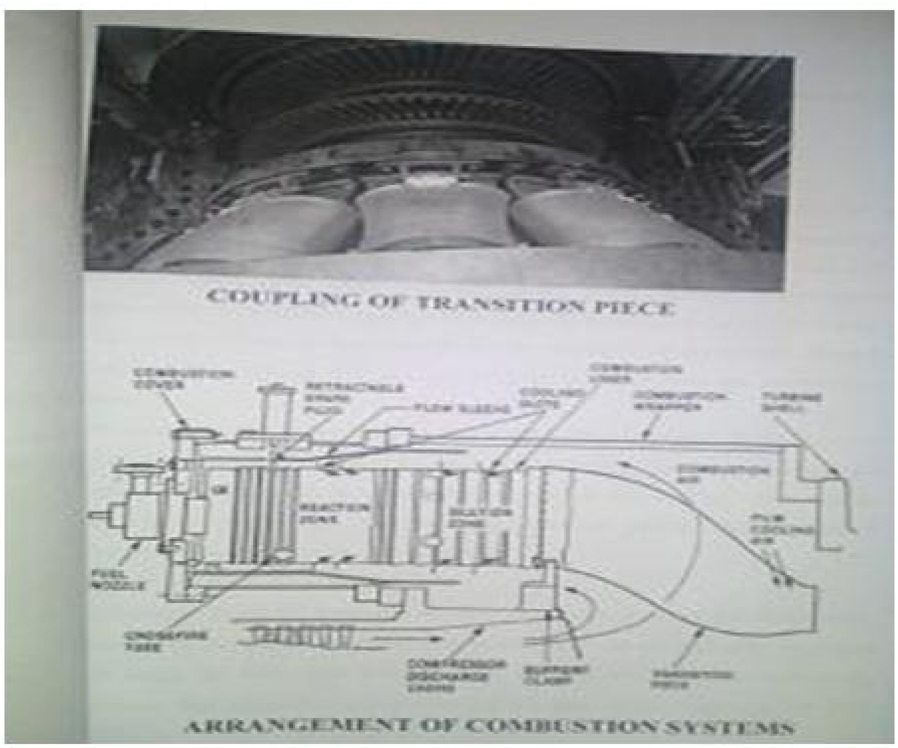

Fig. 15. Arrangement of combustion systems

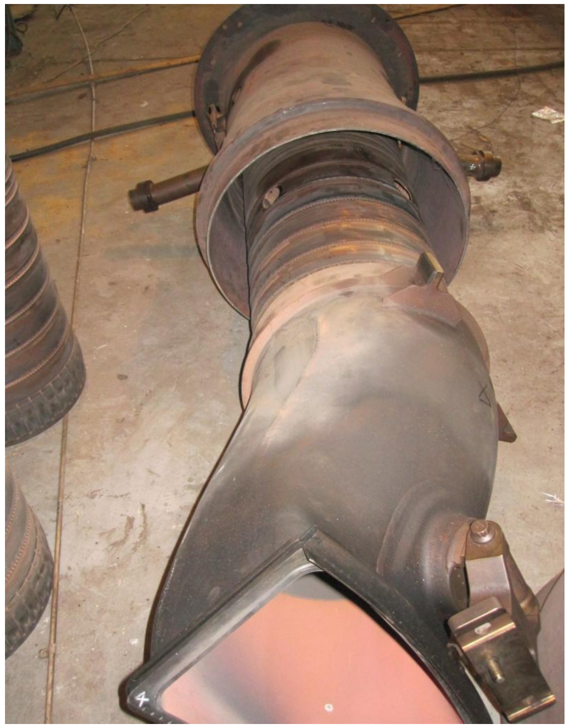

Fig. 16. Linear/flow sleeve/transition piece/cross-fire tube assemble (Back view)

Fig. 17. Linear/flow sleeve/transition piece/cross-fire tube assemble (Front view)

2.3.3 Turbine nozzles

In the turbine section, there are three stages of stationary nozzles which direct the high velocity flow of the expanded hot combustion gas against the turbine buckets causing the turbine rotor to rotate. Because of the high-pressure drop across this nozzles, there are seals at both inside and the outside diameters to prevent loss of system energy by leakage. Since these nozzles operate in the hot combustion gas flow, they are subjected to thermal stresses in addition to gas pressure loadings.

3. GAS TURBINE SYSTEMS

The set of principles or procedures according to which something is done or an organized scheme or method in which a task is done is refer to as SYSTEM. The turbine has various systems which help to efficiently control, coordinate and protect the turbine to ensure proper and efficient performance of the turbine. Some gas turbine systems are:

1. Bearing System
2. Vibration System
3. lube-oil system
4. Fuel system
5. Turbine cooling system
6. Turbine hydraulic oil & trip system
7. Control oil system
8. Exhaust system, etc.

3.1 Bearing System

Bearing No. 1 is located forward of the compressor inlet plenum just before the bell month, it contains both a journal and a thrust bearing. While all journal bearings support the turbine shaft vertically displacement, the thrust bearing limits the horizontal forward and backward movement by the inactive and active thrust pad respectively.

Bearing No. 2 is located between the compressor and the turbine rotor after the compressor and turbine rotor coupling at the centre of the combustions chamber. Bearing No. 3 is located in the Exhaust plenum after the diffuser. Bearing No.3 has a tilting pad journal bearing which helps to prevent vibration of the generator rotor.

The gas turbine contains three journal bearings to support the turbine rotor and one dual direction thrust bearing to maintain the rotor to stator axial position. The bearing are located in the housing at;

- ✓ Bearing number one (1) at the compressor inlet
- ✓ Bearing number two (2) at the combustion chamber area.
- ✓ Bearing number three (3) at the centre of the exhaust frame

All bearings are pressure lubricated by oil supplied from the main lubrication oil system. The number one (1) bearing (journal and thrust) is accessed by removing the top half of the compressor inlet casing, while number two (2) is accessed during a major overhaul. The number three (3) bearing is readily accessible through the tunnel along the centreline of the exhaust diffuser. Bearing protection includes a vibration sensor and drains oil temperature thermocouples.

Types of Bearing:

1. **THRUST BEARING:** this prevent the axial movement of the shaft.
2. **JOURNAL BEARING:** It controls and prevent the radial or lateral movement of the bearing.

3.2 Vibration

The mechanical phenomenon whereby oscillation occurs about an equilibrium point is referred to as VIBRATION. It is a continuous slight shaking movement.

If this undesired/irregular motion is not control by the help of thrust and journal bearing, vibration which is harmful to this machine will take place.

Turbine bucket **Turbine wheel**

Fig. 18. The arrangement of the turbine bucket arranged radially, forms the turbine wheel

Fig. 19. Coupling of shroud block

Fig. 20. Shroud block

Fig. 21. Coupling of nozzle to the shroud

Fig. 22. Nozzle

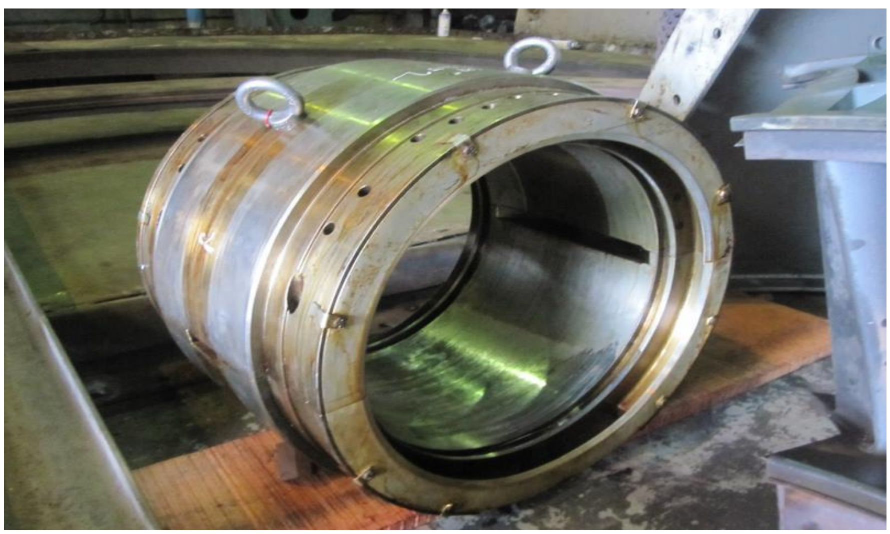

Fig. 23. Journal bearing

The vibration is monitored with the help of a vibration sensor. The maximum overall vibration velocity of this gas turbine should never exceed 25.4mm per seconds in either the vertical or horizontal direction. Corrective action/measure should be initiated when the vibration level exceeds 12.7mm per seconds as indicated on the panel CRT (i.e. cathode ray tube).

Causes of Vibration:

1. Rotor unbalance
2. Shaft misalignment.
3. Start up without sufficient cool down.
4. Sudden change in combustion dynamics.
5. Wear of load gear teeth
6. IGV blade or compressor blade shear and carried along in gas stream.

3.3 Oil Seal or Labyrinth Seal

Lubricating oil on the surface of the shaft is prevented from being spun along the shaft by seal in each of the bearing housing. Oil deflector and labyrinth packing are assembled at the end of bearing. A smooth surface is machined on the shaft and seals are assembled so that only a small clearance exists between oil seal and shaft, and prevent oil leakage or spill.

Fig. 24. Hydrogen seal

Fig. 25. Labyrinth seal

3.3.1 Air inlet system

The air inlet system consists of the following parts;

1. Duct.
2. Expansion joints.
3. Filter compartment.
4. Inlet plenum.
5. Lined elbow.
6. Silencer.
7. Transition piece.

3.3.2 Air filteration

The inlet air treatment system is designed to control air quality to a certain level for the optimal performance of gas turbine and the protection of its components. The main part of the system includes;

- ❖ Air filter housing.
- ❖ Silencer.
- ❖ Ducting.
- ❖ Trash screens.

The inlet house is located at the raised support structure forward and above the accessory compartment of the gas turbine and connected with the inlet ducting. Air inlet filter is a single stage, self-cleaning system type. It utilizes high-efficiency media filter element which is sequentially cleaned during normal operation by pulsed of compressed air. The silencer comes straight after the filter housing and consist of several acoustic panels which contain high-frequency noise generated by the compressor blades within the system.

The arrangement is connected by ducting, with trash screens installed at proper section before the inlet plenum. In the filter housing section, there are air bypass sections acting as pressure relief. The activation and the relief section is linked to the pressure drop of the filter section and/or of the trash screen. Also, there are several screens installed in the bypass sections to prevent solid particles and other foreign materials from entering into the compressor in the event of bypass operation.

Furthermore, there are some maintenance doors (man-hole) installed for the convenience of filter or screen maintenance of the inlet air system.

3.4 Lube-Oil System

The engine lubrication system includes the lubricating oil, oil pump, oil filter and the oil passages. Oil lubrication provides a barrier between rotating engine parts to prevent damage by friction, damage which can result in huge repair bills. The engine oil provides a method of cooling engine parts that are not cooled by the engine cooling system. Engine oil helps to protect engine components from corrosion by neutralizing harmful chemicals that are the by-product of combustion.

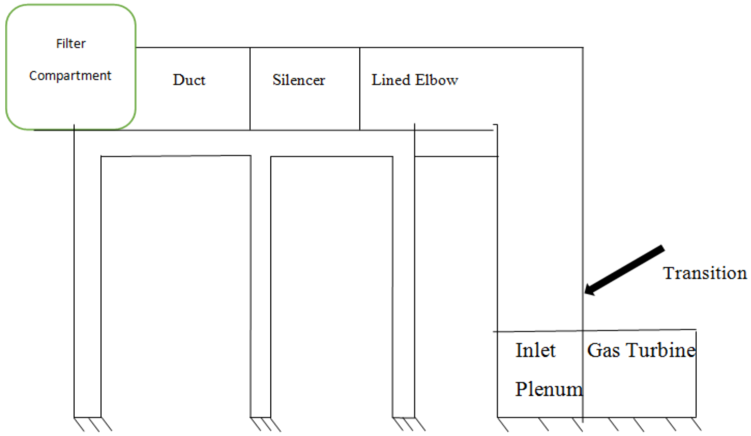

Fig. 26. Air inlet system

Fig. 27. Inlet filters

To protect moving parts and reduce friction, lube oil provides a barrier between the rotating or moving engine components. Ideally, a film of oil should exist between moving components. This is called **full film lubrication**. In order to achieve full film lubrication, a constant supply of clean oil is required. The engine oil system constantly filters and circulates engine oil to ensure that all components are protected.

3.5 Fuel System

Gas turbine fuel system and reciprocating engine are the same. The fuel is delivers to the engine fuel metering system a uniform flow of clean fuel at the Proper pressure and in the necessary quantity in other to operate the engine. Also, in the widely varying atmospheric conditions, the fuel supply must be adequate and continuous to meet the demands of the engine during operation.

Therefore, the fuel system is one of the more complex aspects of a gas turbine engine. Due to the variety of methods used to meet turbine engine fuel requirements makes reciprocating engine carburation seem simply by comparison.

3.6 Cooling Systems

The turbine shaft and bearings, due to its motion created generates heat and also absorbs heat from the combustion chamber. During this process, if the shaft is not cooled there must be an expansion which will result in the reduction of efficiency of the work output and also course damage to the machine and human life.

The lube oil cool the shaft and bearing in other to avoid a rise in temperature which causes expansion, after which the water cools the lube oil. The hot water is being taken away through a channel and cooled by the air. This process is constant as long as the turbine is working and it is achieved through the means of cooling water fan and the heat exchanger.

Fig. 28. Cooling water module

Fig. 29. Heat exchanger

3.7 Turbine Hydraulic Oil and Trip System

3.7.1 Hydraulic oil system

The 120 Psi lube oil from the lube oil pump discharge is filtered by one of two filters and passes to the hydraulic oil system through a restriction orifice. The hydraulic oil is piped to the following:-

- A manual emergency trip valve
- The Solenoid trip valve
- The HP and LP turbine over-speed trips
- The nozzle control oil (NCO) dump valve
- The Fuel gas stop valve

The system operates as follows:

The pressure of the hydraulic oil is holding the NCO dump valve and the Fuel Gas Stop Valve (4 & 5 above), in the 'GO' position - The NCO dump valve is allowing the NCO to pass to the nozzle control cylinder. The fuel gas stop valve is also held open to allow the fuel gas to flow to the combustion chambers. When any trip is activated, (1, 2 or 3 above), the hydraulic oil pressure is dumped to the lube oil tank and drops to zero psi. This causes the Fuel Gas Stop valve to close shutting off the fuel to the combustion chambers.

At the same time the NCO dump valve operates to close the NCO supply and open the dump line from the control cylinder which takes the nozzle control ring to zero settings (nozzles fully open).

The turbine shuts down. The flow of hydraulic oil through the restriction orifice is less than the flow to the dump, keeping the pressure at zero. Before re-starting the machine, speed controls have to be put on manual and set to zero, compressor recycles to manual and fully open and the trip condition has to be corrected and cancelled. As the trip condition is corrected and cancelled, the hydraulic pressure is restored slowly to normal and the operating start up procedure followed to re-start the machine.

3.7.2 Control oil

The flow of oil to the accessory gear also goes to the FUEL GAS REGULATOR which is a device incorporating a pump. This pump increases the oil pressure from 25 Psi to 300 psi which is called the Constant Control Oil (CCO). A Variable Control Oil (VCO) is also put out from the fuel gas regulator, the pressure of which depends on the signal coming from the Turbine Speed Controller. This variable pressure oil (VCO) operates and controls the Fuel Gas Control valve.

Fig. 30. Gas turbine exhaust

3.8 Exhaust Systems

Combustion gas from the turbine is discharge to exhaust plenum, then flow to exhaust duct. Exhaust plenum is supported at the base of the turbine rear parts and cover exhaust frame and diffuser and turning vane of exhaust gas. Heat insulator is installed on the wall of exhaust plenum.

Exhaust frame supports rear sides' flange of turbine casing with bolt. Also exhaust frame support number two bearing and diffuser and turning vane of exhaust gas. Exhaust frame and exhaust plenum is joined with expansion-joint divided by segment so that it absorb the thermal expansion of radical and axial direction. Exhaust frame is cooled by the sixth-stage extract air of compressor. Cooling air received from four holes around the perimeter of the exhaust frame flows into the space between frame outer cylinder and gas path outside wall.

The frame internal part is supported by an outer cylinder with ten (10) columns and these columns are covered so that direct exhaust gases will not affect them. Cooling air goes through these spaces and cools down the columns. After that, it is guided to the space between frame inner cylinders and goes through the inner walls. For the next, this air goes through the space of third-stage wheel rear side through air hole which is furnished at inner cylinder front end part.

After cooling down of the wheel, the air is discharged to the exhaust gas. Exhaust include a silencer to reduce the noise of the gas turbine. To absorb the thermal expansion of the exhaust duct.

4. CONCLUSION

The gas turbine is a machine that operates under thermodynamics process using Brayton cycle, similarly to Rankine cycle used for a steam turbine. A gas turbine has a reduced efficiency compared to a steam turbine owing to the fact that part of the power developed in the combustion process is used to drive the Compressor.

However, a gas turbine exhaust heat can be harness and channelled to boiler to drive a steam turbine, a system known as a combined cycle for which efficiency can be improved and with the same amount of gas, both the gas turbine and the steam turbine can be operated and thereby enormously reducing operating cost. Gas Turbine combustion reaches over a 1000ºc yet the combustion component survive. It a system that could deliver a hydraulic pressure of over 1500psi yet oil leaks will not be found, that is one the difference. The turbine speed reaches 3000 revolutions per minute (RPM) that is about 50 revolutions per second (RPS) when **rotor** weight is well about 70 tons.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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