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Abstract

Gas Turbines (GT) are thermally rated air breathing engine which generates motive power from the combustion of fuel and expansion of gases. Gas turbines are employed in different spares of our daily lives, yet many people are unaware of the cutting-edge technologies used in the creation and operation of these engines. This article explains the principle involved with emphasis on the operation and performance analysis. The application of GT ranges from its use in power generation to aircraft propulsion, ship propulsion, gas compression in pipeline or tankers and others. GT is hugely affected by ambient conditions such as increase or decrease in ambient temperature. The operation of GT follows the Bryton cycle and detail is given in the paper. The effect of increase in ambient temperature on GT performance has been analyzed and discussed. As the ambient temperature increase, the mass flow reduces and therefore the performance of the GT drops.

Keywords (separated by “-”)	Gas turbine - Design - Performance - Temperature - Application - Propulsion

Chapter 9
Gas Turbine Engine: Design, Application and Performance Analysis

Abdulkarim Nasir, Abubakar Mohammed, and Jonathan Y. Jiya

Abstract Gas Turbines (GT) are thermally rated air breathing engine which generates motive power from the combustion of fuel and expansion of gases. Gas turbines are employed in different spares of our daily lives, yet many people are unaware of the cutting-edge technologies used in the creation and operation of these engines. This article explains the principle involved with emphasis on the operation and performance analysis. The application of GT ranges from its use in power generation to aircraft propulsion, ship propulsion, gas compression in pipeline or tankers and others. GT is hugely affected by ambient conditions such as increase or decrease in ambient temperature. The operation of GT follows the Bryton cycle and detail is given in the paper. The effect of increase in ambient temperature on GT performance has been analyzed and discussed. As the ambient temperature increase, the mass flow reduces and therefore the performance of the GT drops.

Keywords Gas turbine · Design · Performance · Temperature · Application · Propulsion

9.1 Introduction

The gas turbine is unquestionably one of the most important inventions of the twentieth century, and it has changed our lives in many ways. Gas turbine development started just before the Second World War with electric power applications in mind, but these were not competitive with existing prime movers such as steam turbines and diesel engines [1]. The first important application of the gas turbine was the development of the military jet engine towards the end of the Second World War, when it provided a step change in speed from the existing propeller driven aircraft. These early engines were fuel inefficient, unreliable and extremely noisy, but in less

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than 20 years they had matured to become the standard form of propulsion for civil aircraft. By the early 1970s continuous progress in gas turbine engineering led to the development of the high bypass ratio turbo fan and the major improvement in fuel efficiency made the high-capacity wide-body airliner possible. It took longer for the gas turbine to have a similar impact in non-aircraft markets. Early gas turbine for power generation applications were of low power and their thermal efficiency was too low to be competitive. By the end of the twentieth century, however, gas turbines were capable of output. of up to 300 MW with thermal efficiency of 40% and the gas turbine (frequently combined with steam turbine) became widely used in power generation. Gas turbine engineering has improved over the years. The best way to visualize its advancement is by looking at their rising efficiencies over time. A doubling of efficiency has occurred for simple cycles, with the introduction of combined cycles causing a tripling in efficiency. Turbine efficiencies, along with cost and reliability, are among the most important criteria when power producers place orders for new plants. Therefore, the gas turbine gains in efficiency, which is as a result of technological development, have been crucial for their success [2].

To increase efficiencies, turbine designers have worked to increase firing temperatures without damaging the turbines themselves. The advantage of having high firing and rotor inlet temperatures (RITs) is that they nudge gas turbine cycles closer to Carnot thermodynamic cycles. However, firing turbines beyond the threshold temperatures of their components threaten their integrity and reliability. Research and development addressing this concern has progressed along two major avenues of development: material improvements and cooling advances [3]. In the family of prime movers, gas turbine has been very prominent because it can be powered using natural gas which is about the environmentally safest fossil fuel [4–6].

9.2 Gas Turbine Operations

9.2.1 Gas Turbine Cycle

The basic principle of a gas turbine is identical to any engine that extracts energy from chemical fuel. The basic four steps for any internal combustion engine are:

1. Intake of air (and possibly fuel).
2. Compression of the air (and possibly fuel).
3. Combustion, where fuel is injected (if it was not drawn in with the intake air) and burned to convert the stored energy.
4. Expansion and exhaust, where the converted energy is used [7]. Figure 9.1 shows gas turbine flow line.

In the turbine engine, however, these same four steps occur at the same time but in different places. Because of this fundamental difference, the turbine has engine sections called:

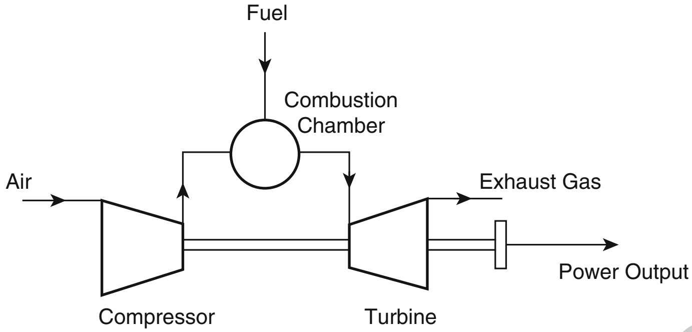

Fig. 9.1 FGas Turbine Line Flow

1. The inlet section.
2. The compressor section.
3. The combustion section (the combustor).
4. The turbine (and exhaust) section.

The turbine section of the gas turbine engine has the task of producing usable output shaft power to drive the propeller. In addition, it must also provide power to drive the compressor and all engine accessories. It does this by expanding the high temperature, pressure and gas velocity and converting the gaseous energy to mechanical energy in the form of shaft power. A large mass of air must be supplied to the turbine for it to be able to produce the necessary power. This mass of air is supplied by the compressor, which draws the air into the engine and squeezes it to provide high-pressure air to the turbine. The compressor does this by converting mechanical energy from the turbine to gaseous energy in the form of pressure and temperature.

If the compressor and the turbine were 100% efficient, the compressor would supply all the air needed by the turbine. At the same time, the turbine would supply the necessary power to drive the compressor. In this case, a perpetual motion machine would exist. However, frictional losses and mechanical system inefficiencies do not allow a perpetual motion machine to operate. Additional energy must be added to the air to accommodate for these losses. Power output is also desired from the engine (beyond simply driving the compressor); thus, even more energy must be added to the air to produce this excess power. Energy addition to the system is accomplished in the combustor. Chemical energy from fuel as it is burned is converted to gaseous energy in the form of high temperatures and high velocity as the air passes through the combustor. The gaseous energy is converted back to mechanical energy in the turbine, providing power to drive the compressor and the output shaft. At peak load operation, gas turbines is made to operate at very high firing temperatures, this obviously leads to the consequence of reduction in the useful lives of the components [8].

9.2.2 Engine Sections

9.2.2.1 Inlet

The air inlet duct must provide clean and unrestricted airflow to the engine. Clean and undisturbed inlet airflow extends engine life by preventing erosion, corrosion, and foreign object damage (FOD). Consideration of atmospheric conditions such as dust, salt, industrial pollution, foreign objects (birds, nuts and bolts), and temperature (icing conditions) must be made when designing the inlet system. Fairings should be installed between the engine air inlet housing and the inlet duct to ensure minimum airflow losses to the engine at all airflow conditions. The inlet duct assembly is usually designed and produced as a separate system rather than as part of the design and production of the engine.

9.2.2.2 Compressor

The compressor is responsible for providing the turbine with all the air it needs in an efficient manner. In addition, it must supply this air at high static pressures. The example of a large turboprop axial flow compressor will be used. The compressor is assumed to contain 14 stages of rotor blades and stator vanes. The overall pressure ratio (pressure at the back of the compressor compared to pressure at the front of the compressor) is approximately 9.5:1. At 100% (>13,000) RPM, the engine compresses approximately 433 cubic feet of air per second. At standard day air conditions, this equals approximately 33 pounds of air per second. The compressor also raises the temperature of the air by about 550° F as the air is compressed and moved rearward. The power required to drive a compressor of this size at maximum rated power is approximately 7000 horsepower.

In an axial flow compressor, each stage incrementally boosts the pressure from the previous stage. A single stage of compression consists of a set of rotor blades attached to a rotating disk, followed by stator vanes attached to a stationary ring. The flow area between the compressor blades is slightly divergent. Flow area between compressor vanes is also divergent, but more so than for the blades.

In general terms, the compressor rotor blades convert mechanical energy into gaseous energy. This energy conversion greatly increases total pressure (P_t). Most of the increase is in the form of velocity, with a small increase in static pressure due to the divergence of the blade flow paths.

The stator vanes slow the air by means of their divergent duct shape, converting ‘the accelerated velocity to higher static pressure. The vanes are positioned at an angle such that the exiting air is directed into the rotor blades of the next stage at the most efficient angle. This process is repeated 14 times as the air flows from the first stage through the fourteenth stage.

The efficiency of a compressor is primarily determined by the smoothness of the airflow. During design, every effort is made to keep the air flowing smoothly through the compressor to minimize airflow losses due to friction and turbulence. This task is a difficult one, since the air is forced to flow into ever-higher pressure zones [9].

9.2.2.3 Diffuser

Air leaves the compressor through exit guide vanes, which convert the radial component of the air flow out of the compressor to straight-line flow. The air then enters the diffuser section of the engine, which is a very divergent duct. The primary function of the diffuser structure is aerodynamic. The divergent duct shape converts most of the air's velocity into static pressure. Thus, the highest static pressure and lowest velocity in the entire engine is at the point of diffuser discharge and combustor inlet.

9.2.2.4 Combustor

Once the air flows through the diffuser, it enters the combustion section, also called the combustor. The combustion section has the difficult task of controlling the burning of large amounts of fuel and air. It must release the heat in a manner that the air is expanded and accelerated to give a smooth and stable stream of uniformly-heated gas at all starting and operating conditions. This task must be accomplished with minimum pressure loss and maximum heat release. In addition, the combustion liners must position and control the fire to prevent flame contact with any metal parts. The engine extracts chemical energy from fuel and converts it to mechanical energy using the gaseous energy of the working fluid (air) to drive the engine and propeller, which, in turn, propel the airplane.

9.2.2.5 Turbine

The turbine converts the gaseous energy of the air/burned fuel mixture out of the combustor into mechanical energy to drive the compressor, driven accessories, and, through a reduction gear, the propeller. The turbine converts gaseous energy into mechanical energy by expanding the hot, high-pressure gases to a lower temperature and pressure.

Each stage of the turbine consists of a row of stationary vanes followed by a row of rotating blades. This is the reverse of the order in the compressor. In the compressor, energy is added to the gas by the rotor blades, then converted to static pressure by the stator vanes. In the turbine, the stator vanes increase gas velocity, and then the rotor blades extract energy [10]. Gas turbine is affected by environmental conditions, this view is upheld by Nasir et al. [11] in which the impact of temperature on gas turbine performance was studied.

9.3 Gas Turbine Applications

Gas turbine plants are used as standby plants for the hydroelectric power plants. Gas turbine power plants may be used as peak loads plant and standby plants for smaller power units. Gas turbines are used in jet aircraft and ships. Pulverized fuel-fired plants are used in a locomotive.

9.3.1 Aircraft Application

To move an airplane through the air, we have to use some kind of propulsion system to generate thrust. The most widely used form of propulsion system for modern aircraft is the gas turbine engine. Turbine engines come in a variety of forms.

9.3.2 Application in Power Generation

In electricity generating applications the turbine is used to drive a synchronous generator which provides the electrical power output but because the turbine normally operates at very high rotational speeds of 12,000 r.p.m. or more it must be connected to the generator through a high ratio reduction gear since the generators run at speeds of 1000 or 1200 r.p.m. depending on the AC frequency of the electricity grid.

9.3.3 Gas Turbine Application in Marines

Gas turbines are used in many naval and civilian vessels, where they are valued for their high power-to-weight ratio and their ships' resulting acceleration and ability to get underway quickly.

9.4 Design and off-Design Performance Module

In carrying out gas turbine design point simulations, a pressure ratio, component efficiencies and maximum cycle temperature are selected to achieve a required engine performance. The design point simulation determines the thermal efficiency and airflow rate for a given power demand. The modelling and performance simulation of gas turbine engine of simple cycles was carried out using GasTurb. Model results of gas turbine of 40.7 MW Simple Cycle Two Shaft (SCTS) model is presented.

Table 9.1 Coal deposits in Nigeria

Design parameter	40.7 MW SCTS	LM2500+
Mass flow (kg/s)	126.6	69.0
Overall pressure ratio	30.01	18.8
Turbine entry temp. (K)	1540	1505
Thermal efficiency (%)	40.04	37.9

The design point simulation was done based on certain parameters which are estimated to obtain the desired power output. The off-design simulation was done with the prevailing ambient temperature profile of the region where the engine will be installed. The effect of elevation on gas turbine performance is not a major concern in this research because the highest elevation point is 177 m. Although it was shown by Mohammed et al. [7] that power output and mass flow rate reduce as altitudes increase, while the cycle efficiency reduces with increase altitude, change in ambient pressure is important in the performance analysis of a gas turbine because this affects the pressure ratio across the power turbine. One very important parameter from the simulation, which obviously affects the economics of gas turbine project, is the fuel consumption. The basic performance parameters of the gas turbines are presented in Table 9.1.

9.4.1 40.7 MW Simple Cycle Two-Shaft Gas Turbine

This gas turbine was modelled as a simple cycle engine with the configuration of having a two spool with the low pressure (LP) turbine aerodynamically connected to the power turbine. The model is conceived to have a LP compressor with pressure ratio of 2.45:1 and driven by a LP turbine, high pressure (HP) compressor with pressure ratio of 12.25:1 and driven by a HP turbine. Air leaving the LP compressor is directed into the HP compressor with zero pressure loss and this gives the gas turbine an overall pressure ratio of 30.01. The high and low- pressure turbines drive the high and low-pressure compressor respectively, through concentric drive shafts which rotate independently.

The off-design operating range considered for the simulation of ambient temperature ranging from 10 °C to 50 °C. The effects of varying ambient temperature on some performance parameters are presented in Figs. 9.2, 9.3, 9.4, 9.5 and 9.6. For the worst scenario of ambient condition, the gas turbine output power is sufficient for the power demand to compress the natural gas in the modelled natural gas pipeline system. The simulation results of a gas turbine with thermal efficiency of 40.04%, with an overall pressure ratio of 30.01:1 shows the fuel flow of the gas turbine at design point to be 2.3587 kg/s. The effect of the ambient temperature and turbine entry temperature (TET) on the power output is shown in Fig. 9.2. The output power increases with TET and reduces with increase ambient temperature. From materials point of view, the TET cannot be increased ad infinitum to avoid early failure of major components and consequently reduced life of the gas turbine.

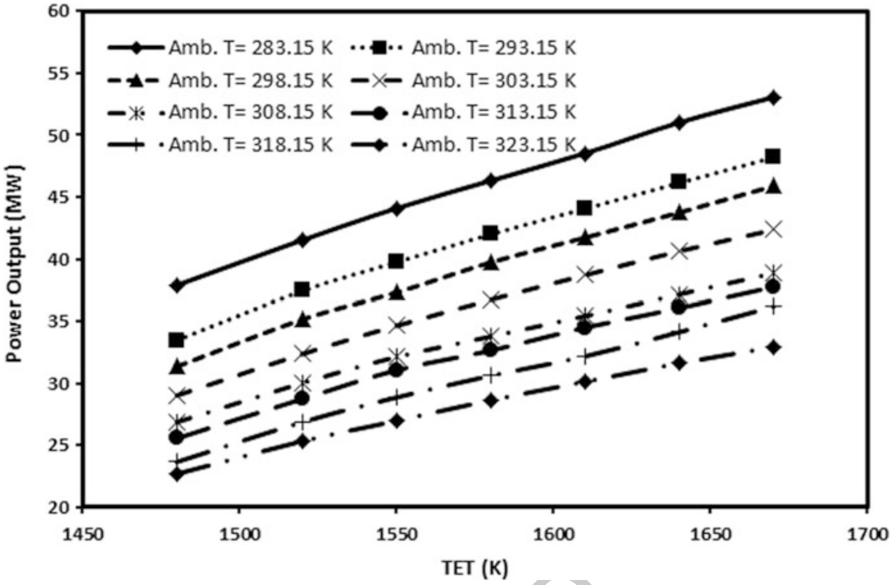

Fig. 9.2 Power output against TET for 40.7 MW SCTS

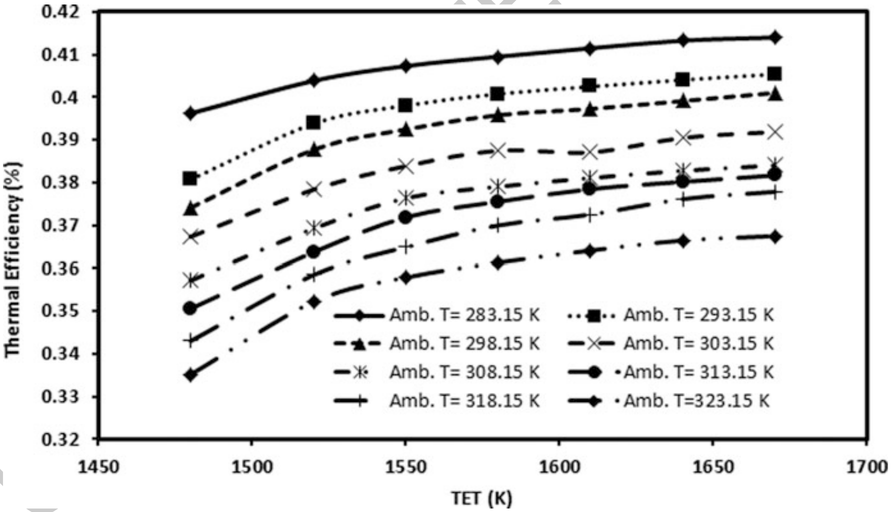

Fig. 9.3 Thermal efficiency against TET (K) for 40.7 MW SCTS

Figure 9.3 shows increase in thermal efficiency with TET at varying ambient temperature.

Figure 9.4 shows the change in fuel flow against TET for different ambient temperatures. At off-design condition having higher ambient temperature than the design point, the fuel flow increases, and this is a major parameter in the

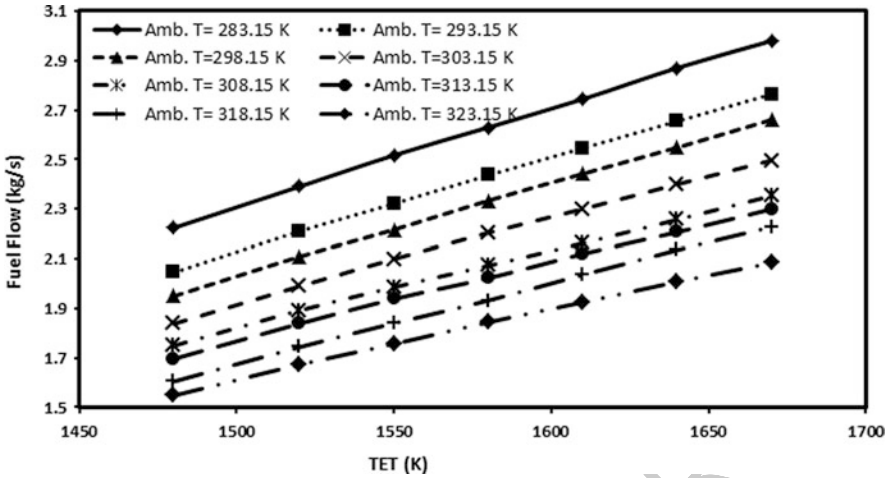

Fig. 9.4 Fuel flow against TET for 40.7 MW SCTS

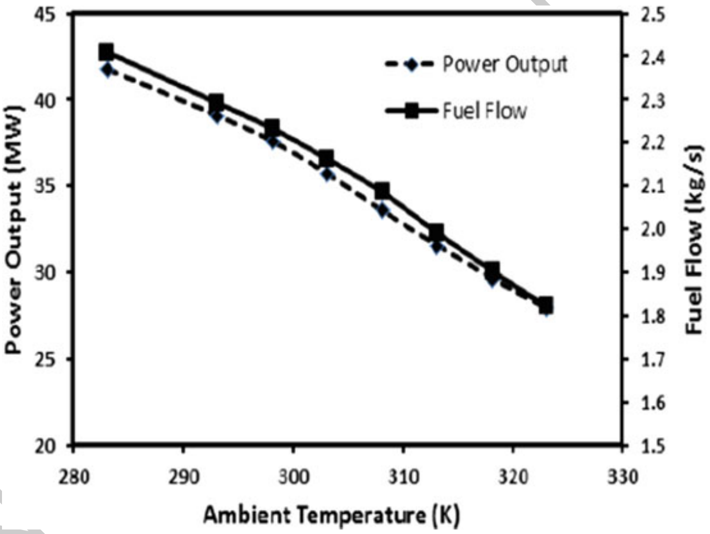

Fig. 9.5 Variation of power output and fuel flow with ambient temperature at constant TET for 40.7 MW SCTS

establishment of the life cycle cost of the plant and the general natural gas pipeline system.

At constant TET, the power output and fuel flow variation with ambient temperature is shown in Fig. 9.5. As the ambient temperature increases, the power output decreases with consequent reduction in fuel flow. A 6.8% drop in output power which is equivalent to 2.7 MW occurs with a 3.5% rise in ambient temperature, and consequent 5.1% reductions in fuel flow.

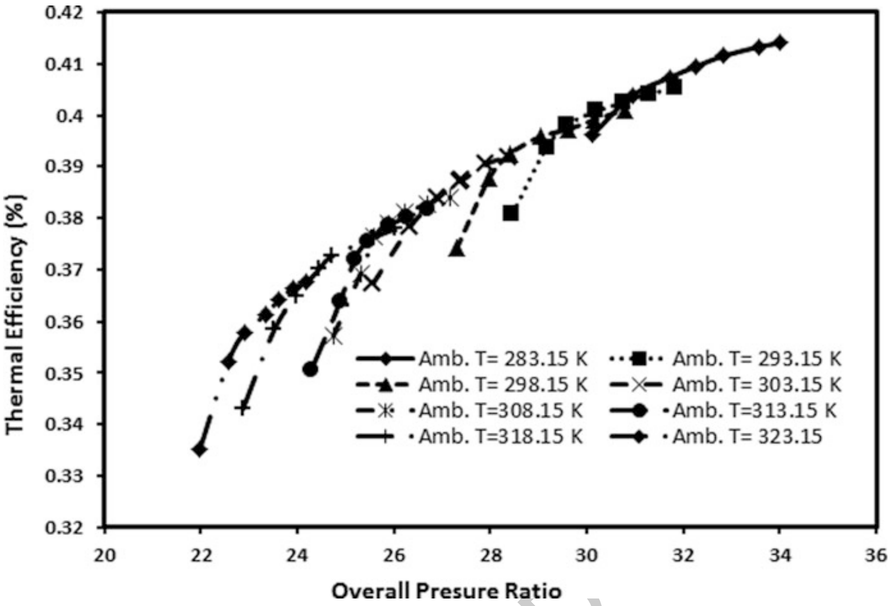

Fig. 9.6 Thermal Efficiency at a pressure ratio for 40.7 MW SCTS

9.4.2 Gas Turbine Performance Analysis

The type of operation for which the engine is designed dictates the performance requirement of a gas turbine engine. The performance requirement is mainly determined by the amount of shaft horsepower (s.h.p.) the engine develops for a given set of conditions. Most aircraft gas turbine engines are rated at standard day conditions of 15 °C and 1.01325 bar. This provides a baseline to which gas turbine engines of all types can be compared.

The change in thermal efficiency with variation in overall pressure ratio is shown in Fig. 9.6. As the pressure ratio increases the thermal efficiency increases. This has a limit because of material property.

The need for high efficiency in the engine becomes more important as fuels become more expensive. Engine efficiency is primarily defined by the specific fuel consumption (s.f.c.) of the engine at a given set of conditions. Many factors affect both the efficiency and the performance of the engine. The mass flow rate of air through the engine will dictate engine performance. Any restrictions acting against the smooth flow of air through the engine will limit the engine's performance.

The pressure ratio of the compressor, the engine operating temperatures (turbine inlet temperature), and the individual component efficiencies will also influence both the performance and the efficiency of the overall engine. All these factors are considered during the design of the engine. An optimum pressure ratio, turbine inlet temperature, and air mass flow rate are selected to obtain the required performance in the most efficient manner. In addition, individual engine components are designed to minimize flow losses to maximize component efficiencies.

9.4.2.1 Effect of Turbine Temperature

The materials used in the turbine section of the engine limit the maximum temperature at which a gas turbine engine can operate. The first metal the hot gases from the combustion section strike is the turbine inlet. The temperature of the gas stream is carefully monitored to ensure that over temperature does not occur. Compromises are made in turbine design to achieve the optimum balance of power, efficiency, cost, engine life, and other factors. The higher temperature allows for increased power and improved efficiency while adding higher cost for the direct cooling of the first turbine stage airfoils and other components.

9.4.2.2 Effect of Atmospheric Condition

The performance of the gas turbine engine is dependent on the mass of air entering the engine. At a constant speed, the compressor pumps a constant volume of air into the engine with no regard for air mass or density. If the density of the air decreases, the same volume of air will contain less mass, so less power is produced. If air density increases, power output also increases as the air mass flow increases for the same volume of air. Atmospheric conditions affect the performance of the engine since the density of the air will be different under different conditions. On a cold day, the air density is high, so the mass of the air entering the compressor is increased. Thus, higher horsepower is produced. In contrast, on a hot day, or at high altitude, air density is decreased, resulting in a decrease of output shaft power.

9.5 Conclusion

This paper has discussed the operation and performance analysis of a SCTS 40.7 MW gas turbine engine. The operation follows the Bryton and the performance analysis based on ambient condition shows high performance with reduction in ambient temperature as the efficiency increases considerably. Its application span from it being used for propulsion to shaft power delivery. Because gas turbine is a breathing engine, its performance is highly influenced by ambient condition.

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