Proceedings of the World Congress on Engineering 2018 Vol II
WCE 2018, July 4-6, 2018, London, U.K.

Design and Off-Design Operation and Performance Analysis of a Gas Turbine

A. Nasir, *Member, IAENG,* A. Mohammed and J. Y. Jiya

Abstract—Gas Turbine (GT) engine is a breathing engine which generates motive power from the combustion 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.

Index Terms—Gas Turbine, operation, combustion, performance

I. Introduction

THE gas turbine is unquestionably one of the most important inventions of the 20th 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 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 20th century, however, gas turbines were capable of output of up to 300 MW with thermal efficiency of 40 per cent 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 [4,5,6]

II. 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 40.7MW Simple Cycle Two Shaft (SCTS) model is presented.

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 177m. 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

Manuscript received October 05, 2017; revised November 06, 2017

A. Nasir is an Associate Professor of Mechanical Engineering and Deputy Dean of Engineering, Federal University of Technology, Minna, Nigeria (Corresponding Author phone: +2348033183561; e-mail: a.nasir@futminna.edu.ng).

A. Mohammed and J. Y. Jiya are lecturers in the Department of Mechanical Engineering, Federal University of Technology, Minna, Nigeria.

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 I.

TABLE I
PERFORMANCE PARAMETERS

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

A. 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 10^0 C to 50^0 C. The effects of varying ambient temperature on some performance parameters are presented in Figures 1 to 5. 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. 1. 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. 2 shows increase in thermal efficiency with TET at varying ambient temperature.

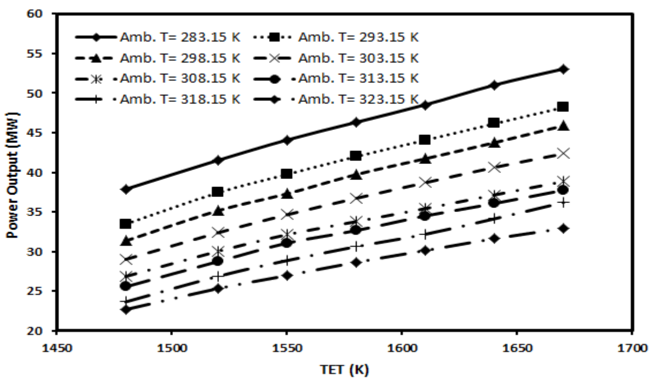

Fig. 1: Power output against TET for 40.7 MW SCTS

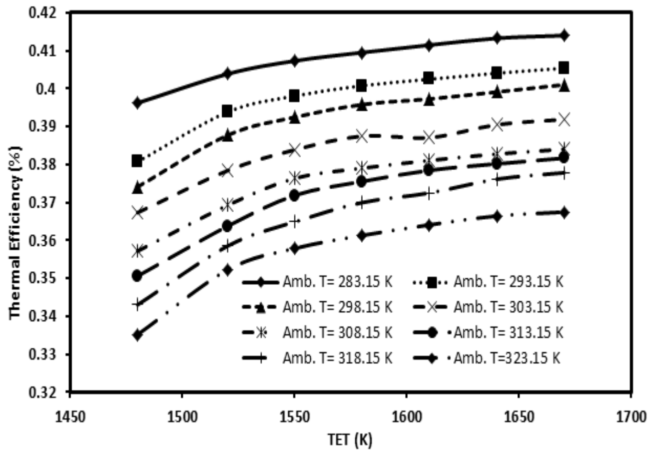

Fig. 2: Thermal efficiency against TET (K) for 40.7 MW SCTS

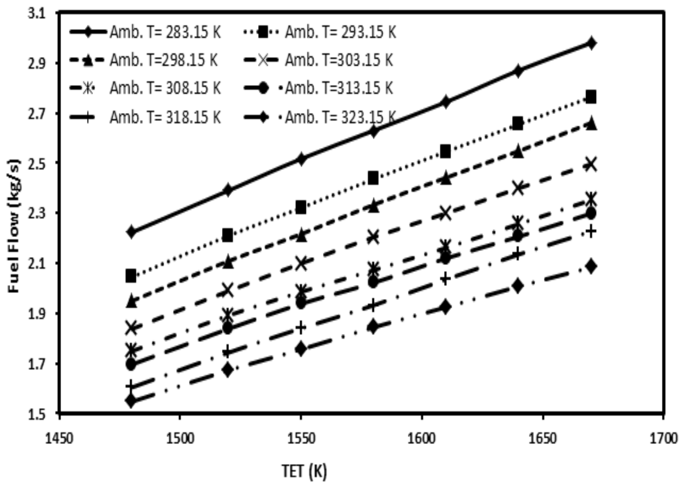

Fig. 3: Fuel flow against TET for 40.7 MW SCTS

Fig. 3 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 establishment of the life cycle cost of the plant and the general natural gas pipeline system. The change in thermal efficiency with variation in overall pressure ratio is shown in Fig. 4. As the pressure ratio increases the thermal efficiency increases. This has a limit because of material property.

At constant TET, the power output and fuel flow variation with ambient temperature is shown in Fig 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.

III. GT 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^oC

and 1.01325 bar. This provides a baseline to which gas turbine engines of all types can be compared.

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.

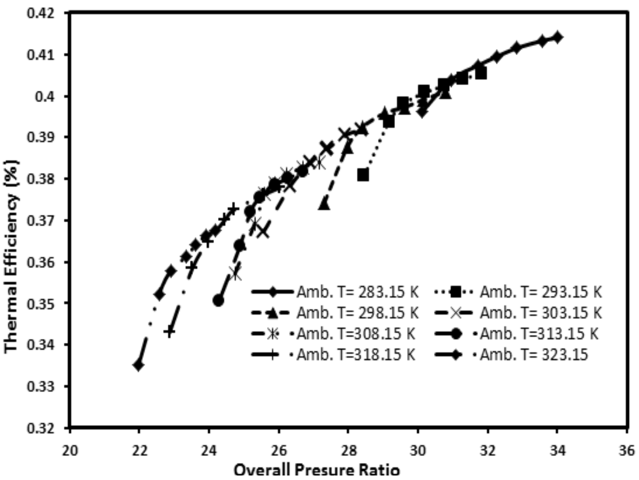

Fig. 4: Thermal efficiency versus pressure ratio for 40.7 MW SCTS

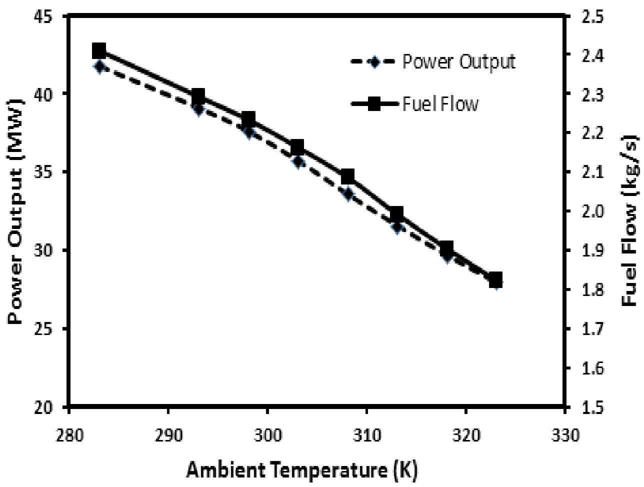

Fig. 5: Variation of power output and fuel flow with ambient temperature at constant TET for 40.7 MW SCTS

IV. EFFECTS 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.

V.EFFECTS OF ATMOSPHERIC CONDITIONS

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.

VI. 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.

ACKNOWLEDGMENT

The authors wish to thank the Tertiary Education Trust Fund (TETFund) Nigeria and Federal University of Technology, Minna, Nigeria.

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