Scholars Journal of Engineering and Technology
Abbreviated Key Title: Sch J Eng Tech
ISSN 2347-9523 (Print) | ISSN 2321-435X (Online)
Journal homepage: https://saspublishers.com/journal/sjet/home

OPEN ACCESS

Energy Analysis of a Gas Turbine Generator (a Case Study of 3 X 2.5MW Centaur 40)

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| **Received:** 15.05.2019 | **Accepted:** 25.05.2019 | **Published:** 30.05.2019
DOI: 10.36347/sjet.2019.v07i05.007

Abstract **Original Research Article**

Gas turbine power plants have gained a wide spread acceptance in power generation and mechanical drive. Their compactness, high power to weight ratio, ease of installation, early commissioning, fast starting and quick shut down time have made them popular prime mover. Drop in gas turbine efficiency are tied to many factors which include; operation mode, poor maintenance procedures, age of plant, discrepancies in operating data, compressor inlet temperature, etc. In this research work, energy analysis of gas turbine generators was carried out. Four years data (i.e. 2014, 2015, 2016, and 2017) were used for the analysis. MATLAB editor was used in modeling and simulating the gas plants. Overall efficiency, thermal efficiency, thermal power, heat rate, specific fuel consumption, and work ratio were all analyzed and evaluated for performance. The results obtained on the simulation of the gas turbines show that the average overall efficiency, average thermal efficiency, average heat rate, average thermal power, average specific consumption, and average work ratio of centaur gas turbine generators were obtained as16.09 %, 16.98%, 22636 kW, 5197 kW, 0.4619 kg/Kw-h, and 0.4605. Furthermore, the results revealed that overall efficiency, thermal efficiency, thermal power decrease because of increase in compressor inlet temperature. However, specific fuel consumption, and heat rate increases with increase in compressor inlet temperature. The work ratio decreases with increase in compressor inlet temperature, and this confirmed that gas turbine generators are susceptible to high irreversibility at high compressor inlet temperature. Therefore, for improve and optimum efficiency of the gas turbine investigated, cooling of the compressor inlet air temperature is required.
Keywords: Gas turbine generators, overall efficiency, ambient temperature, MATLAB, compressor, inlet temperature.

INTRODUCTION

The availability of natural gas and prices compared to distillate fuels has made many countries in the world including Nigeria to utilize large conventional gas turbines as based load units [1, 2]. A gas turbine (Fig.1), also called a combustion turbine is a rotary engine that extracts energy from a flow of combustion of gas. It has an upstream compressor coupled to a downstream turbine, and a combustion chamber in between. Energy is released when the air is mixed with fuel and ignited in the combustor, the resulting gases are directed over the turbine's blades spinning the turbine and powering the compressor. Gas turbines are widely being used for producing electricity, operating air planes and for various industrial applications such as refineries and petrochemical plants [3]. In air craft propulsion, gas turbines are chosen due to their large power to weight and power to volume ratio. Furthermore, for certain operating conditions the cycle efficiency of gas turbine is high compared to piston engines. In the field of power generation, gas turbines have often been chosen in the past when fast start and shut down on demand is required. This is especially needed for compensating peak loads over the daytime. In contrast, steam cycle as used for coal and oil firing or nuclear power are base-load machines since the start and shut down is tremendously longer due to the large heat capacity in the cycle [4].

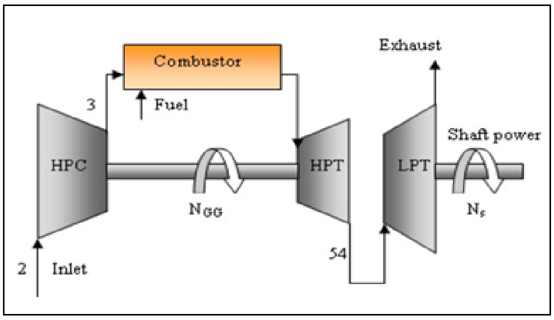

Fig-1: Two shafted Gas Turbine with Sensor Placement

Gas turbines have been used for electricity generation in most countries around the world [5]. In the past, their uses have been generally limited to generating electricity in periods of peak electricity demand. Gas turbine are ideal for this application as they can be started and stopped quickly enabling them to be brought into service as required to meet energy demand peaks [6-7]. However, due to availability of natural gas at relatively cheap prices compared to distillate fuel, many countries around the world just like Nigeria, use large conventional as base load unit while small ones is use to meet any shortages in available electricity supplies occurring during an emergency or during the peak load demand periods. Such systems, especially those operating in an open or simple cycle have the disadvantage of low efficiency and so the unit cost of generated electricity is relatively high [1]. The low efficiencies of the gas turbine plants are tied to many factors, which include operation mode, poor maintenance procedures, age of plant, and discrepancies in operating data, high ambient temperature and relative humidity.

Energy analysis is carried out to know the sources of losses during conversion process in the plant, and other possible factors that can affect the performance of the plant. For a better understanding of the factors that affect the efficiency of a gas turbine power plant, energy analysis of the gas turbine and its components are required. Energy analysis is traditionally used in industries to carry out performance comparisons and optimizations. The conventional methods of energy analysis are based on the first law of thermodynamics, which is concerned with the conservation of energy [8]. Energy analysis of heat and power cycles are today the most common way of evaluating thermal systems regarding, for instance, fuel utilization and electrical efficiency. Throughout the whole 20th century, energy analysis matured and is today considered a well-established tool to evaluate thermal systems [9,10]. The major aim of an energy analysis is to optimize the thermal efficiency of a system. In this research work, energy analysis of 3 x 2.5mw centaur gas turbine generators were carried out.

RESEARCH METHODOLOGY

2.1 Description of the Gas Turbine

Centaur 40 gas turbine generators are of a two shaft, axial flow design consisting of;

i. Accessory drive assembly ii. Air inlet assembly
iii. Engine compressor assembly
iv. Combustor assembly v. Turbine assembly
vi. Exhaust collector vii. Output drive shaft

Fig. 2 shows the schematic diagram and Fig. 3 shows the T-S diagram of the gas turbine.

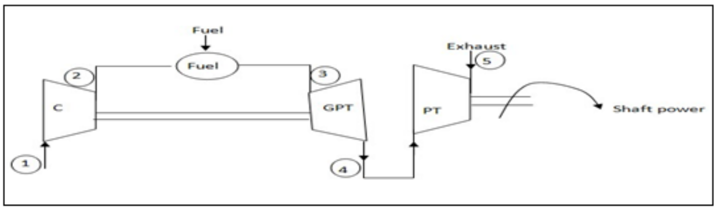

Fig-2: Schematic Diagram of the Gas Turbine Generators

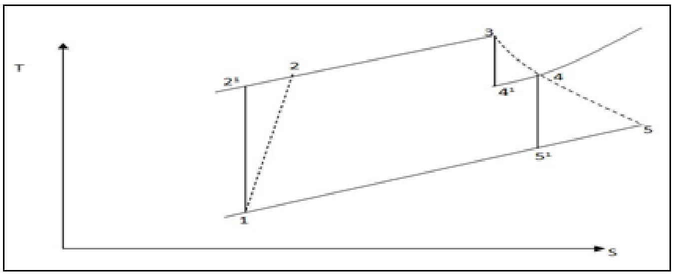

Fig-2: T-S Diagram of the Gas Turbine Generators

The major components of the engine are maintained in accurate alignment by mating flanges with pilot surfaces and are located together to form a rigid assembly. The accessory drive assembly, bolted to the air inlet assembly, is driven by the engine compressors rotor shaft. The accessory drive assembly support and drives the lube oil pump and other accessories and is initially driven by the shaft system.

Engine Compressor Assembly

The engine compressor assembly is a twelve-stage, axial flow type, incorporating and air inlet assembly, compressor variable vane assemblies, compressor case assembly, diffuser assembly, compressor bearing support housing and compressor rotor assembly. The air inlet assembly has an annular opening covered with a heavy mesh screen. The air inlet housing supports the compressor rotor shaft forward bearing and the accessory drive housing. The variable vane assemblies consist of the inlet guide vane assembly, the first three stator assembly, and the variable control actuator.

Gas Producer Turbine Assembly

The gas producer turbine assembly includes, the gas producer bearing support housing, the combustor assembly, and the two- stage gas producer turbine rotor that drives the compressor. The combustor housing is bolted to the aft flange of the gas producer bearing support housing and the forward flange of the turbine exhaust diffuser. Twelve fuel injectors are mounted on bosses around the combustor housing and protrudes through the combustor dome and end into the combustor chamber. The turbine nozzles are contained in a nozzle casing which in cantilevered forward from the flange of the combustion housing. The gas producer rotor bearings are supported by a bearing support assembly. The turbine nozzles are cooled by additional air passed through the engine.

Energy Analysis Equations

The energy analysis equation used in this research is given by Equations (1 -16). Work done by compressor is given by Equation (1).

$$W_c = maCp_a(T_2 - T_1) \quad (1)$$

The work done by turbine is given by Equation (2),

$$W_T = M_{exh}C_{exh}(T_3 - T_4) \quad (2)$$

The generator losses are translated to heat that is removed by air blower

$$Q_w = maCp_a(Tca_2 - Tca_1) \quad (3)$$

The electrical power generated is given by equation (4).

$$P_E = P_{TH} - P_{ML} - P_{GL} - P_{AUX} \quad (4)$$

The mechanical efficiency is given by Equation (5)

$$\eta_m = \frac{P_{TH} - P_{ML}}{P_{TH}} \quad (5)$$

The generator efficiency is given by Equation (6),

$$\eta_g = \frac{P_{TH} - P_{ML} - P_{GL}}{P_{TH} - P_{ML}} \quad (6)$$

where,

W_C = Work done by compressor

$\dot{m}_a$ =Mass flow rate of air through compressor

C_{pa}= Specific heat capacity of air

W_T = Work done by Turbine

$\dot{m}_{exh}$ = Mass flow rate of exhaust

T_3 = Combustion chamber temperature

T_4 = Turbine temperature

T_5 = Exhaust temperature

P_{GL} = Generator losses

P_{AUX} =Auxilliary losses

P_{ML} = Mechanical losses

RESULTS AND DISCUSSION

The performance of the plant was determined by simulation using MATLAB 2014. This was used to obtain the compressor work, turbine work, other results achieved such as net-power, thermal efficiency, specific fuel consumption, and heat rate.

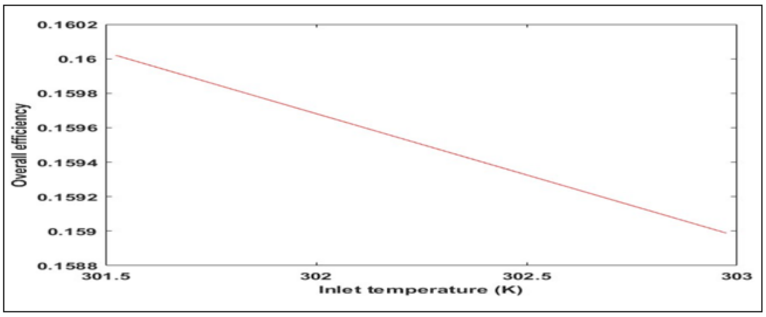

Fig-3: Effect of Compressor Inlet Temperature on the Overall Efficiency of the Gas Turbine Generator

The average overall efficiency, average thermal efficiency, average heat rate, average thermal power, average specific consumption, and average work ratio of the gas turbine generators were obtained as 16.09 %, 16.98%, 22636 kW, 5197 kW, 0.4619 kg/Kw-h, and 0.4605. Figure 3 shows the effect of compressor inlet temperature on the overall efficiency of the Centaur 40 gas turbine generators, it was observed that as the compressor inlet temperature increases, the power overall efficiency decreases. Fig. 4 shows the plot of compressor inlet temperature and thermal efficiency of the gas turbine generators. The results obtained show that the thermal efficiency of both gas turbine generator decreases with an increasing compressor inlet temperature. The decrease in thermal efficiency was because of decrease in net power output of the gas turbine cycle and this led to increase in compressor power, thus decreased in mass flow rate of gases.

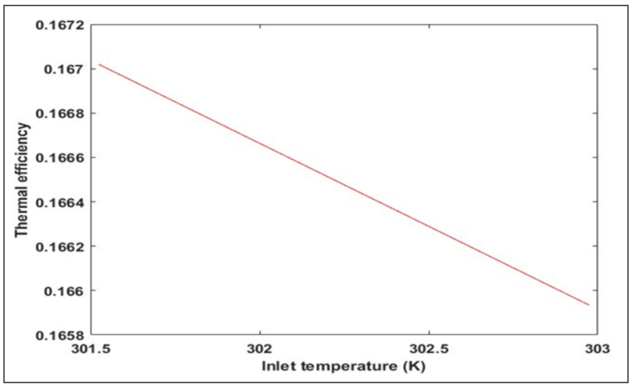

Fig-4: Effect of Compressor Inlet Temperature on the Thermal Efficiency of the Gas Turbine Generator

Fig. 5 shows the plot of compressor inlet temperature and heat rate of the gas turbine generators. From the performance evaluation, it can be seen that as the compressor inlet temperature increases the heat rate increases. The increased in heat rate (HR) further confirm why there was dropped in both thermal and overall efficiency.

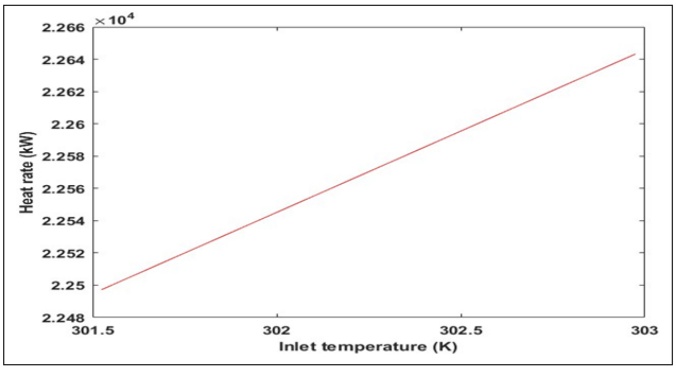

Fig-5: Effect of Compressor Inlet Temperature on the Heat Rate of the Gas Turbine Generator

Fig. 6 show the graph of compressor inlet temperature and heat rate of the gas turbine generators. It was observed that as the compressor inlet temperature increases, the thermal power output decrease. The highest thermal power was obtained at the lowest compressor inlet temperature while the lowest thermal power achieved at the highest compressor inlet temperature in both gas turbine generators used in this research work.

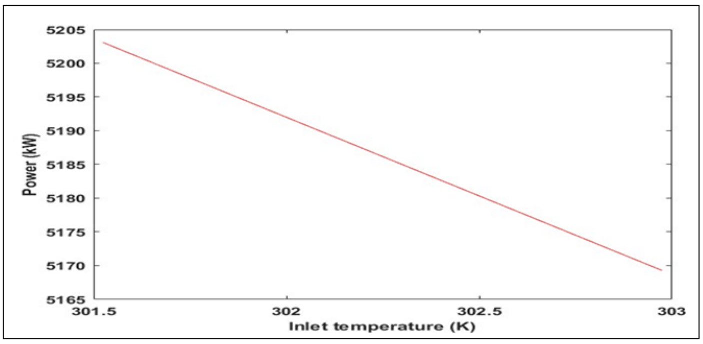

Fig-6: Effect of Compressor Inlet Temperature on the Thermal Power of the Gas Turbine Generator

Fig. 7 shows the graph of compressor inlet temperature and specific fuel consumption of the gas turbine generators. It was observed that the compressor inlet temperature has a significant effect on specific fuel consumption of both gas turbine generators. An increased in compressor inlet temperature brings about a corresponding increase in the specific fuel consumption. The corresponding increase was because of increase in compressor power due to a higher intake of ambient air temperature. This increase in specific fuel consumption because of increase in compressor inlet temperature further confirmed the resulted decrease overall efficiency, thermal efficiency, and thermal power.

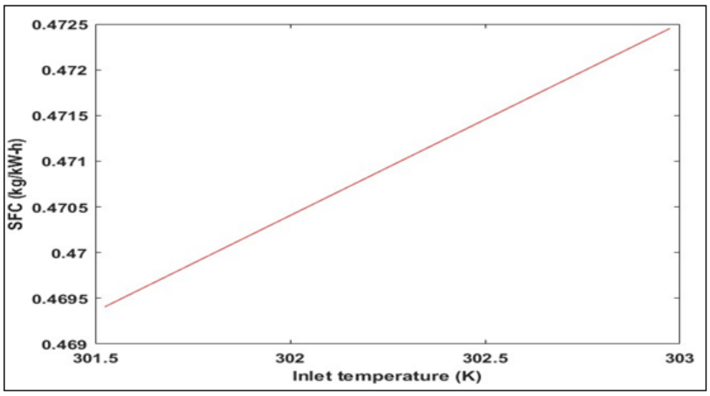

Fig-7: Effect of Compressor Inlet Temperature on Specific Fuel Composition of the Gas Turbine Generator

From Fig. 8, as the compressor inlet temperature increases the work ratio decrease. This decrease in work ratio reduces the effectiveness of the gas turbine generator. This is because a high work ratio is less vulnerable to irreversibility than low a work ratio.

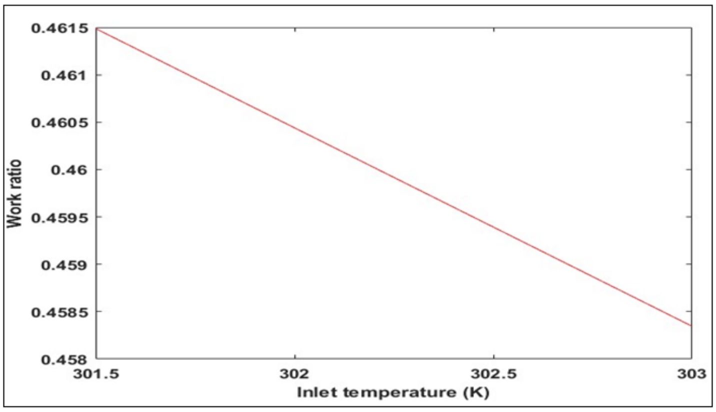

Fig-8: Effect of Compressor Inlet Temperature on Work Ratio of the Gas Turbine Generator

CONCLUSION

Energy analysis is usually carried out to know the sources of losses during conversion process in gas turbine generators, and other possible factors that can affect its performance. In this research work, the overall efficiency, average thermal efficiency, average heat rate, average thermal power, average specific consumption, and average work ratio of the Centaur 40 Gas Turbine Generators were obtained as 16.09 %, 16.98%, 22636 kW, 5197 kW, 0.4619 kg/Kw-h, and 0.4605. For 1K rise in inlet temperature, there is 0.087% drop in overall efficiency, 0.09% drop in thermal efficiency, 117kW rise in heat rate, 27kW drop in power, 0.0024kg/Kw-h rise in SFC and 0.00248 drop in work ratio. Furthermore, the compressor inlet temperature increases the specific fuel consumption and heat rate and decreases the work ratio. The overall efficiency, thermal efficiency, thermal power decreases with increasing compressor inlet temperature.

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