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Thermodynamic Performance Analysis of Simple Cycle Gas Turbine Power Plant

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ABSTRACT: The effects of ambient temperature on the performance of a simple cycle gas turbine power plant using the Siemens SGT5-2000E gas turbine at the Geregu power plant in Nigeria was investigated in this study. Thermodynamic equations were used to analyze the performance of gas turbine power plant using ambient conditions and operational data obtained from the Nigerian Metrological Agency (NiMet) for the location and control room of the power plant. The results of the analysis show that ambient temperature significantly impacts compressor exit temperature, compressor work, net work, efficiency, power output, and specific fuel consumption. The findings indicate that as ambient temperature increases, compressor exit temperature, compressor work, and specific fuel consumption increase, while net work, efficiency, and power output decrease. This study offers crucial guidance for enhancing the performance and efficiency of simple cycle gas turbine power plants, particularly in hot climates.

KEYWORDS: Ambient temperature, Gas turbine, Performance, Net work, Power output, Efficiency

I. INTRODUCTION

Gas turbines are internal combustion engines that produce power through continuous combustion [1] that can be considered as an energy conversion devices. The energy stored in the fuel is converted into useful mechanical energy in the form of rotational power. The term "gas" refers to ambient air that is absorbed by the engine and used as a workplace in the energy conversion process.Gas turbines operate on the Brayton thermodynamic cycle either in open or closed cycle configuration. However, despite the numerous benefits of the closed cycle, its application remains very rare because of the inability to run it at very high turbine inlet temperature like the open cycle. The open cycle gas turbine in its basic term consists of the compressor, the combustion chamber, and the gas turbine coupled to an electric generator. Gas turbine has its basic components to include the compressor, the combustion chamber, and the turbine[1].

A gas turbine works through some thermodynamic processes in series. Fresh atmospheric air is first drawn into the circuit continuously and energy is added in the combustion chamber by fuel addition and the products of combustion are expanded through the turbine which produces the work and finally discharges to the atmosphere[2]. The turbine gases expand during these processes and eventually become exhausted in the atmosphere.

The gas turbine power plants using open (simple) cycle configurations are the most operated in Nigeria because they have the advantage of early commissioning, commercial operation, fast starting acceleration, and quick shut down. However, the simple cycle gas turbine has its own challenges of low efficiency, low power output, emission of exhaust gases (useful waste heat) to the environment which occurs as a result of factors such as ambient conditions, non-utilization of exhaust gases and over-utilization of power developed by the turbine used in rotating the compressor. The aforementioned drawbacks of the simple cycle are not without negative consequences on the day-to-day running of the plant.

For instance, when the ambient temperature is high as expressed during hot days, the power output of the gas turbine drops while still consuming the same quantity of fuel thus impacting negatively on the fuel economy of the overall plant. It is therefore very important to devise means for overcoming these setbacks so, this can be done through carrying out assessment on the existing gas turbine to know the effects of the ambient conditions such as ambient temperature, pressure and relative humidity on the performance of gas turbine power plant.

The demand of energy in Nigeria is expected to rise in the near future due to increased economic activities, population growth, improved standard of living of the citizens. Investment in the establishment of the Geregu gas turbine power plant located in Ajaokuta, Kogi State is influenced by low price of fuel, low cost of installation, higher efficiency, minimum emissions of pollutants, etc.

There have been various studies conducted by different researchers which are related to performance analysis of simple cycle gas turbine power plants.

[3].The study on the effective parameter of gas turbine model with intercooled compression process was carried out and parametric study of a gas turbine cycle was proposed and modelled with intercooler compression process. The results show that increasing turbine inlet temperature and pressure ratio can improve the performance of the intercooled cycle.

[4].The impact of operational conditions and ambient temperature on gas turbine power plant performance was presented to evaluatethe effect of ambient temperature and operation conditions such as compression pressure ratio, turbine entry temperature, air-fuel ratio and compressor/turbine efficiencies on gas turbine power plant performance and computational model developed using the MATLAB codes. The results obtained show the thermal efficiency increases linearly with increases in compression ratio and decreases in ambient temperature. Also. the specific fuel consumption increases with increases in ambient temperature and lower turbine inlet temperature.

[5].Investigated the SGT5-2000E gas turbine power plant performance in Benin City based on energy analysis. The performance analysis results using the MATLAB software showed the average net thermal efficiency of the SGT5-2000E was 30.21 % when ambient temperature ranges from 21 to 35 ^{o}C, pressure ratio of 10.73 to 10.96, net output power of 148.92 MW to 160.70 MW, and 60.16 % of the fuel energy input lost to the environment as waste heat.

[6].Thermodynamic analysis of gas turbine conducted to analyse the performance of a gas turbine engine using operating factors such as pressure ratio, turbine inlet and exhaust temperatures, fuel to air ratio, isentropic compressor and turbine efficiencies and ambient temperature. The simulation result from mathematical equation using Microsoft Office Excel software could be used to suggest the optimum cycle operating condition.

[7].Parametric study of a two-shaft gas turbine power plant was proposed to evaluate parameters such as power output, compressor work, specific fuel consumption and thermal efficiency with respect to the ambient temperature and compressor pressure ratio for a typical set of operating conditions. Two shafts gas turbine cycle with realistic parameters was modeled using the MATLAB codes. The results obtained show that the turbine work is found to decrease as ambient temperature increases as well as the thermal efficiency decreases with the thermal efficiency, power output increases linearly with increases of compression ratio while decreases of ambient temperature and the simulated power of the two shafts gas turbine can reach to 135 MW, which is higher than the Baiji gas turbine power plant with less than 131 MW.

[8].A technical review of gas turbine power plant's performance from simple to complex cycle was carried out review various gas turbine power plants, with a focus on a simple cycle gas turbine power plant with a 2-shaft, regenerative, reheat, intercooler, complex cycle with effective intercooler, regenerative and reheat.

[9].Performance analysis of Delta III GT9 Transcorp gas turbine power plant, Ughelli in Nigeria was conducted to analyze and evaluate thermodynamic principles and technical data obtained from the plant. The results of the analysis covering one year show that 92% of the expected capacity was available in the period under study.

[10].Comparative performance assessment of different gas turbine configurations of a local power station in Nigeria was carried out on Omotosho power station. The cycle with its modification were investigated utilizing thermal efficiency, specific fuel consumption and power output. A multiplatform open-cape software called DWSIM was used for simulations. The results obtained showed the performance of the modified cycle was better than the simple cycle when thermal efficiency, specific fuel consumption and power output were considered.

In this current work, thermodynamic analysis of simple cycle gas turbine power plantis carried out.

The Geregu gas turbine power plant is owned by the Niger Delta Power Holding Company Limited (NDPHC). It has three gas turbine plants and usually called The Geregu Gas Turbine Power Plant. Geregu power station gas turbines are installed in a phase of three units of SGT5-2000E

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gas turbines, three SGen5-100A generators, as well as the electrical systems and the SPPA-T3000 control system. These are respectively referred as Siemens GT-21, GT-22 and GT-23 with total installed capacity of 506.1 MW (ISO) and 435 MW (Net). The turbine used for this study is the Siemens GT-21 at Geregu with a capacity of 145 MW. During the period of study, design data were monitored and the off-design data were analyzed using the Microsoft Excel spreadsheet for analysis.

In Nigeria, the use of gas turbines utilizing natural gas will remain crucial as a source of energy for many years. They are widely used due to their high power density and lack of friction among the components which makes it very reliable[11]. This unique features make gas turbines the best choice of both present and future power generating systems as well as their efficiency in energy conversion, reduction in cost of electricity, lower cost of installation and maintenance, ability to be put into service without so much delay of time, compactness, and their ability to use a wide range of hydrocarbon fuels[12].

The off-design effect of ambient and operating conditions at the Geregu gas power plant such as the temperature, turbine inlet temperature, pressure ratio influence the performance of the gas turbine cycle. However, ambient temperature and turbine inlet temperature have the most influence on some of the performance parameters such as power output, efficiency and specific fuel consumption. One unique feature of the Geregu power plant is that it has the capacity to meet the energy demand of the electricity grid during the rainy season, when temperatures are cooler. The variations in the energy demand caused by extreme weather condition is more pronounced in the dry than in the rainy season. However, in Ajaokuta, where the gas turbine is located, the average ambient temperature is approximately 28.6 °C.

II. METHODOLOGY

The study procedure utilized for this research was data collection which included the gas turbine log sheet through the use of human machine interface (HMI), original equipment manuals (OEMs) for a period of 10 years running from January, 2012 to December, 2022. Also, ambient data for the location was collected from NiMet. Performance analysis of the gas turbine was done through the use of thermodynamics equations to determine the effect of ambient temperature on parameter such as compressor exit temperature, net work, turbine work, efficiency, specific fuel consumption and power output. The results of the analysis were therefore displayed using the Microsoft excel plot.

1. Thermodynamic Analysis of the Gas Turbine Cycle Model

The Fig. 1 shows a schematic diagram of simple open cycle gas turbine having its components as the compressor, the combustion chamber and the turbine.

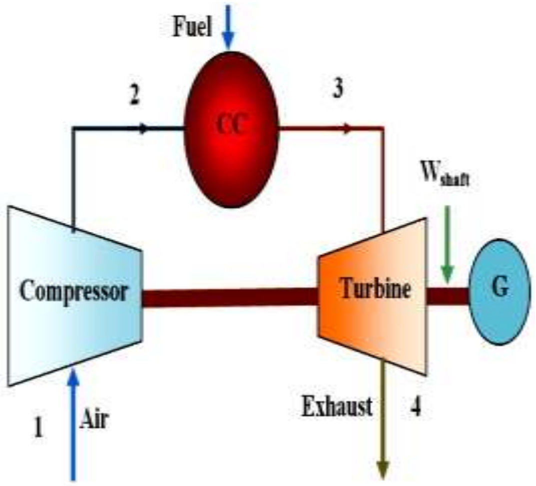

Figure 1: Schematic Diagram of Simple Cycle Gas Turbine Showing the Basic Components[13]

The compressor takes in atmospheric air from the environment and compresses it to increase the temperature and pressure before delivering it into the combustion chamber, where fuel is added for combustion to take place. The product of this combustion is thereafter expanded in the turbine where work is developed. Part of the work developed is used to rotate the compressor which is on a common shaft with the turbine and the remaining is used to generate electricity and the rest emitted into the environment in form of pollutant.
The temperature-entropy diagram of the simple open gas turbine cycle is shown in Fig. 2.

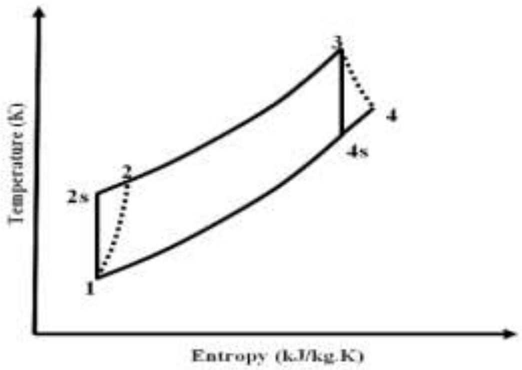

Figure 2: Temperature-Entropy Diagram for Simple GT Cycle [13].

2. Gas Turbine Modeling

The data used for computing in the present study for work output and thermal efficiency were obtained from the Geregu gas turbine power plant.

The relevant steady flow energy equation is;

$(Q_{in} – Q_{out}) + (W_{in} – W_{out}) = \Delta h$ (3.1)

Where:

Q_{in} = heat added to working fluid

Q_{out} = heat rejected from the working fluid

W_{in} = work done by compressor to compress working fluid

W_{out} = work done by turbine to generate shaft power

Δh = change in enthalpy

Therefore,

Compressor Work:

$W_C = (h_2 – h_1) = \dot{m}_a c_{pa} (T_2 - T_1)$ (3.2)

$T_2 = T_1(P_2/P_1)$^(y-1)/y (3.3)

Heat Added in The Combustion Chamber:

$Q_{added} = (h_3 – h_2) = \dot{m}_g c_{pg}(T_3 – T_2)$ (3.4)

Turbine Work:

$WT = (h_3 – h_4) = \dot{m}_g c_{pg}(T_3 – T_4)$ (3.5)

$T_4 = T_3(P_4/P_3)$^(y-1)/y (3.6)

Gas Turbine Efficiency:

$\eta_{th} = W_{T,net}/Q_{added} = W_T – W_C/Q_{added}$ (3.7)

Or

η_{th} (Brayton) = 1 – 1/(rp^(y-1)/y) (3.8)

Where:

rp = P_2/P_1 and y, are pressure and specific heat ratios.

Power Output = W_{net} x $\dot{m}_a$ (3.9)

SFC = (3600 x f)/P_{out} (3.10)

HR = Q_{added}/P_{out} (3.11)

AFR = LHV/ Q_{added} (3.12)

Table 1: Design Data of SGT5-2000E Gas Turbine

S/N	Parameters	Symbol	Unit	Value
1	Ambient temperature	T_1	K	288
2	Compressor outlet temperature	T_2	K	623
3	Turbine inlet temperature	T_3	K	1333
4	Turbine exit temperature	T_4	K	813
5	Compressor inlet temperature	P_1	Bar	1
6	Compressor outlet pressure	P_2	Bar	11
7	Compressor pressure ratio	r_p		11:1
8	Turbine pressure ratio	r_p		1:11
9	Power output	P_{out}	MW	145
10	Mass flow of air in gas turbine	$\dot{m}_a$	kg/s	500
11	Mass flow of fuel in gas turbine	$\dot{m}_f$	kg/s	8
12	Specific heat ratio			1.4
13	Specific heat of air	c_{pa}	kJ/kg	1.005
14	Specific heat of gas	c_{pg}	kJ/kg	1.14

Table 2: Results of Gas Turbine Analysis

Months	T1 (K)	T2 (K)	Wc (kJ/kg)	Wnet (kJ/kg)	Qadded (kJ/kg)	Eff (%)	PWR (kW)	SFC (kg/kWh)	HR (kJ/kWh)	AFR
Jan	300.6	596.3687	297.2476	295.7524	839.7596	0.352187	147876.2	0.194757	5679	57.13123
Feb	303.5	602.1221	300.1152	292.8848	833.2008	0.351518	146442.4	0.196664	5690	57.58096
Mar	304.8	604.7012	301.4007	291.5993	830.2606	0.351214	145799.6	0.197531	5695	57.78487
Apr	303.5	602.1221	300.1152	292.8848	833.2008	0.351518	146442.4	0.196664	5690	57.58096
May	301.9	598.9478	298.5331	294.4669	836.8195	0.351888	147233.5	0.195608	5684	57.33196
Jun	300.9	596.9639	297.5442	295.4558	839.0811	0.352118	147727.9	0.194953	5680	57.17743
Jul	300.1	595.3768	296.7532	296.2468	840.8905	0.352301	148123.4	0.194432	5677	57.0544
Aug	299.9	594.98	296.5554	296.4446	841.3428	0.352347	148222.3	0.194303	5676	57.02372
Sep	300.1	595.3768	296.7532	296.2468	840.8905	0.352301	148123.4	0.194432	5677	57.0544
Oct	300.9	596.9639	297.5442	295.4558	839.0811	0.352118	147727.9	0.194953	5680	57.17743
Nov	302	599.1462	298.632	294.368	836.5933	0.351865	147184	0.195673	5684	57.34746
Dec	300.6	596.3687	297.2476	295.7524	839.7596	0.352187	147876.2	0.194757	5679	57.13123

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III. RESULTS

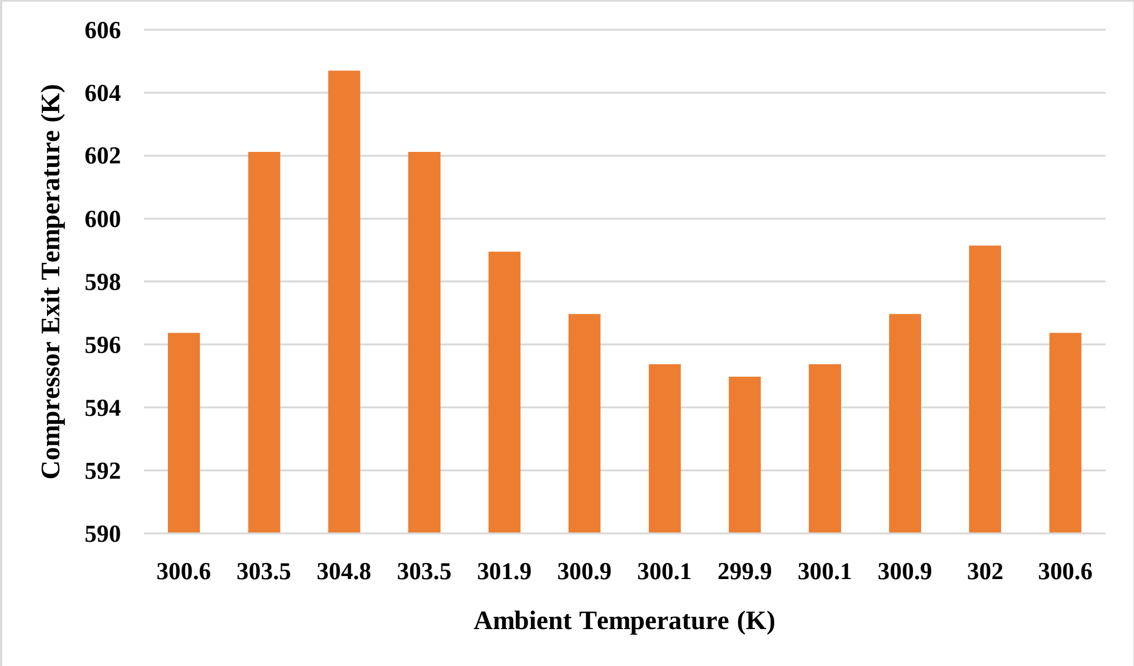

Figure3: Effect of Ambient Temperature on Compressor Exit Temperature

The Fig. 3 presents effect of ambient temperature on compressor exit temperature. It can be noticed from the figure that as the ambient temperature increases, the compressor temperature also increases. This is because as the ambient temperature increases, the air entering the gas turbine compressor becomes hotter and less dense, thus resulting in a higher compressor exit temperature. However, decrease in the air entering the compressor results in a lower compressor exit temperature. In the same vein, ambient temperature also affects compressor efficiency. This is because as the ambient temperature increases, the compressor efficiency decreases, leading to a higher compressor exit temperature.

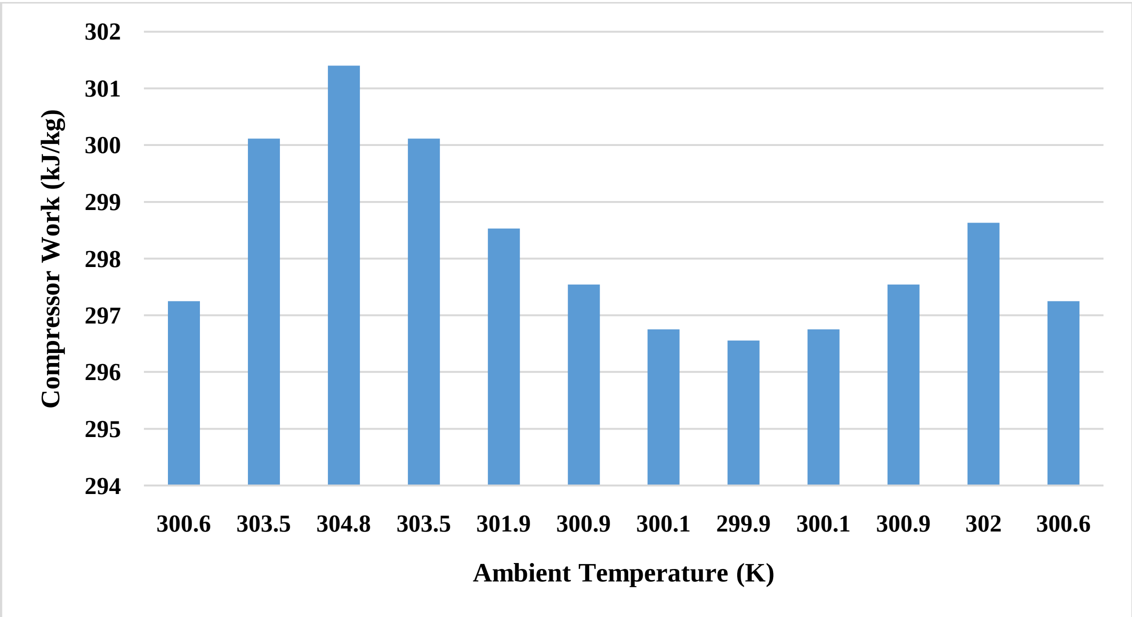

Figure 4: Effect of Ambient Temperature on Compressor Work

The Fig. 4 presents effect of ambient temperature on compressor work. It can be noticed from the figure that increase in ambient temperature leads to increase in compressor work as the air entering into the compressor becomes hotter and less dense. The compressor must work very hard to compress the hotter air. Similarly, decrease in ambient temperature leads to decrease in compressor work as the compressor becomes cooler and denser, thus resultingin decrease in compressor work as cooler air can easily be compressed efficiently. The highest compressor work is 302 kJ/kg and occurred in March, which has the highest ambient temperature of 304.8 K. Similarly, the lowest compressor work is 294 kJ/kg in August with lowest ambient temperature of 299.9 K. The ambient temperature has a significant impact on compressor work, with higher ambient temperature resulting in higher compressor work. This relationship is crucial for optimizing gas turbine performance and efficiency.

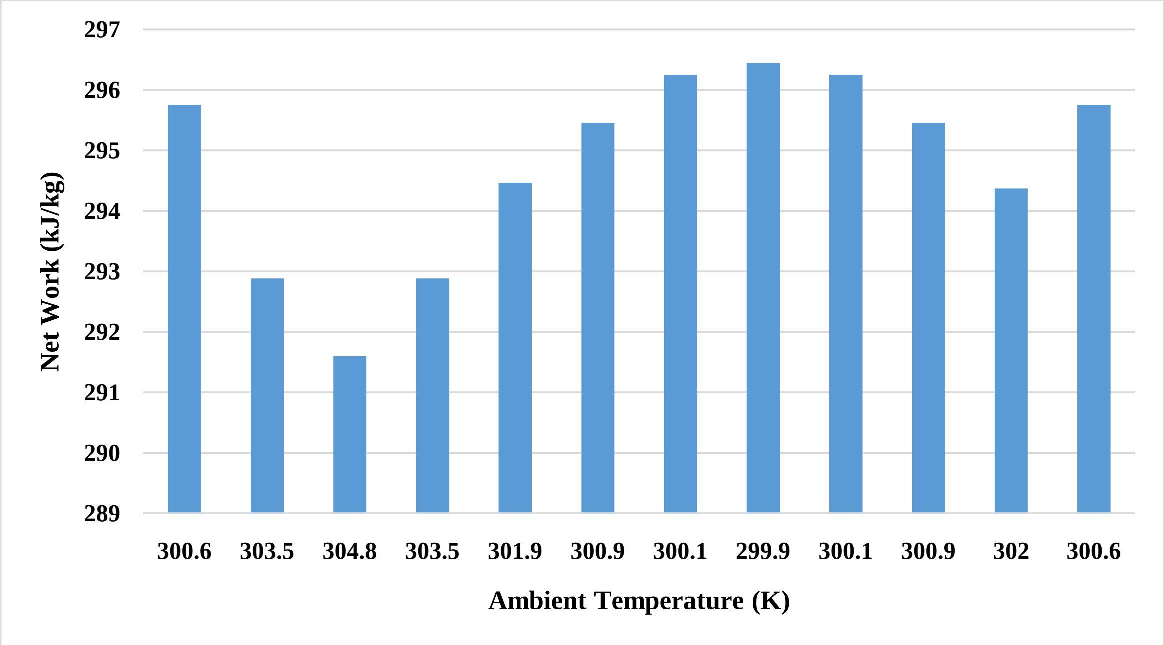

Figure5: Effect of Ambient Temperature on Net Work

The Fig. 5 presents impact of ambient temperature on gas turbine net work. As can be seen from the figure, increase in ambient temperature leads to decrease in the net work of gas turbine. The highest value of ambient temperature is 304.8 K in March corresponding to the lowest net work of 292 kJ/kg. Also, decrease in ambient temperature ingresses the net work. This is seen in the figure for a lowest temperature in August and highest net work of 297 kJ/kg. Conclusively, the results indicate that the net work is inversely proportional to the ambient temperature. As the ambient temperature increases, the net work decreases, and vice versa. This further suggests that the compressor work is affected by the ambient temperatures resulting in lower net work values.

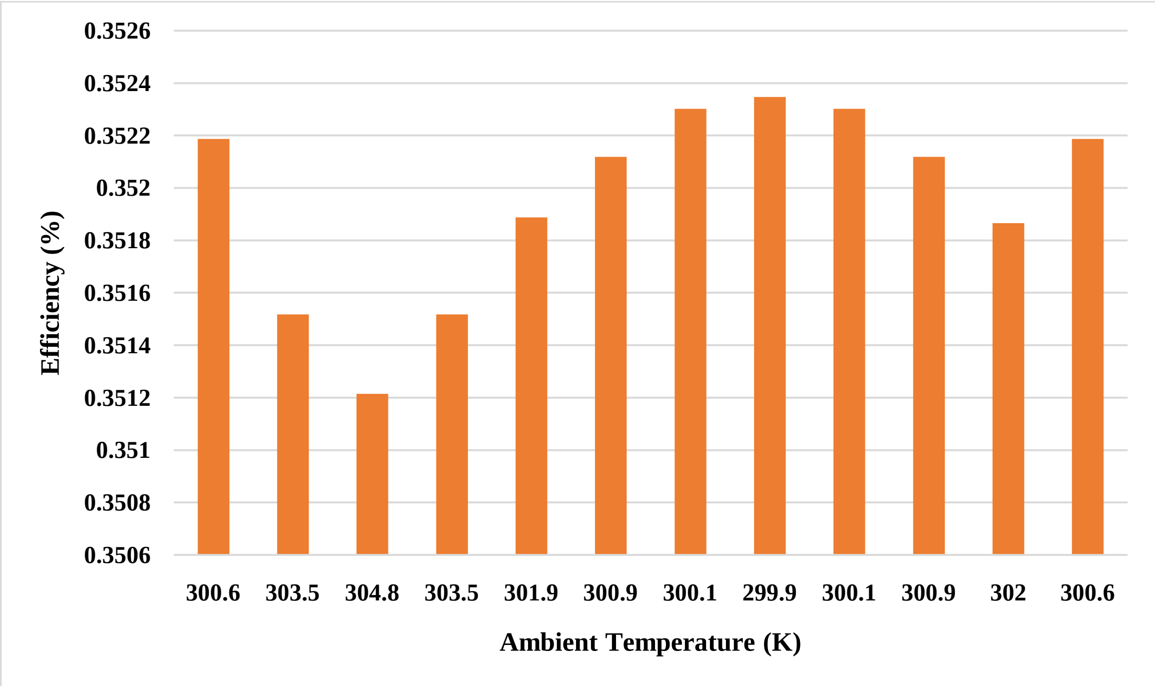

Figure6: Effect of Ambient Temperature on Efficiency

The Fig. 6 presents effect of ambient temperature on efficiency of gas turbine. It can be observed from the figure that as the ambient temperature increases, the efficiency decreases. Similarly, when it decreases, the efficiency increases. The results show gas turbine efficiency decreases with increase in ambient temperature and vice versa. Finally, the gas turbine's efficiency remains relatively stable across varying ambient temperatures, making it suitable for diverse environmental conditions.

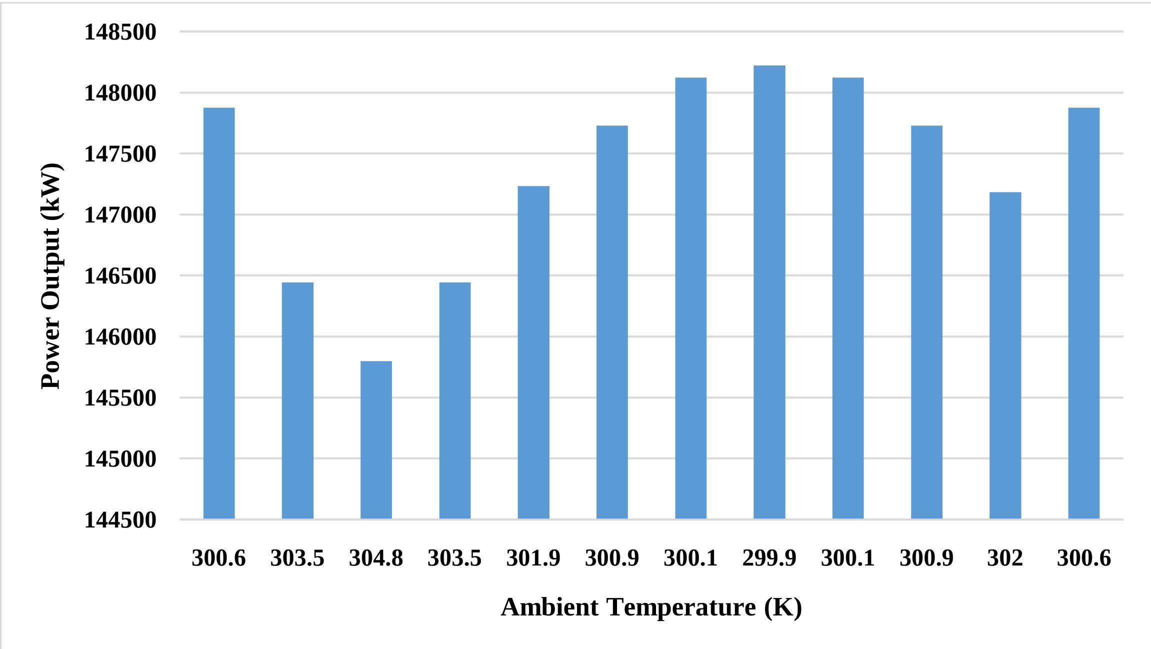

Figure7: Effect of Ambient Temperature on Power Output

Fig. 7 presents the effect of ambient temperature on power output. It can be observed from the figure that as the ambient temperature increases, power output decreases. The highest power output is 148222 kW at the lowest ambient temperature of 299.9 K in August. Similarly, decrease in ambient temperature leads to increase in power output. As the ambient increases, the power output decreases, and vice versa. This suggests that the compressor work is affected by the ambient temperature, with higher ambient temperature resulting in lower output values.

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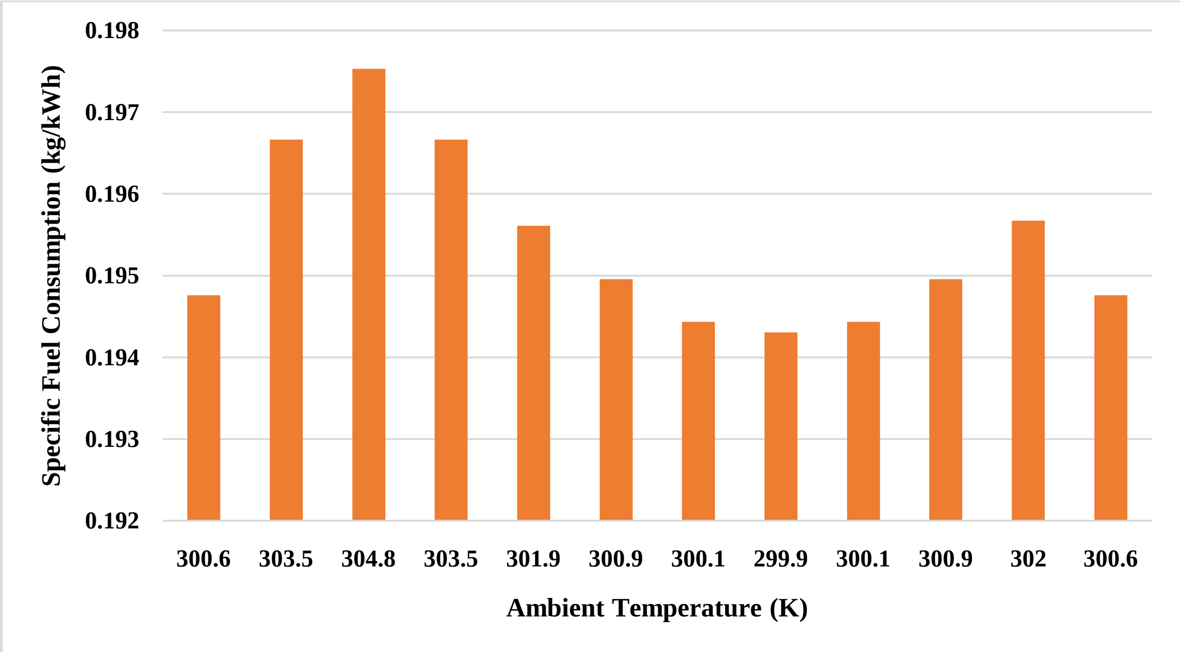

Figure8: Effect of Ambient Temperature on Specific Fuel Consumption

The Fig. 8 presents the effect of ambient temperature on specific fuel consumption. It can be noticed from the figure that as the ambient temperature increases, specific fuel consumption also increases. The highest specific fuel consumption is 0.197 kg/kWh occurs at the highest ambient temperature of 304.8 K in March. Similarly, as the ambient temperature decreases, specific fuel consumption deceases. The lowest specific fuel consumption is 0.194 kg/kWh occurs at the lowest ambient temperature of 299.9 K in August. Conclusively, the results indicate that the specific fuel consumption is directly proportional to the ambient temperature. As the ambient temperature increases, the specific fuel consumption also increases, indicating a decrease in compressor efficiency. This suggests that the compressor work is affected by the ambient temperature, with higher ambient temperature resulting in higher specific fuel consumption values.

IV. CONCLUSION

This study examined how ambient temperature affects the performance of a simple cycle gas turbine power plant using the Siemens SGT5-2000E gas turbine at the Geregu power plant in Nigeria. The results show that ambient temperature has a significant impact on the compressor exit temperature, compressor work, net work, efficiency, power output, and specific fuel consumption of the gas turbine.

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