Analysis and Performance Evaluation of Gas Turbine by Incorporating a Wetted Evaporative Media Cooler

Ukwuaba, Samuel Ifeanyi, Agberegha, Orobome Larry, Mohammed, Bello Ahmed

Abstract: Gas turbine shows great inverse effect on ambient air temperature. The efficiency and net power output of the gas turbine increases with decrease in ambient air temperature. Nigeria with an average ambient air temperature of 31℃ tends to experience a drop in gas turbine efficiency and net power output. It has been proven that by employing wetted evaporative media cooler to the inlet of the compressor, the gas turbine plant performance can be maximized; this employed devise reduces the inlet temperature. An open cycle gas turbine Frame 9E in Ihovbor power plant Benin Edo State, Nigeria generating electricity at a capacity of 450MW was used as a retrofitted study for the research by using Aspen HYSY V9 simulation one software model. The results, from plots of graphs, when interpreted, depicts a direct proportionality between ambient air temperature and compressor work; an inverse proportionality between ambient air temperature and net power output of the turbine; a direct proportionality between ambient air temperature and specific fuel consumption; an inverse proportionality between ambient air temperature and plant efficiency. The numerical value for the drop in ambient air temperature consequent upon the use of evaporative cooler is 11.25^{0}C. Since the gas turbine is a thermal engine, its inlet temperature – ambient temperature – has significant effect on the aforementioned parameters; so that, results from the study, shows; the evaporative cooler results in a drop in ambient temperature of 11.25℃, showing an increase of about 3.7% efficiency and 11.56MW net power output of the turbine. Drop in specific fuel consumption is 0.024kg/KWh. From the research, it is deduced that gas turbine plants perform better in temperate regions than tropical regions. Therefore, to maximize the performance of a gas turbine plants in high temperature climates, retrofitting it with an air cooler will lower the temperature to a value close to the design temperature before compression takes place and it will tend to improve gas turbine performance in tropical country like Nigeria.

Key words: Gas turbine, efficiency, ambient temperature, net power output, simulation

I. INTRODUCTION

Gas turbine is a rotary machine comprising of a compressor, combustion chamber and a turbine. The compressor supplies air at a very high pressure and temperature to the combustion chamber [1].

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***** Correspondence Author (s)
Ukwuaba, Samuel Ifeanyi*, Department of Mechanical Engineering, Petroleum Training Institute, Effurun, Nigeria
Agberegha, Orobome Larry, Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Nigeria
Mohammed, Department of Mechanical Engineering, Federal University of Petroleum Resources, Effurun, Nigeria
Bello Ahmed, Department of Mechanical Engineering, Petroleum Training Institute, Effurun, Nigeria

Most gas turbine installed in the tropical region are designs meant for other climate regions, thus this tend to affect the gas turbine performance. Incorporating an evaporative media cooler at the compressor inlet will reduce the ambient air temperature [2]. This reduces the compression ratio, thus increasing the air density and air mass flow rate and less work is done by the compressor. This leads to an increase in the thermal efficiency and net power output of the gas turbine [3].

Evaporative cooling is similar to the fogging system; however, water is not directly injected to the compressor inlet. Instead, inlet air is allowed to travel through a shower of water and the latent heat of water of evaporation absorbs energy from the inlet air. Excess water is drained away from the system. This is a low cost method of inlet air cooling. But the performance is limited by the wet bulb temperature reading (relative humidity value), that is again limited by the relative humidity of ambient air. In an effort to boost the performance of gas turbine power plant, a wetted media evaporative cooler is used with a gas turbine. This increases the combustion air density; and consequently, an increase, also, of power output.[14]

Evaporative media cooling which involves heat and mass transfer by the formation of saturated air and water vapor mixture; this occurs when occurs when water and the unsaturated air mixture is mixed.[5]. This heat and mass transfer is due to the temperature and vapor pressures differentials between the air and water. Owing to the fact that heat transfer from air to water evaporates the water, and the water evaporating into the air constitutes mass transfer, Heat and mass transfer are both operative in the evaporative cooler [7]. The water vapor, after this process, becomes a constituent of air, which carries the latent heat with it. Since it gives up the sensible heat, the air dry-bulb temperature decreases. Theoretically, the incoming air and water in the evaporative cooler are considered as isolated system due to no heat is added to or removed from the system.

Power is one of the major factors of development in a nation, for a nation to strive it most have to improve on its power sector [9]. The work of Ibrahim*et al.*, [10] established that an increment of 1℃ in the compressor air inlet temperature decreases the gas turbine power output by 1%. From the [9] to [10], it is evident that the performance of a gas turbine performance is affected by the temperature of the ambient air.

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As the temperature of ambient air increases, the performance there is decrease in the efficiency of the gas turbine plant and net power output, due to the inverse mathematical relationship existing between air density and temperature cooling the inlet air of the gas turbine, while as the ambient air temperature decreases the air density increases thereby, increasing the mass flow rate, thereby increasing the thermal efficiency and the power output of the gas turbine [11]. The gas turbine power plant is designed to operate under given local weather conditions according to International Standardization Organization (ISO) [12]. The gas turbine, a turbomachine, is designed to operate with a constant air volume flow in the compressor [5].Here in the tropical Africa like Nigeria with average ambient temperature of about 26℃ and above, these tend to affect the performance of the gas turbine power plant. Incorporating the wetted media evaporative cooler in gas turbines will reduce the ambient air temperature and make the gas turbine work effectively in Nigeria.

II. RESEARCH METHODOLOGY

2.1 Description of the Power Plant

Ihovbor power plant was used in this research work. The power plant is a 4×(112.5MWe) GT-9E OCGT power plants with 450MW capacity, connected to the National Grid. It is owned by Niger Delta Power Holding Company (NDPHC). The plant was constructed by Marubeni Engineering West Africa and is located at North East of Benin City; Edo State Nigeria with location coordinates of lat. 6.40446°N and long. 5.68276°E [13].

2.2 Data Collections

The operating data for Ihovbor Power Plant were collected from the control log sheet for 2014. These collected data were analyzed statistically and mean values were collected for the period of January to December with an overall average. Summary of operating parameter of a (GE Frame 9E) x4 gas turbine unit used for this study is presented in Table 1. Thermodynamic analysis were carried out on each components of the gas turbine. Mass and energy conservation laws were applied as governing equations of each of the component and the performances of the plant were evaluated having evaporative cooler

Table 1: Data from Gas Turbine Power Plant

S/N	Operating Parameters	Valve	Unit
1	Air Mass flow rate through compressor (ma).	376.75	Kg/s
2	Inlet air to compressor Temperature (T_1)	298.8	^{0}k
3	Pressure of inlet air to compressor (P_1)	101.32	Kpa
4	Outlet temperature of air from compressor (T_2)	629.00	^{0}k
5	Outlet pressure of air from compressor (P_2)	972.672	Kpa
6	Fuel gas (natural gas) mass flow rate (mf)	6.7	Kg/S
7	Air – fuel ratio at full load (on mass basis)	56:1	
8	Inlet pressure of fuel gas	22.8	Bar
9	Inlet temperature of gas turbine (T_3)	1362.43	^{0}K
10	Maximum exhaust temperature of T. outlet	831.73	^{0}K
11	Combustion compressor efficiency $\cap_{ce}$	99.0%	
12	Temperature of the gas in the combustion chamber	55	^{0}C
13	Lower heating valve (LHV)	466.70	kj/kg
14	Isentropic eff. Of compressor	87.8	%
15	Isentropic eff. Of Turbine	89.4	%
16	Specific heat capacity of air Cpa	1.005	KJ/kg k
17	Specific capacity of gas Cpg	1.15	KJ/kg k
18	Fuel heating valve (cv)	46670	KJ/kg k

2.3 Thermodynamic Analysis and Simulation of Gas Turbine

A gas turbine power plant consists of a compressor, combustion chamber and a turbine. A wetted evaporative media is fitted before the compressor as shown in Figure 1 and Figure 2. The performance of the gas turbine is evaluated using Aspen HYSY V9 – ASPEN ONE simulation model and compared with values from the simple gas turbine simulation. In the evaporative cooler, water drains through the distribution pad into the media, by gravity action down ward and wets the media surface. The dry air as it passes through the wetted pad becomes saturated such that the dry bulb temperature (DBT) of the inlet air reaches initial wet bulb temperature (WBT). It is assumed that the relative humidity of outlet air from the cooler will not exceed 100% despite the inlet air condition. The relative humidity efficiency is assumed to be 100%. The gas turbine power plant with an evaporative cooler is modeled in the following assumptions.

i. The process modeling was a steady-state simulation
ii. The combustion of the process was assumed to be a conversion reaction in HYSYS.
iii. There is about 95% energy conversion in the reactor.
iv. From the modeled power plant the compressor adiabatic efficiency is 87.80%, while turbines adiabatic efficiency is 89.40%.
v. The component of the natural gas is methane.
vi. The natural gas in the feed comes directly at the pressure of 22.8 bars.
vii. The pressure drop across the combustion chamber is 0.012%.

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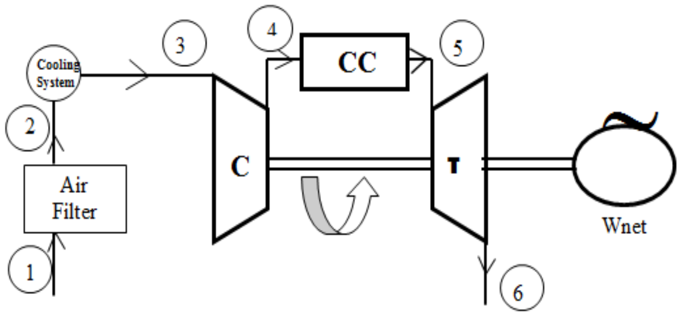

Figure 1: Gas Turbine Cycle with a Wetted media Evaporative Cooler

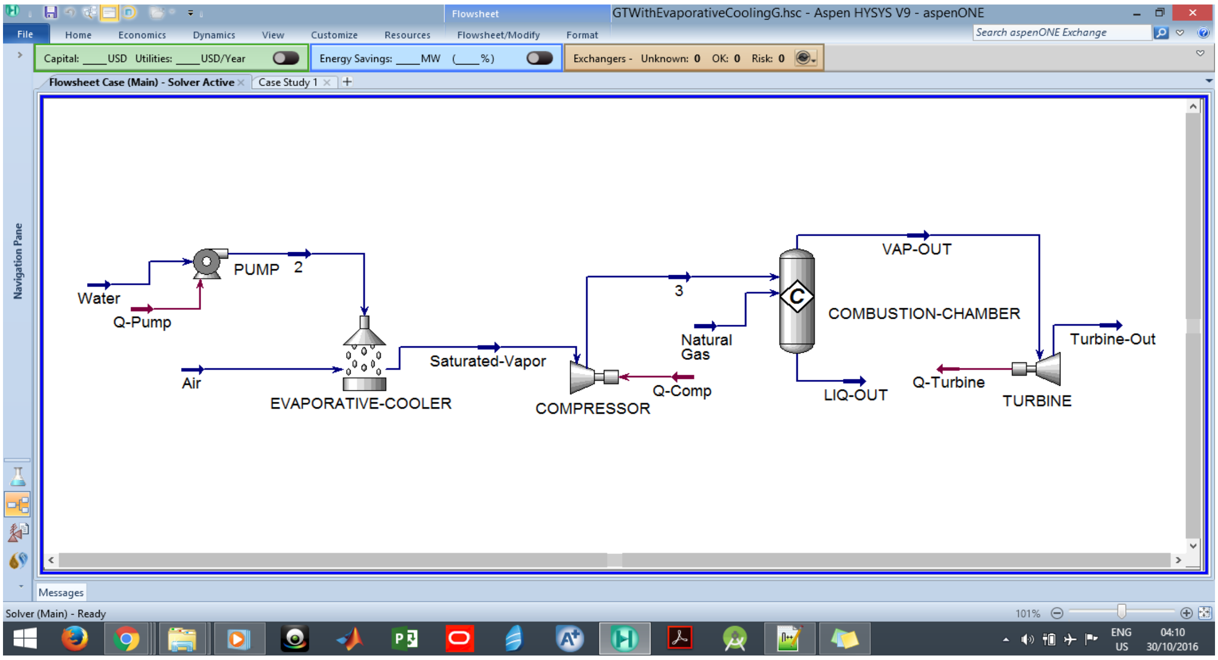

Figure 2: Gas Turbine Cycle Flow Chart with a Wetted Media Evaporative Cooler

2.4 Process Simulation

Aspen HYSY V9 – ASPEN ONE simulation model was used to model the gas turbine with and without an evaporative cooling unit. The simulation environment was entered to begin building the process model. The pump, evaporative cooler, compressor, conversion reactor, turbine icons from the model palette were clicked and placed on the flow sheet. Figure 3 shows the parameters for the incoming air.

Worksheet | Attachments | Dynamics

Worksheet: Conditions, Properties, Composition, Oil & Gas Feed, Petroleum Assay, K Value, User Variables, Notes, Cost Parameters, Normalized Yields

Stream Name	Air	Vapour Phase
Vapour / Phase Fraction	1.0000	1.0000
Temperature [C]	25.00	25.00
Pressure [kPa]	100.0	100.0
Molar Flow [kgmole/h]	4.701e+004	4.701e+004
Mass Flow [kg/h]	1.356e+006	1.356e+006
Std Ideal Liq Vol Flow [m3/h]	1568	1568
Molar Enthalpy [kJ/kgmole]	-8.076	-8.076
Molar Entropy [kJ/kgmole-C]	151.8	151.8
Heat Flow [kJ/h]	-3.797e+005	-3.797e+005
Liq Vol Flow @Std Cond [m3/h]	1.111e+006	1.111e+006
Fluid Package	Basis-1	
Utility Type		

Figure 3: Parameters for the incoming Air.

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The evaporative-cooler unit has two inlets; one for air and the other for water. The higher temperature of the air causes the water to evaporate upon contact. This acts as the inlet to the compressor.

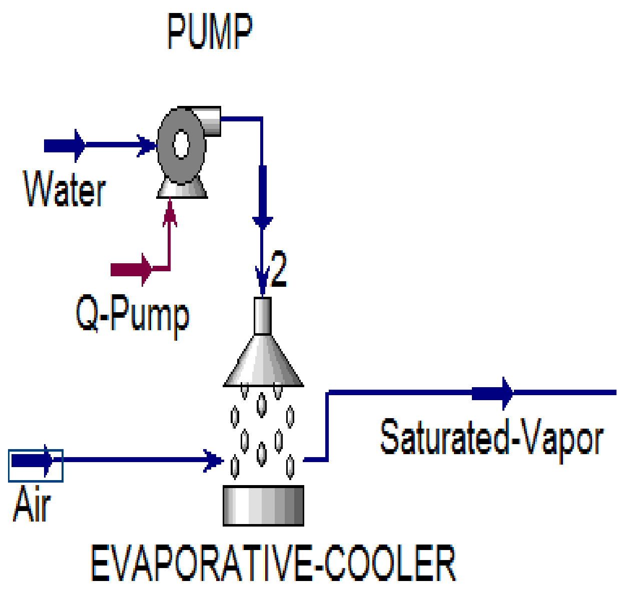

Figure 4: Evaporative Cooler with Pump

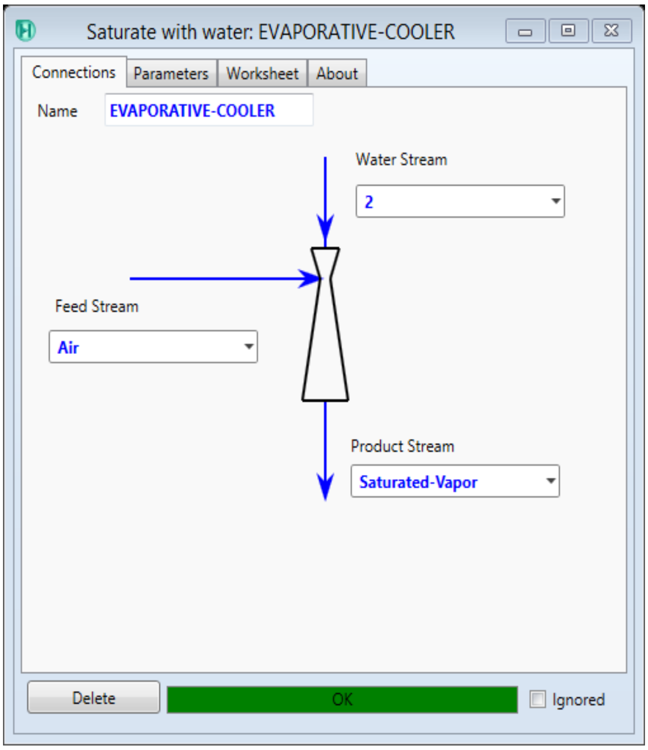

Figure 5: Evaporative Cooler Unit

III. RESULTS AND DISCUSSION

Table 2 shows the results obtained when the power plants for simple gas turbine without evaporative cooler was simulated with ASPEN HYSY V9 – ASPEN ONE software model at an ambient air temperature of 25℃, atmospheric pressure 1.013 bar and relative humidity 70.8% in the region at the particular time.

Table 2: Parameter values obtained by Simulating the Gas Turbine Power Plant without an Evaporative Media Cooler

Parameter values without evaporative cooler	Values
Ambient air temperature ℃	25
Saturated vapor temperature ℃	25
Compressor Power Kw	138401.1245
Turbine Power Kw	240596.76
Net Power Kw	102195.6382
Thermal efficiency %	32.68283765
Specific fuel consumption kg/ kwh	0.236017909
Net station Heat Rate kg/ kwh	11014.95843

Table 3 shows the results obtained when the power plants for simple gas turbine with an evaporative cooler was simulated with a ASPEN HYSY V9 – ASPEN ONE software Model at an ambient air temperature of 25℃, atmospheric pressure 1.013 bar and Relative Humidity 75.8% in the region at the particular time.

Table 3: Parameter values obtained by Simulating the Gas Turbine Power Plant without an Evaporative Media Cooler

Parameter values with evaporative media cooler	Valves
Ambient air temperature℃	25
Saturated vapor temperature ℃	13.7456
Water mass flow rate kg/h	27549.29
Compressor Power Kw	121833.3976
Turbine Power Kw	235588.2341
Net Power Kw	113754.8365
Thermal efficiency %	36.3795455
Specific fuel consumption Kg/Kwh	0.21203495
Net station Heat Rate Kg/Kwh	9895.67068

Figure 6 shows that varying ambient temperature causes change in power output of the gas turbine. The lower the ambient temperature, the higher the power output of the gas turbine. A 1℃ reduction in the ambient temperature results in an increase of about 4.6MW power output. At ambient air temperature of 25℃ into the compressor, the net power output was 102195.64KW (102.196MW) while when the ambient air temperature is brought down from 25℃ to about 13.75℃ incorporated with a wetted evaporative media cooler. The net power output increased to 113754.84KW (113.755MW).

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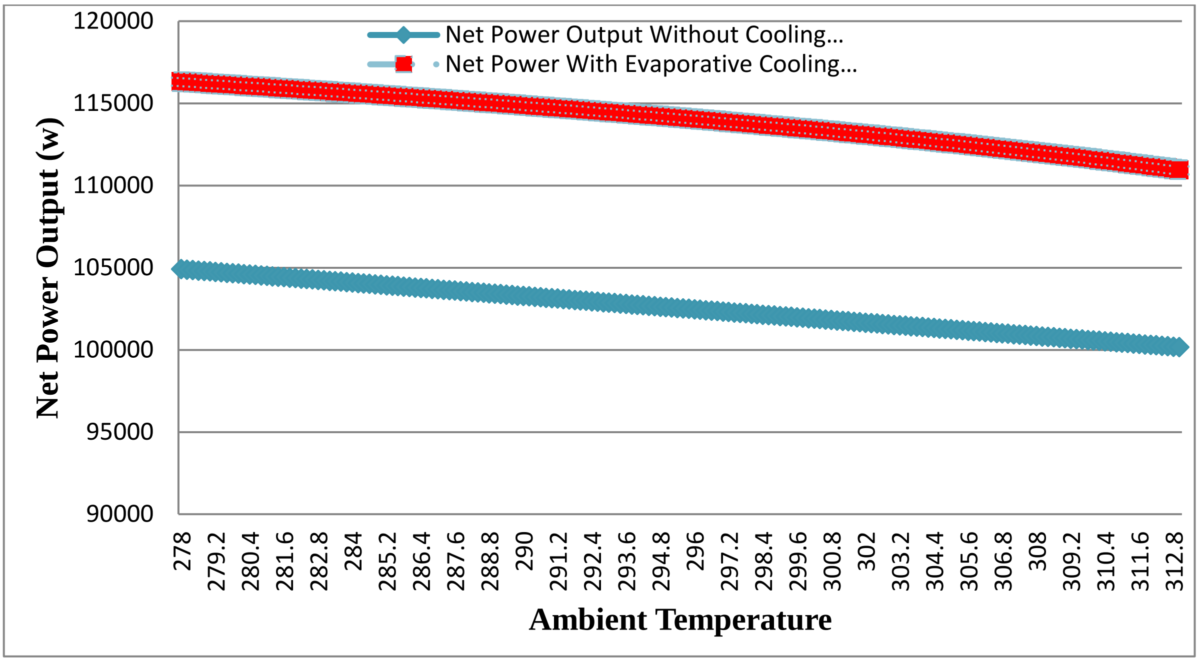

Figure 6: How Air Ambient Temperature Affects Turbine Net Power Output

Figure 7 shows that the ambient air temperature do have a significant influence on the specific fuel consumption (SFC) of the gas turbine. The graph shows the SFC is proportional with increase in ambient air temperature; it decreases with decrease in turbine inlet temperature. The result shows that temperature reduction of 4.1℃ produce a drop in the SFC by 0.02398kg/W. The implication here is that, the less the SFC the more the power output.

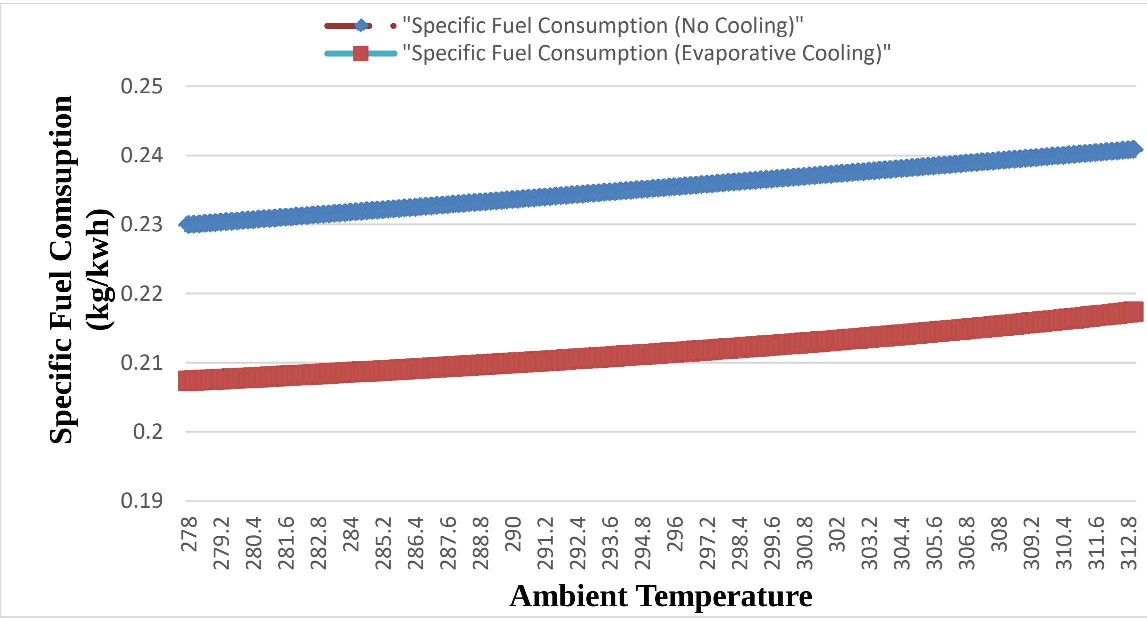

Figure 7: Effect of Ambient Temperature on Specific Fuel Consumption

From figure 8, it is observed, that the thermal efficiency of the gas turbine is affected by the ambient air temperature due to the change in air density and compressor work [16] reports that a a lower ambient temperature leads to a higher density of air and less work of the compressor which in turn provides a greater output power of the gas turbine. It can be seen that when the ambient temperature increases, the thermal efficiency decreases [16]. This is due to the fact that the entrance of the mass flow of air to the compressor increases with the decrease of the ambient temperature. Therefore, the mass flow of fuel will increase, since the air to fuel ratio remains constant [16]. There is increase in efficiency with decrease in compressor inlet temperature in the incorporated air cooling gas turbine the least ambient temperature at 298.8k gives, an efficiency of 32.68%. Incorporating an evaporative cooling media, the ambient air temperature dropped to 286.7k with an increase efficiency of 36.38%.

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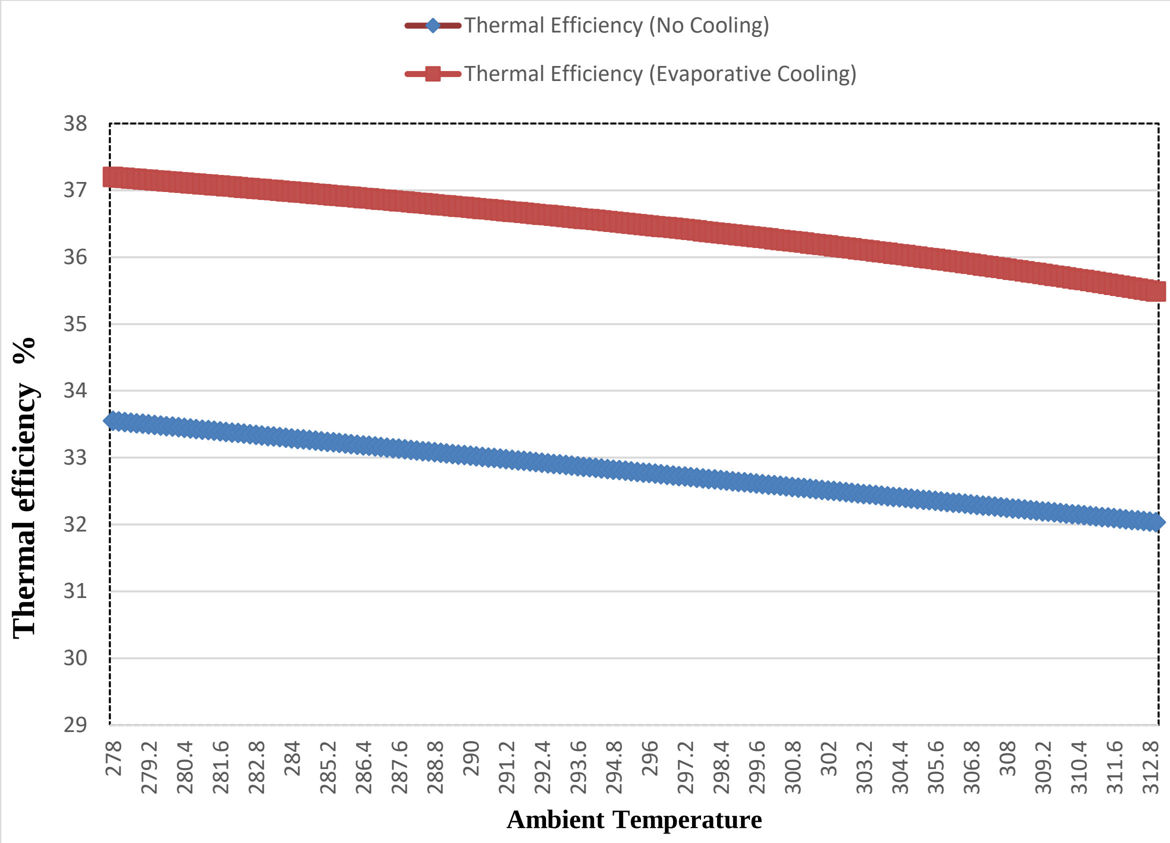

Figure 8: Effect of Ambient temperature on Thermal Efficiency

The heat rate is influence by the varying ambient air temperature on the operation of the gas turbine. As the ambient air temperature increases, the heat rate also increases. Useful heat is lost to the surrounding environment. The effect of the ambient air temperature on the open cycle net heat rate per kilowatt hour is shown in Figure 9, which clearly shows that the improvement in the sensible heat rates is associated with the fact that the heat rate improves as which decreases the compressor inlet temperature.

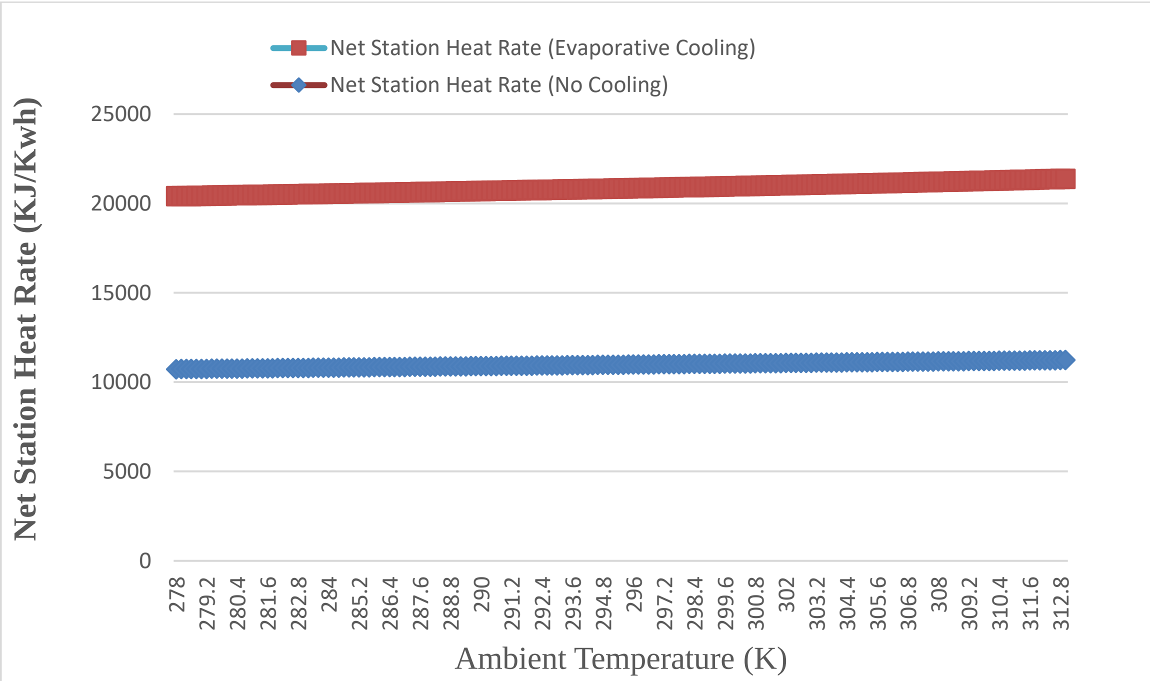

Figure 9: Effect of Ambient temperature on Net Station Heat Rate

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IV. CONCLUSION

Inlet air cooling systems are very useful tools to increase the efficiency of the gas turbine and the net power. The reduction in the ambient air temperature entering the compressor inlet increases the density of the air and the mass flow, which makes the compressor do less work and, therefore, increases the net power, efficiency and reduces the specific fuel consumption (SFC) and heat (HR). . In this study, a humid evaporative media cooler was incorporated into a simple gas turbine. The data was analyzed for each system with respect to the ambient air temperature.

, thermal efficiency, net power output, SFC and HR. A simple gas turbine plant without a cooler was simulated for compression with the retrofitted gas turbine with an evaporative media cooler. Results obtained showed an increase in net power output from (102.195MW to 113.754MW), thermal efficiency (32.68% to 36.38%) and reduction in Specific fuel consumption from (0.23602kg/kwh to 0.21203 kg/kwh) and heat rate (11014.95843 kg/kwh to 9895.67068 kg/kwh). All this indicates that incorporating a wetted media evaporative cooler to gas turbine enhances the performance of the plant.

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AUTHOR PROFILE

Ukwuaba, Samuel Ifeanyi, FNSE, COREN, FNIMechE, FAutoEI, FIRAMN, JP. is a lecturer in Petroleum Training Institute, Effurn, Nigeria. He is Director of Engineering, PTI.

Agberegha Orobome Larry is a lecturer in Federal University of Petroleum Resources, Effurun, Nigeria..

Mohammed, Bello Ahmed is a lecturer in Petroleum Training Institute, Effurn, Nigeria

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