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Full Length Paper

Improvement of Gas Turbine Performance by Incorporating Cooler Media

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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°C tends to experience a drop in gas turbine efficiency and net power output. In this research work, an open cycle gas turbine power plant generating electricity at a capacity of 450MW was used as a retrofitted study for the research by using Aspen HYSY V9 Simulation Model. The results showed that as the ambient temperature was lowered, the compressor work reduces, turbine net power output increases, specific fuel consumption reduces while the efficiency of the plant increased. It was observed that the evaporative cooler results in a drop in ambient temperature of 11.25°C leading to an increase of about 3.7% and 11.56MW in efficiency and net power output of the turbine respectively and also, 0.024kg/KWh drop in specific fuel consumption. Therefore, to increase the performance of an existing gas turbine plants in high temperature climates, retrofitting it with an air cooler will reduce the temperature to a value close to the design temperature before compression is necessary and it will tend to improve gas turbine performance in tropical country like Nigeria.

Keywords: *Gas Turbine, Aspen HYSY V9 Simulation Model, Power Output, Gas Turbine Efficiency, Specific Fuel Consumption*

INTRODUCTION

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 [1]. Gas turbine is a rotary machine comprising of a compressor, combustion chamber and a turbine, it is mainly used for power generation. 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. This reduces the compression ratio, thus increasing the air density and air mass flow rate and less work is done by the compressor. The thermal efficiency and net power output of the gas turbine is increased [2]. According to Ibrahim *et al.* [3], an increment of 1℃ in the compressor air inlet temperature decreases the gas turbine power output by 1%. These serve as evidence that gas turbine performance is sensitive to the ambient air temperature. As the ambient air temperature increases, the performance of the plant efficiency and net power output decreases, due to the inverse relation 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 [4]. The gas turbine power plant is designed to operate under given local weather conditions according to International Standardization Organization (ISO) [5]. The gas turbine is designed to operate with a constant air volume flow in the compressor [6].

Evaporative media cooling involves heat and mass transfer, which occurs when water and the unsaturated air mixture to form saturated air and water vapor mixture [6]. This transfer is a function of the differences in temperatures and vapor pressures between the air and water. Heat and mass transfer are both operative in the evaporative cooler because of heat transfer from air to water evaporates the water, and the water evaporating into the air constitutes mass transfer [7-8]. The water vapor becomes part of the air and carries the latent heat with it. The air dry-bulb temperature decreases because it gives up the sensible heat. The air wet-bulb temperature is not affected by absorption of latent heat in the water vapor because the water vapor enters the air at air wet-bulb temperature. 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. The process of exchanging the sensible heat of the air for latent heat of evaporation from water is adiabatic [9-10]. In this research work, a gas turbine power plant was improve by cooling the inlet air of the plant with retrofitted wetted media evaporative cooler.

RESEARCH METHODOLOGY

2.1 Description of Power Plant

The power plant is a 4×(112.5MWe) GT-9E OCGT power plants with 450MW capacity, connected to the National Grid. 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.

2.2 Collections of Power Plant Data

The operating data of the gas turbine for the year 2018 were collected daily and the daily average operating variables were statistically analyzed. The summary of operating parameter of the gas turbine unit used for this study is presented in Table 1. The analysis of the plant was divided into different control volumes and performances of the plant. Mass and energy conservation laws were applied to each of the component and the performances of the plant were determined for a system with an evaporative cooler.

Table 1. Operating data of the Gas Turbine Power Plant for the Year 2018

S/N	Operating Parameters	Valve	Unit
1	Mass flow rate of air through compressor (ma).	376.75	Kg/s
2	Temperature of inlet air to compressor (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 the Gas Turbine Unit without a Wetted Media Evaporative Cooler

Figure 1 shows the schematic cycle without a wetted media evaporative cooler. The compressor inlet temperature under the weather condition ISO (International Standard Organization) conditions without pressure drop at inlet and exhaust dusts. The air and combustion products are assumed to behave as ideal gases

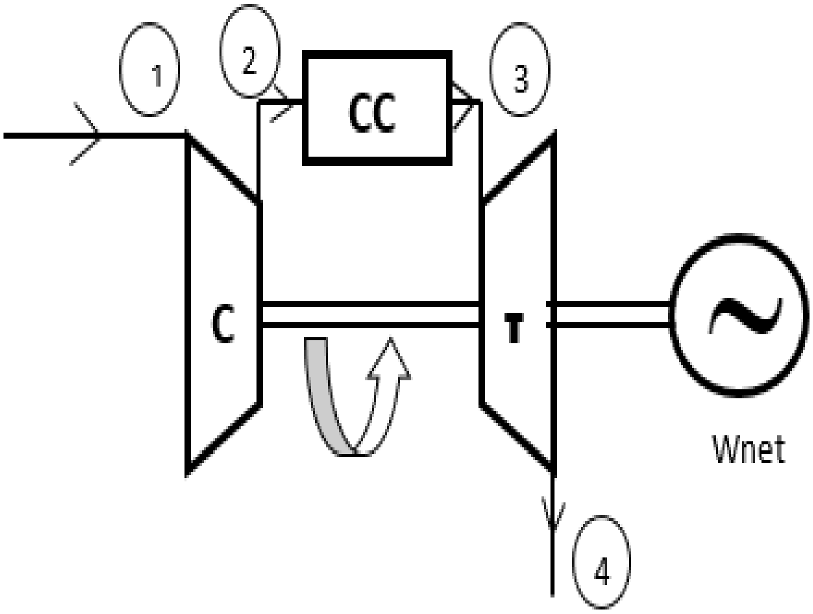

Figure 1: Schematic of a standard gas turbine cycle without a wetted media cooler

The gas turbine power plant without evaporative cooler is modeled using the following assumptions;

i. The process modeling was a steady-state simulation, that is, all the operating conditions are constant.
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. In the compressor the adiabatic efficiency was 87.80%, while turbines adiabatic efficiency was 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%.

Figure 2 shows the schematic of a standard gas turbine cycle flow chart without a wetted media cooler.

The Mathematical Model of Cooling System

Evaporative cooling mathematical model

Air cooling mass flow rate depends on the area of evaporative main brain(pad), generated from continuity equation given as

$Ma = ƒ_a AV_a$

Where Ma is mass flow rate, $ƒ_a$ is air density, V is air speed, A is area of evaporative pad

(EL-Ladan and Haas, 2017)

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There are two commonly used methods of evaporative cooling, direct evaporative cooling (DEC) and indirect evaporative cooling (IEC).

DEC is the oldest, simplest and most widespread form of evaporative cooling.

The direct evaporative cooling system adds moisture to cool air, while on the other hand an indirect evaporative system provides only sensible cooling to the process air without moisture addition.

The principles of DEC is the conversion of sensible heat to latent heat. That is in DEC the hot outside air passes a porous wetted medium, heat is absorbed by the water as evaporated.

In DEC evaporative cooling, the transformation of heat and mass between air and water causes decrease in the air- dry- bulb temperature (Tab) and increase in its humidity, while the enthalpy is basically constant in an assumed perfect process. The temperature that is attained is the wet-bulb temperature (Twb) of incoming air which the air has humidified.

Therefore, to determine the mean degree of cooling (T_{ao}-T_{ai}) and the wet-bulb depression

(T_{ao}-T_{wb})

Therefore, cooling effectiveness ‘η’

is given as $\eta = \frac{(Tao - Tai)}{(T_{ao}-T_{wb})} x100$

(Sirelkhatiin and Emad, 2012)

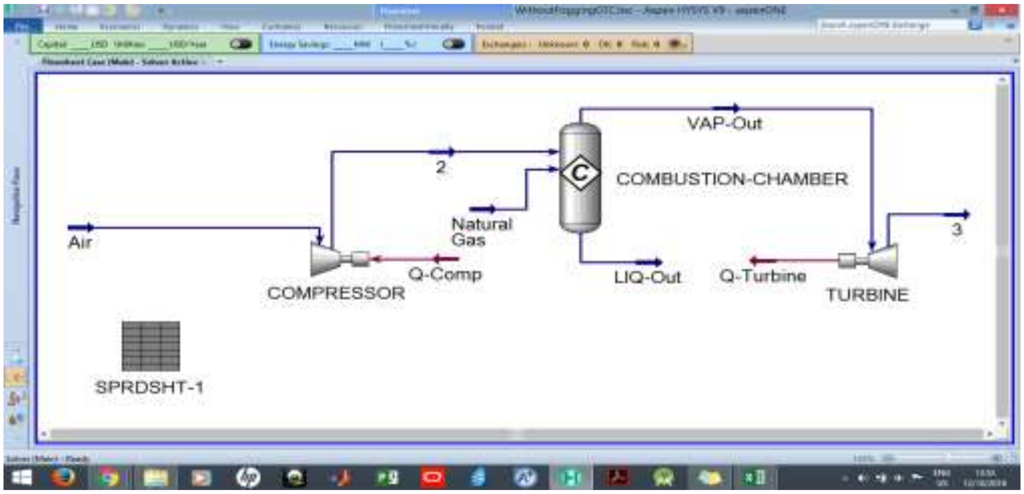
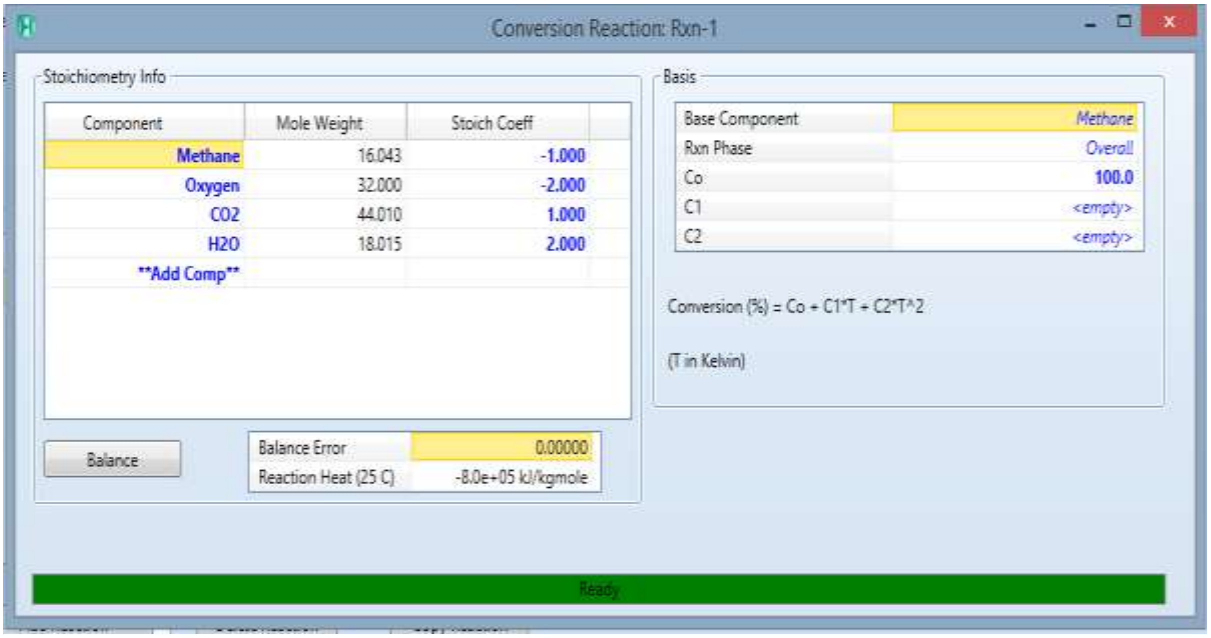


Figure 2: Schematic of a standard gas turbine cycle flow chart without a wetted media cooler.

2.4 Process Simulation

Aspen HYSY V9 model was used to simulate the gas turbine with and without an evaporative cooling unit. The selected components required for the Gas Turbine simulation are shown in Figure 1. A standard set of components and a thermodynamic basis to model the physical properties of these components selected. When the component list was created, then HYSYS created a new component list called "Component List-1". This was follow by the selection of a fluid package for it. The fluid package which is the thermodynamic system associated with the chosen list of components. To account for the reaction that will be taking place in the combustion chamber the parameter in Figure 3 was added to the process simulation.



Conversion Reaction: Rxn-1

Stoichiometry Info

Component	Mole Weight	Stoich Coeff
Methane	16.043	-1.000
Oxygen	32.000	-2.000
CO2	44.010	1.000
H2O	18.015	2.000
Add Comp		

Basis

Base Component	Methane
Rxn Phase	Overall
Co	100.0
C1	<empty>
C2	<empty>

Conversion (%) = Co + C1*T + C2*T^2

(T in Kelvin)

Balance Error	0.00000
Reaction Heat (25 C)	-8.0e+05 kJ/kgmole

Figure 3. Parameters for the reaction in the Combustion Chamber

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

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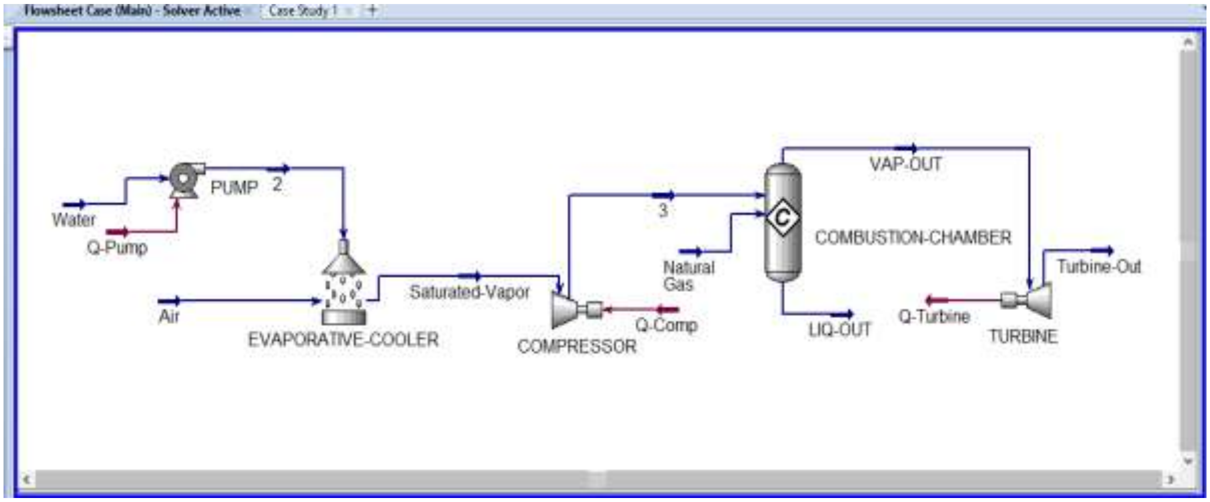
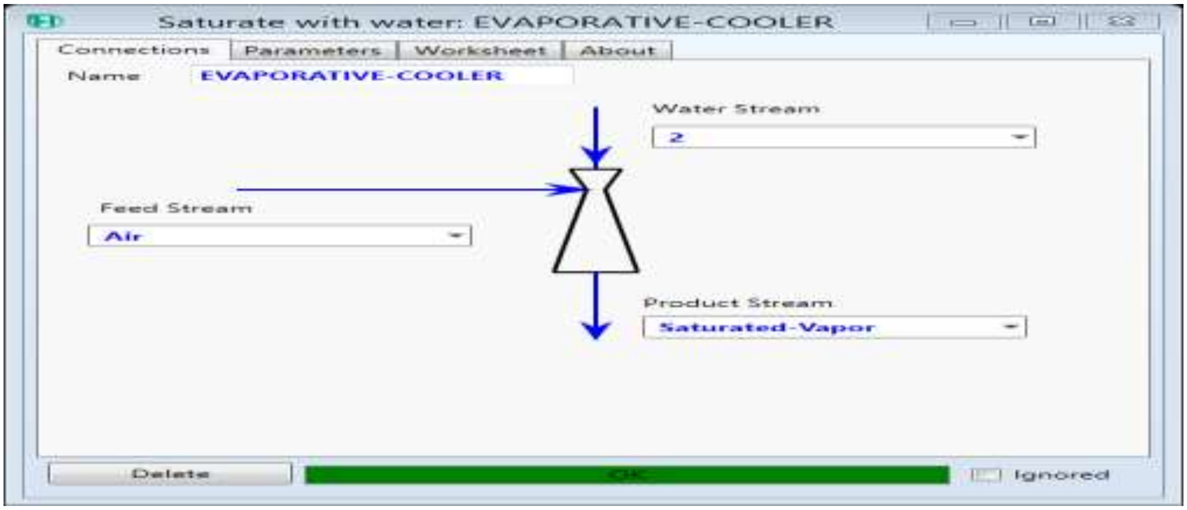


Figure 4: Process Flow sheet for Gas Turbine with Evaporative Unit

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. Which act as the inlet to the compressor



Saturate with water: EVAPORATIVE-COOLER

Name EVAPORATIVE-COOLER

Water Stream 2

Feed Stream Air

Product Stream Saturated-Vapor

Figure 5: Evaporative Cooler Unit

RESULTS AND DISCUSSION

The effect of evaporative inlet air cooling on gas turbine performance has been shown through the performance of gas turbine cycle power plant presented in this section. The effects of operation conditions on the net power output, specific fuel consumption and efficiency are obtained by the energy-balance utilizing Aspen HYSY V9 software. The gas turbine was simulated employing the ISO conditions without cooling and varying ambient air temperature, turbine inlet temperature and compression ratio. 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).

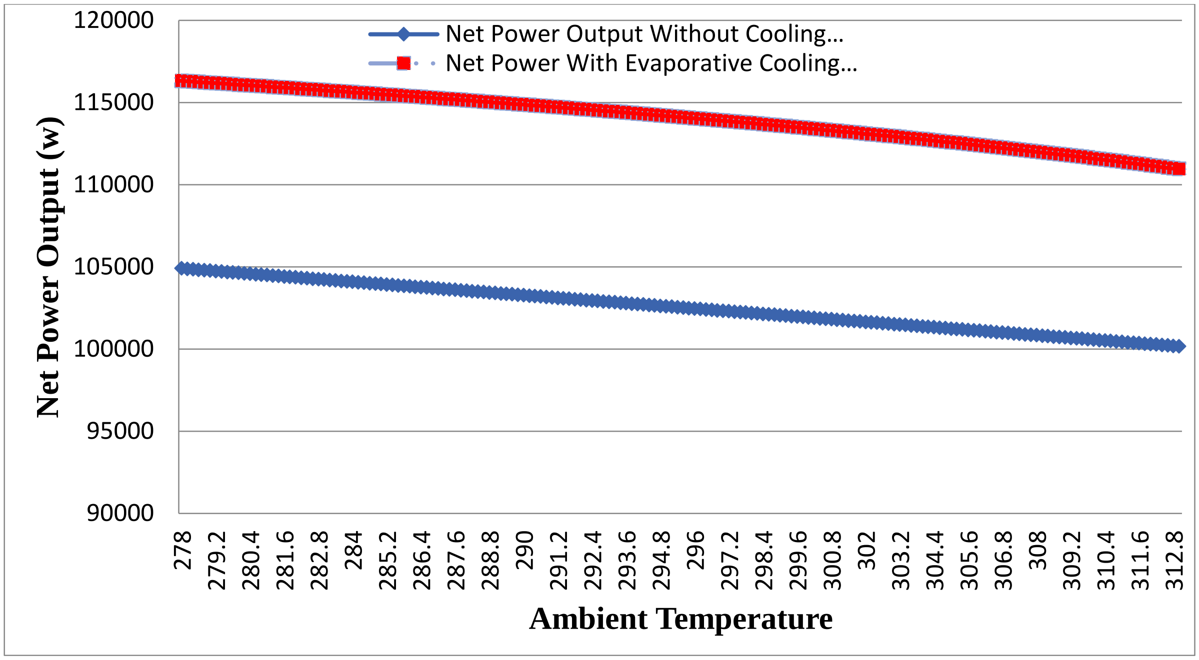


Figure 6: Effect of Ambient Temperature on Net Power Output

Figure 7 shows that the ambient air temperature does have a great influence on the specific fuel consumption (SFC) of a gas turbine.

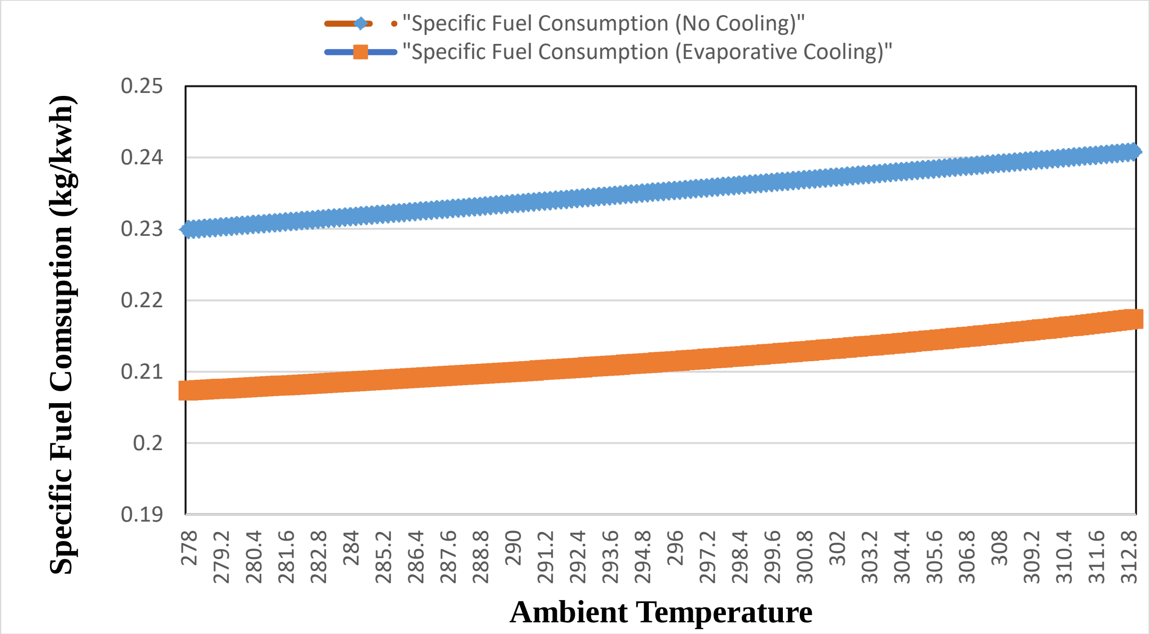


Figure 7: .Effect of Ambient Temperature on Specific Fuel Consumption

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 8 shows that the gas turbine thermal efficiency is affected by ambient temperature due to the change of air density and compressor work. A lower ambient temperature leads to a higher air density and a lower compressor work that in turn gives a higher gas turbine output power as shown in Figure 8. It can be seen that when the ambient temperature increases the thermal efficiency decreases. This is because, the air mass flow rate inlet to compressor increases with decrease of the ambient temperature. So, the fuel mass flow rate will increase, since air to fuel ratio is kept constant. 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%.

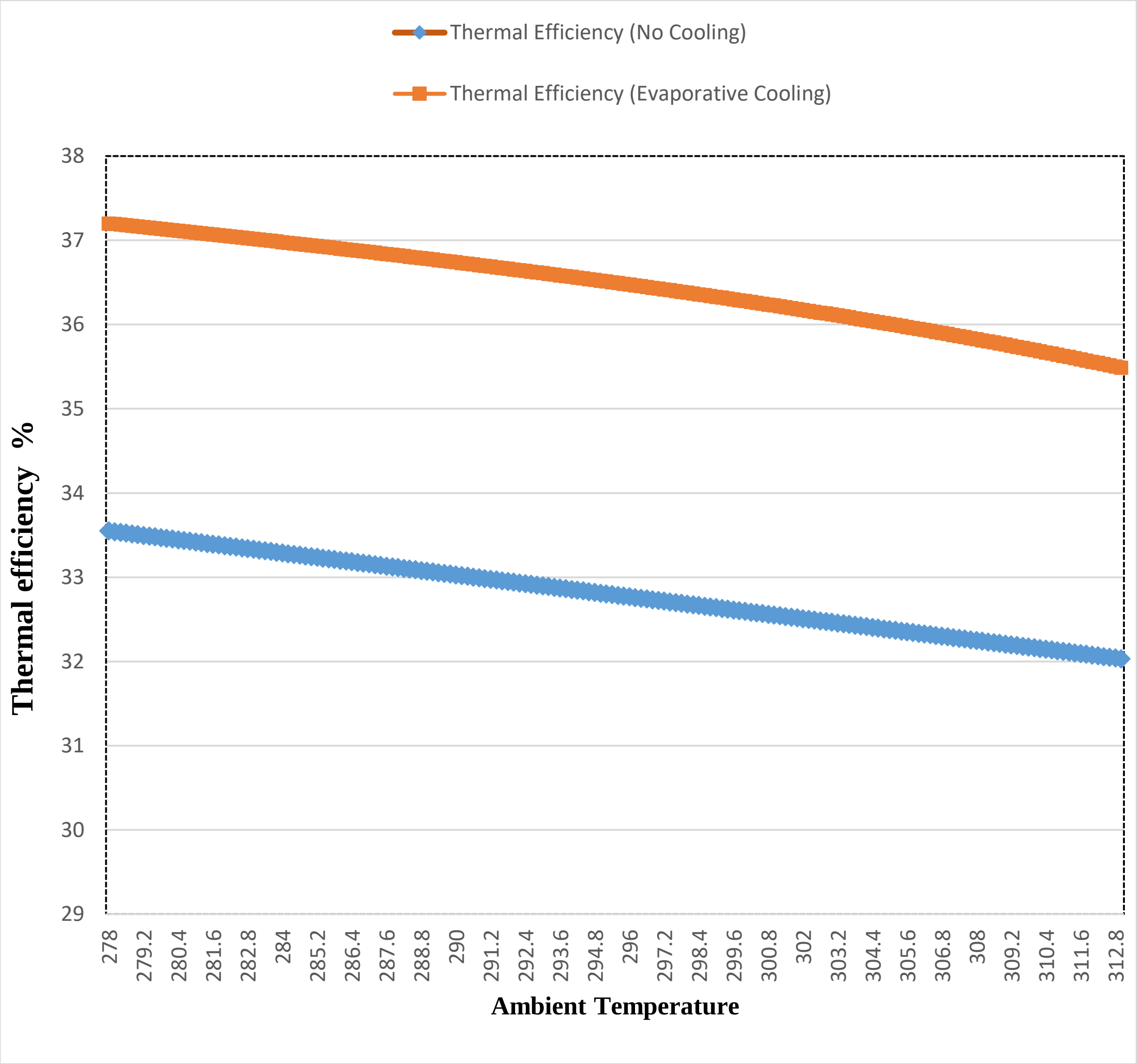


Figure 8: Effect of Ambient Temperature on Thermal Efficiency

The heat rate is influence by the varying ambient air temperature on 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 ambient air temperature on the open-cycle net heat rate per kilowatt hour is plotted in Figure 9, which clearly shows improvement in sensible heat rates is associated with that the heat rate improves as the compressor inlet temperature decreases. Reducing the heat rate of a power plant is an effective way of reducing fuel consumption, and thus, CO_2 emissions.

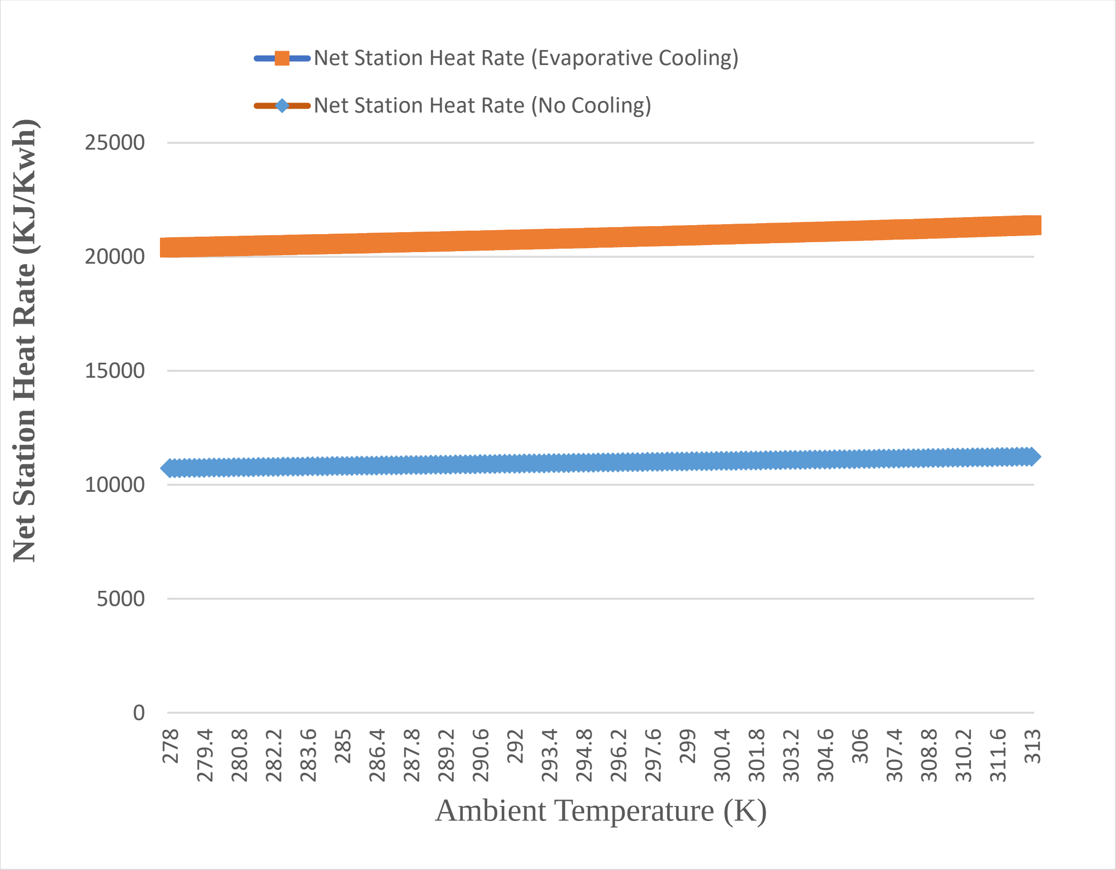


Figure 9: Effect of Ambient temperature on Net Station Heat Rate

CONCLUSION

In this research work, wetted evaporative media cooler was incorporated to a simple gas turbine. Data were analyzed for each system with respect to 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).

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