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INTERNATIONAL JOURNAL OF PROGRESSIVE RESEARCH IN ENGINEERING MANAGEMENT AND SCIENCE (IJPREMS)
(Int Peer Reviewed Journal)
Vol. 05, Issue 01, January 2025, pp : 756-763

e-ISSN :
2583-1062
Impact
Factor :
7.001

# EXAMINING THE THERMODYNAMIC EFFECT OF INCORPORATING WETTED MEDIA EVAPORATIVE SYSTEM GAS TURBINE POWER PLANT

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DOI: https://www.doi.org/10.58257/IJPREMS38151

## ABSTRACT

The most important way to improve gas turbine performance is to add a wetted evaporative media cooler to the compressor inlet. The research conducted a retrofitting study on a 450 MW gas-generating electricity plant using the Aspen HYSY simulation model. The results showed that the compressor work decreased, the turbine's net power production increased, the amount of specific fuel used fell, and the plant's efficiency increased when the outside temperature dropped. An ambient temperature reduction of 11.25°C was determined to be caused by the evaporative cooler, increasing the turbine's efficiency and net power generation by roughly 3.7% and 11.56 MW, respectively. Additionally, it led to a 0.024 kg/KWh reduction in particular fuel usage. Therefore, by lowering the temperature to a level close to the design temperature before compression is needed, an air cooler added to an existing gas turbine plant will improve its performance in high-temperature settings. In tropical countries like Nigeria, this will also tend to improve gas turbine performance.

**Keywords:** Gas Turbine, Aspen HYSY, Simulation, Thermodynamic Modeling, Ambient Temperature

## 1. INTRODUCTION

One of Nigeria's most urgent issues at the moment is power availability [1–3]. The power sector is one of the most important aspects of a nation's development; it must advance if it is to prosper [4-6]. A gas turbine is a spinning device that consists of a compressor, combustion chamber, and turbine. Its main function is to produce power. The compressor delivers extremely high-pressure, high-temperature air to the combustion chamber [7–10]. The power produced by the gas turbine is directly proportional to the air mass flow rate because the combustor's volume is constant. When designing a gas turbine, the weather is usually taken into consideration because the ambient air temperature significantly affects the turbine's performance [11, 12]. An evaporative media cooler at the compressor inlet will lower the ambient air temperature, which will reduce the compression ratio and increase the air density and air mass flow rate. This will increase the air density and compressor efficiency, increasing the thermal efficiency and net power output of the gas turbine. Since most gas turbines installed in the tropical region are designed for other climate regions, this tends to affect the gas turbine performance [13–15]. While evaporative cooling and fogging systems are similar, the compressor inlet is not immediately filled with water. Rather, a shower of water is let to pass through the inlet air, and the energy from the inlet air is absorbed by the latent heat of the evaporating water. The system is emptied of any extra water. This is an inexpensive way to cool intake air. However, the wet bulb temperature reading (relative humidity value) limits the performance, which is further limited by the surrounding air's relative humidity [36, 37].

The usage of a wetted media evaporative cooler in conjunction with a gas turbine is an attempt to improve the efficiency of gas turbine power plants. As a result, the combustion air's density rises, producing more power. A wet porous pad makes up the evaporation surface. A distribution pad sits atop the media after water is directed downward via a header at the top of the media and sprays into the top of an inverted half-pipe [16–19]. By means of gravity action, water flows through the distribution pad and into the media, where it wets a vast expanse of the surface that comes in touch with air moving through the cooler [20, 21]. Johnson (1989) asserts that the process of evaporating water into the incoming air lowers its temperature and raises its density via increasing air density. The water vapor causes a very small increase in fuel consumption as it goes through the turbine. 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 [22]. 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 [23-25]. The water used in conjunction with evaporative coolers frequently contains dissolved salts, such as potassium and sodium chlorides, which when combined with sulfur in the fuel, form primary ingredients in hot gas path corrosion. For this reason, water quality and preventing water carryover are crucial factors when using evaporative coolers.

The direct evaporative cooling process functions primarily by converting sensible heat into latent heat, and the ambient air around the panel is cooled by evaporating the water [27–29]. The addition of water vapour to the air increases its latent heat and relative humidity. Heat and mass transfer are involved in evaporative media cooling, and this happens when water and unsaturated air combine to generate saturated air and water vapor mixture [30]. According to research by [4, 31], the gas turbine power production drops by 1% for every degree Celsius that the compressor air input temperature is raised. These demonstrate how the temperature of the surrounding air affects gas turbine performance. Because air density and temperature have an inverse relationship that cools the gas turbine's inlet air, when ambient air temperature rises, plant efficiency and net power output perform worse. Conversely, when ambient air temperature falls, air density rises and increases mass flow rate, which raises thermal efficiency and the plant's performance [32-34]. The International Standardization Organization (ISO) [35] states that the gas turbine power plant is built to function in the specific local weather conditions. The compressor's air volume flow must remain constant for the gas turbine to function. The average ambient temperature in this tropical region of Africa, Nigeria, is roughly 26°C, and this tends to have an impact on the efficiency of gas turbine power plants. Gas turbines in Nigeria will operate more efficiently and with lower ambient air temperatures if they are equipped with a wetted media evaporative cooler [36].

## 2. MATERIALS AND METHODS

Connected to the National Grid, the gas turbine is a 4 (112.5 MWe) GT-9E OCGT power plant with 450 MW capacity. The daily turbine control log sheet provided the operational data for the gas turbine unit for a period of one year. After statistical analysis of the daily average operational variables, mean values were gathered with an overall average for the months of January through December. Table 1 displays a summary of the gas turbine unit's operating parameters that were employed in this investigation.

**Table 1.** Summary of operating parameter of the gas turbine unit

| 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 |

The turbine, combustion chamber, and compressor make up the gas turbine power plant. As seen in Figure 1, a wetted evaporative medium is installed prior to the compressor. Utilizing the Aspen HYSY Simulation Model, the gas turbine's performance is assessed and contrasted with results from a basic gas turbine simulation. Water enters the evaporative cooler through the distribution pad, where it is drawn down by gravity and wets the media surface. The dry air enters the wetted pad and becomes saturated, bringing the incoming air's dry bulb temperature (DBT) up to the starting wet bulb temperature (WBT). Notwithstanding the inlet air condition, it is anticipated that the cooler's exit air's relative humidity won't rise above 100%. The relative humidity efficiency is assumed to be 100%.

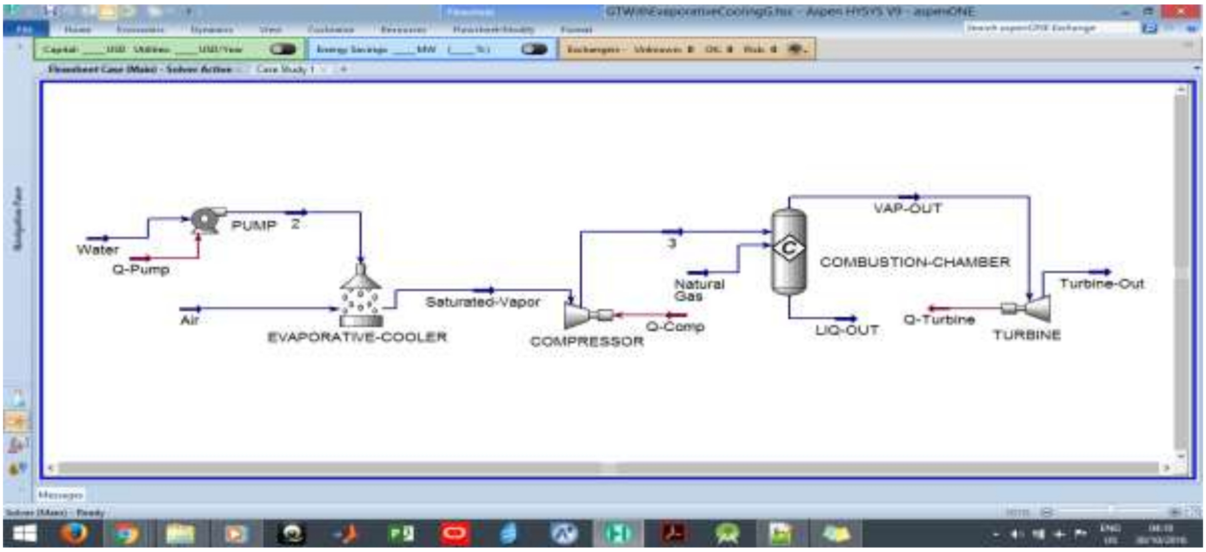

**Figure 1.** schematic diagram of the gas turbine cycle flow chart with a wetted media evaporative cooler.

The gas turbine power plant with an evaporative cooler is modeled based on the following assumptions;

- The process modeling was a steady-state simulation, that is, all the operating conditions are unchanging with time.
- The combustion of the process was assumed to be a conversion reaction in HYSYS.
- There is about 95% energy conversion in the reactor.
- From the modeled power plant, the compressor adiabatic efficiency is 87.80%, while turbines adiabatic efficiency is 89.40%.
- The component of the natural gas is: Methane.
- The natural gas in the feed comes directly at the pressure of 22.8 bars.
- The pressure drop across the combustion chamber is 0.012%.

The pressure of the air leaving the compressor ($P_{02}$) is determined as:

$$P_2 = r_p \cdot P_1 \qquad (1) \qquad r_p = \frac{P_2}{P_1} \qquad (2)$$

Using the polytrophic relation of the ideal gas and knowing the isentropic efficiency of the compressor, the discharge temperature ($T_{02}$) can be determined as

$$T_2 = \frac{T_1}{\eta_c}\left[r_p^{\frac{\gamma-1}{\gamma}} - 1\right] + T_1 \qquad (3)$$

Where $T_1$ is the ambient temperature, $\eta_c$ is the isentropic efficiency of the compressor, and $T_2$ is the compressor discharge temperature (CTD) from the log sheet in Table 1. The combustion discharge temperature $T_3$ can be determined as:

Heat supplied by fuel = heat taken by burning gases

$$\eta_{cc} \times m_f \times C_v = (m_a + m_f) C_{pg}(T_3 - T_2) \qquad (4)$$

$$\eta_{cc} \times C_v = \left\{\frac{m_a}{m_f} + 1\right\} C_{pg}(T_3 - T_2) \qquad (5)$$

Where $\frac{ma}{mf}$ is the air – fuel ratio and CV is the Calorific valve of fuel. The compressor work can be estimated using the first law of thermodynamics

$$W_c = m_a \cdot C_{pa}(T_2 - T_1) \qquad (6)$$

Where ma is the mass flow rate of air and $C_{pa}$ is the specific heat of dry air at constant pressure, determined as a function of the average temperature across the compressor. Assuming a pressure drop ($\Delta P_{CC}$ combustion), the combustion chamber discharge pressure ($P_3$) can be calculated as.

$$P_3 = P_2 - \Delta P_{CC} \qquad (7)$$

Where the pressure drops at the combustion chamber (Δpcc) is 0.0 12%. The heat delivered by the combustion chamber is;

$$Q_{in} = m_a \, . \, C_{pg}(T_3 - T_2) \qquad (8)$$

The turbine power is determined as:

$$W_t = m_a \, . \, C_{pg}(T_3 - T_4) \qquad (9)$$

Also, the mass flow rate (mg) of the gas is determined as:

$$M_g = m_a + m_f \qquad (10)$$

$T_{04}$ is the maximum exhaust temperature from the turbine outlet. The net power obtained from the gas turbine is given by;

$$W_{net} = W_t - W_c \qquad (11)$$

The specific fuel consumption (sfc) is determined as;

$$Sfc = \frac{3600.mf}{W_{net}} \qquad (12)$$

The heat rate (HR) is calculated as:

$$HR = Sfc \text{ x } LHV \qquad (13)$$

The thermal efficiency of the gas turbine is determined by Equation (14)

$$\eta_{th} = \frac{\text{work output}}{\text{Heat Supplied}} = \frac{W_{net}}{Q_{in}} \qquad (14)$$

## 3. RESULTS AND DISCUSSION

When the ASPEN HYSY software model was used to simulate the power plants for a basic gas turbine without an evaporative cooler at a specific time and ambient air temperature of 25, atmospheric pressure of 1.013 bar, and relative humidity of 70.8% in the area, the results are displayed in Table 2.

**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 |

When the ASPEN HYSY software model was used to simulate the power plants for a basic gas turbine with an evaporative cooler at a certain time and ambient air temperature of 25, atmospheric pressure of 1.013 bar, and relative humidity of 75.8% in the area, the results are displayed in Table 3.

**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 |

The performance of the gas turbine cycle power plant described in this section serves as an example of how evaporative inlet air cooling affects gas turbine performance. Energy balancing using Aspen HYSY V9 software determines how operating circumstances affect net power production, specific fuel consumption, and efficiency. This work uses numerical simulation to model the operation of a natural gas-powered single-shaft gas turbine. The ISO settings were used to model a basic gas turbine without cooling and with different ambient air temperature, turbine inlet temperature, and compression ratio. Figure 2 illustrates how variations in the surrounding temperature affect the gas turbine's power output. The gas turbine's power output increases with decreasing ambient temperature. A 1°C drop in the outside temperature leads to a 4.6 MW increase in power production. When the ambient air temperature drops from 25 to roughly 13.75, a wetted evaporative media cooler is included into the compressor, resulting in a net power production of 102195.64 KW (102.196 MW). The output of net power rose to 113.755 MW, or 113754.84 KW.

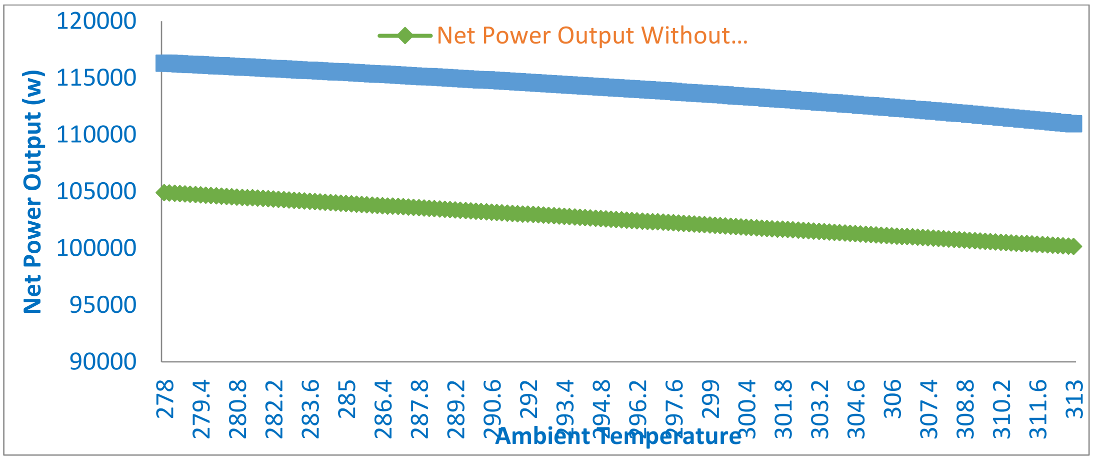

**Figure 2.** Effect of Ambient Temperature on Net Power Output

Figure 3 demonstrates that a gas turbine's specific fuel consumption (SFC) is significantly impacted by the outside air temperature. According to the graph, the SFC falls as the turbine inlet temperature drops and increases proportionately with the ambient air temperature. The outcome demonstrates that an SFC decrease of 0.02398 kg/W is produced by a temperature reduction of 4.1. This suggests that the power output increases with decreasing SFC. Figure 4 illustrates how changes in air density and compressor work are caused by ambient temperature, which in turn affects gas turbine thermal efficiency. Lower outside temperatures increase air density and reduce compressor work, which raises gas turbine performance. In the integrated air-cooling gas turbine, efficiency increases with a drop in compressor inlet temperature; the lowest ambient temperature of 298.8k results in an efficiency of 32.68%. By adding an evaporative cooling medium, the efficiency increased by 36.38% and the ambient air temperature decreased to 286.7k.

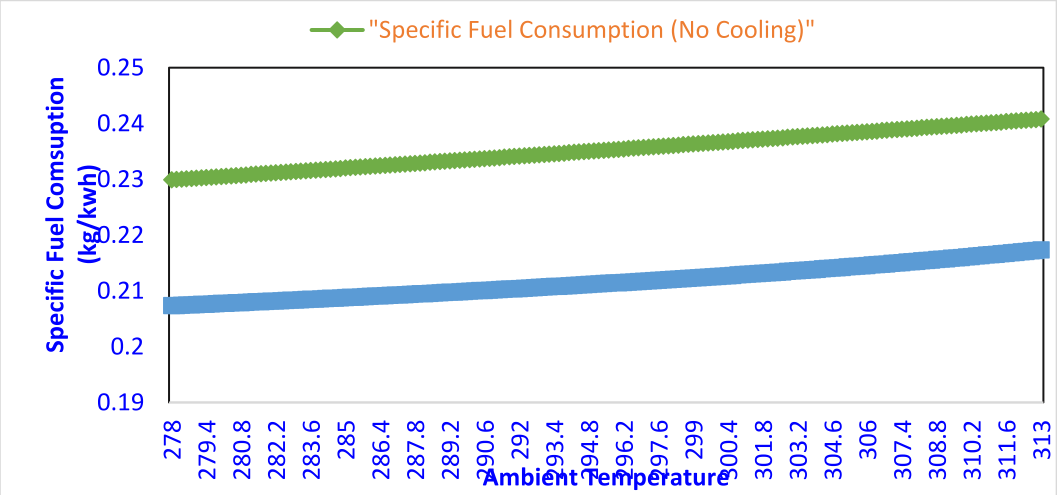

**Figure 3**. Effect of Ambient Temperature on Specific Fuel Consumption

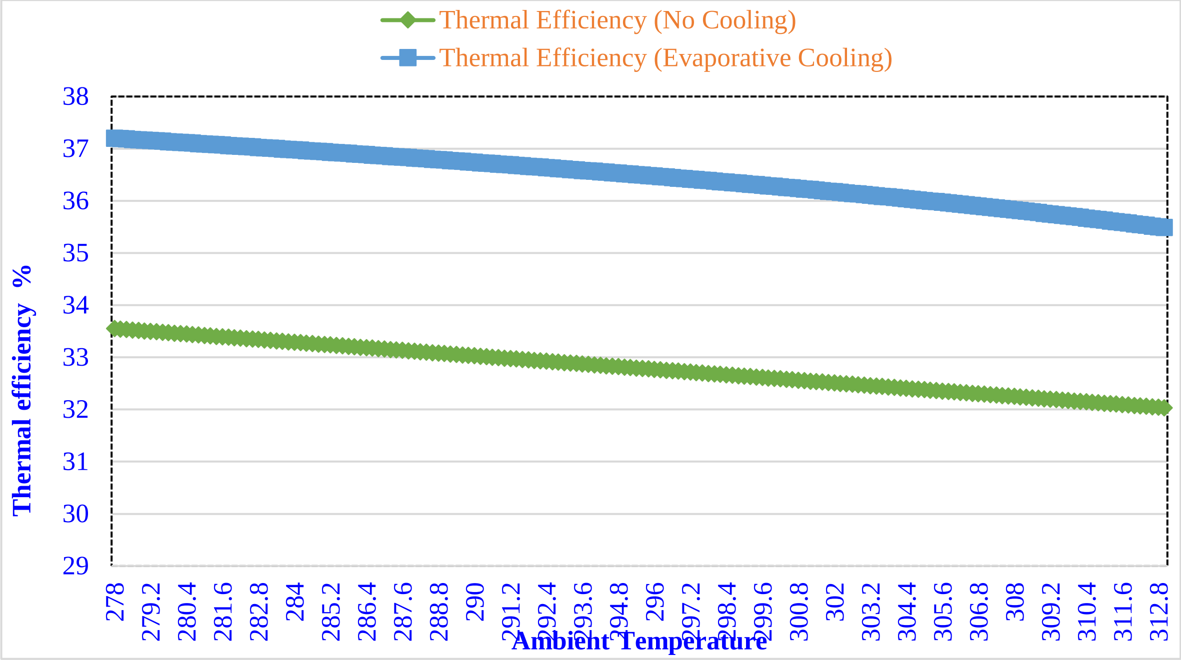

**Figure 4.** Effect of Ambient temperature on thermal efficiency

The fluctuating outside air temperature has an impact on the gas turbine's heat rate. The heat rate rises in tandem with the ambient air temperature. Heat that is useful is wasted to the surroundings. Figure 5 illustrates the impact of ambient air temperature on the open-cycle net heat rate per kilowatt hour. It is evident that a decrease in compressor inlet temperature is positively correlated with an increase in sensible heat rates. One efficient technique to lower fuel usage and, consequently, CO2 emissions from power plants is to lower their heat rate.

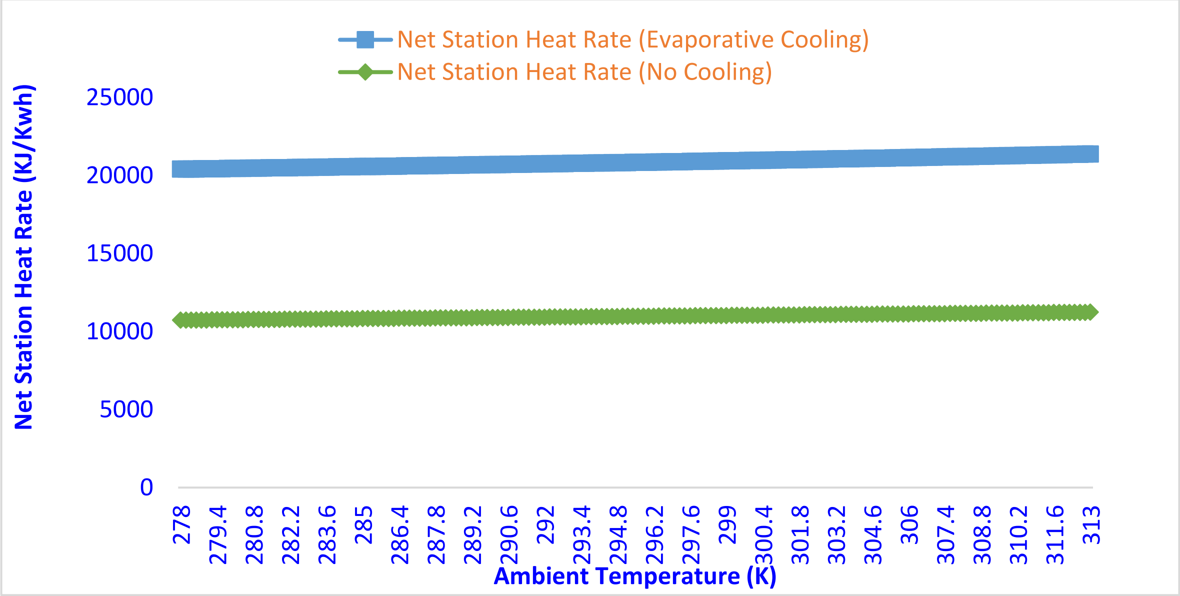

**Figure 5**. Effect of Ambient temperature on Net Station Heat Rate

## 4. CONCLUSION

The net power production and gas turbine efficiency can both be raised with the help of the inlet air cooling systems. Lowering the outside air temperature at the compressor inlet raises the mass flow rate and air density, which means the compressor needs to work less to produce more net power and efficiency, which lowers the specific fuel consumption (SFC) and heat rate (HR). In this work, a basic gas turbine was equipped with a wetted evaporative media cooler. For every system, data on the ambient air temperature, thermal efficiency, net power production, SFC, and HR were examined. The modified gas turbine with an evaporative media cooler was used to emulate a basic gas turbine plant without a cooler for compression. The obtained results indicated a decrease in specific fuel consumption from 0.23602 to 0.21203, a rise in net power production from 102.195 MW to 113.754 MW, a decrease in thermal efficiency from 32.68 to 36.38, and an increase in heat rate from 1014.95843 to 9895.67068.

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