INTERNATIONAL JOURNAL OF LATEST TECHNOLOGY IN ENGINEERING, MANAGEMENT & APPLIED SCIENCE (IJLTEMAS)

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VIII, August 2025

Comparative Study of Inlet Air Cooling Technologies for Gas Turbines Under Tropical Conditions

Ojeh-Oziegbe E. O[1], Oyedepo SO[2]

[1]Department of Mechanical Engineering, Faculty of Engineering, University of Benin, PMB 1154, Benin City, Nigeria.

[2] Department of Mechanical Engineering, College of Engineering, Covenant University, Ota, Ogun State.

DOI: https://doi.org/10.51583/IJLTEMAS.2025.1408000162

Received: 18 Aug 2025; Accepted: 22 Aug 2025; Published: 18 September

Abstract: In this paper, a comparative thermodynamic performance analysis is presented for Evaporative Cooling and Mechanical Chilling, two inlet air cooling techniques for simple cycle gas turbines in tropical environments. While numerous papers in the literature have examined different cooling methods, this study is particularly focused on the evaluation and comparison of the performance of these two widely employed techniques under Nigerian Climatic Conditions.

The research employs operating data from a Nigerian gas turbine power station combined with MATLAB-based modeling to simulate the effect of each cooling method. Performance was assessed under two Relative Humidities, 30% and 70%, typical of the country's two major climatic zones. The key parameters assessed are net work output, Thermal Efficiency, and heat rate.

The findings indicate that, against common belief, Evaporative Cooling performs more positively in both low- and high-humidity environments. Although Mechanical Chillers achieve ambient-independent cooling performance regardless of the ambient conditions, their advantage is limited to extremely high ambient temperature with high Relative Humidity conditions, where Evaporative Cooling becomes inefficient. In most other situations, Evaporative Cooling performs better in enhancing Gas Turbine performance.

These results necessitate the need for a climate-sensitive approach in the selection of Inlet Air Cooling technologies. Rather than adopting a single-fit-all approach, power plant operators are encouraged to align their choice of cooling systems with the prevailing environmental conditions in specific locations. Practical suggestions that can assist in improving overall efficiency and reliability of power generation in Nigeria's different climatic regions are provided by the study. By determining the conditions under which each cooling technology is optimally effective, the paper contributes to more informed decision-making in Gas Gurbine performance enhancement in tropical climates.

Keywords: gas turbine, inlet air cooling, evaporative cooler, mechanical chiller, tropical climate, thermal efficiency, relative humidity

I. Introduction

Gas turbine power plants are widely used for electricity generation due to their high power-to-weight ratio, rapid start-up capability, and relatively low installation costs (Ozgoli et al., 2015). In Nigeria, they form a critical part of the national grid, providing both base-load and peak-load generation capacity. However, their performance is highly sensitive to ambient conditions, particularly **temperature** and **humidity**—two parameters that vary considerably across Nigeria’s diverse climate zones.

The thermal efficiency and power output of a gas turbine depend strongly on the density of the inlet air, which depend greatly on ambient temperatures, and seasonal humidity variations. As ambient temperature increases, air density decreases, resulting in a lower mass flow rate through the compressor. This leads to reduced turbine work output and higher specific fuel consumption. A study done by Kakaras et al.,(2004) showed a power loss of over 20%, in combination with a substantial increase in specific fuel consumption, when ambient air temperatures are significantly higher than ISO conditions. In a converse but supporting study, Zuniga (2005), shows an increase in air density, and consequently, air mass flow rate, power output and efficiency by about 0.7% for every degree Celsius drop in temperature in heavy duty gas turbines. Da Costa et al (2021) in a study done in an integrated steel mill in Brazil, to analyse the techno-economic feasibility of installing inlet air cooling on the gas turbines there. The results showed an estimated inprovement of 4.22% on power output, equivalent to about 3.92 million USD saved per year.

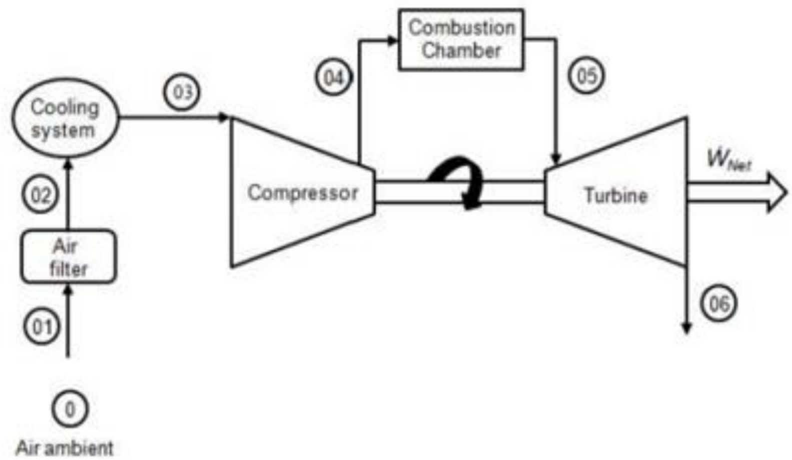
Relative humidity is also a factor, especially in inlet air cooling (IAC) systems involving the use of evaporation. Evaporation processes work less efficiently in humid locations because there is less water evaporation potential in extremely moist air.

To offset such losses, inlet air cooling technologies have been developed that reduce compressor inlet temperature, thereby increasing air density and overall cycle performance for simple gas turbines as well as combined cycle power plants. (Ehyaei et al., 2014; Goldborough et al., 2011; Zhiyan and Obed, 2024). Of these, two are the most widespread methods in use: evaporative cooling and mechanical chilling.

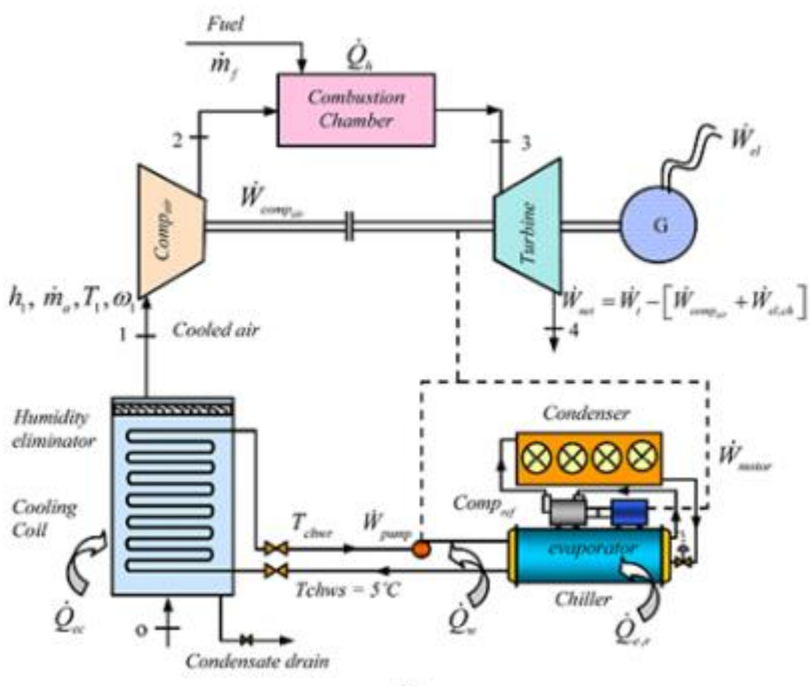
* Evaporative Cooling utilizes the latent heat of vaporization of water to cool the inlet air through adiabatic saturation. It is energy-efficient, relatively low-cost, and easy to install. Its efficiency, though, is limited by the wet-bulb temperature of the ambient air, and hence it is less effective in warm climatic conditions. Ibrahim et al. (2011) conducted a technical analysis of several air inlet

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VIII, August 2025

cooling systems and determined that evaporative systems are better suited for hot, dry climates than for hot, humid climates. Under hot, dry climates, they reported that power output is most likely to be increased by as much as nearly 12%, whereas in hot, humid climates, the power output is typically improved by no more than 5–7%.



*Mechanical Chilling employs a refrigerant cycle to cool supply air below the wet-bulb temperature, achieving greater cooling reductions and consistent performance with changing humidities. It is more expensive to purchase initially, more complicated to operate, and experiences parasitic losses of power through chiller operation. Alhazmy et al. (2004) carried out an experiment proving that, for an 8 pressure ratio gas turbine, lowering the inlet air temperature from about 50 °C to 40 °C results in a power boost of 3.85%, but at the expense of 1.037% in thermal efficiency.



Nigeria experiences extremely variable climate conditions between the dry northern areas (low RH, often below 35%) and humid southern coastal areas (high RH, often above 70%). Such a disparity requires site-specific choice of inlet air cooling technology. Initial assumptions would assume that while evaporative cooling may be perfect for northern environments, mechanical chilling may suit humid southern climates better. However studies by Carmona, 2015, show that evaporative cooling may be better in both conditions.

Previous studies (e.g., Johnson & Cambron, 2006; Al-Ibrahim & Varnham, 2010) have shown that application of inlet cooling in general can contribute to increased net output by 5–15% depending on climate and type of cooling. However, few studies examining Nigerian climatic conditions exist comparing evaporative and mechanical cooling systems with similar operating conditions. This research bridges that gap by conducting a comparative thermodynamic analysis of the two technologies under two common humidity levels—30% and 70%—using operating data from a Nigerian gas turbine power station.

The findings are meant to provide practical recommendations for climate-appropriate cooling strategies for power plant operators in Nigeria and other tropical nations, such that they can make informed decisions for maximum cost-effectiveness and efficiency.

Limitations to Study

This study is limited only to the improvement of the efficiency of existing simple gas turbines in Nigeria. Analysis will be based on the principles of thermodynamics and mass conservation. The climate of the country brings about certain unique parameters that would affect the study, but may not be applicable to gas turbines functioning in areas with a different climate. Results may be used for studies of areas with similar climate. The inlet air cooling technologies being considered are the evaporative cooler and the mechanical chiller.

II. Materials and Methods

Data Source and Thermodynamic Analysis

For the analysis of this system, the first law of thermodynamics was used, as well as laws of mass and enthalpy conservation. The reference model was developed from operational records(including average operating temperatures and pressures) of a Nigerian gas turbine power station collected over an average period of 12 months. Other variables (Wc, Wt, Wnet,η_{th}, SFC) were derived from the appropriate equations using MATLAB programming language.

The behavior of the simple gas turbine cycle was evaluated under two modes of inlet cooling: evaporative cooling and mechanical refrigeration, at relative humidities of 30% and 70%. The performance of each component of the power plant, and consequently the entire power plant is examined with each air cooler. In order to simplify the analysis, the combustion chamber is assumed to be insulated. The working fluid passing through the turbine is assumed to be an ideal mixture of flue gases and water vapour, and air and water vapour and flue gases are assumed to behave as ideal gases.

Ambient temperatures were shifted from 280 K to 325 K in steps of 5 K. Compressor and turbine work equations, cooling load calculations, and energy balance equations are regulatory equations employed.

Cooling Methods

* **Evaporative Cooling**: Direct-type media with effectiveness, $\varepsilon_{evap} \approx 0.85$.

***Mechanical Chilling:** Vapor compression cycle chiller with Coefficient of Performance (COP) = 4.5.

Assumptions

1. Steady-state, steady-flow operation.
2. Ideal gas behavior for inlet air.
3. There is complete combustion of natural gas fuel.
4. Cooling system pressure drops are negligible.
5. The chiller power consumption is deducted from net turbine output.

Governing Equations

Evaporative Cooling Humidifier and Compressor Process.

Applying the mass balance equation across the humidifier control volume boundary gives

$$w_{a,e} = w_{a,i} + m_w \qquad 2.0$$

where w is the specific humidity, at evaporative cooler exit and inlet respectively, and is calculated for a certain temperature as

$$w = \frac{0.622P_v}{P-P_v} \qquad 2.1$$

Where $P_v = \varphi . P_{sat}$ is the partial pressure of vapour, φ = the relative humidity and P_{sat} is the saturation pressure of air corresponding to the desired temperature.

The energy balance equation for the humidifier is given as

$$h_{a,e} = h_{a,i} + (w_{a,e} - w_{a,i}) h_w \qquad 2.2$$

Where $h_{a,e}$ and $h_{a,i}$ are the enthalpy of the moist air at outlet and inlet of the air humidifier respectively and are calculated as follows:

$$h_{a,e} = C_{p,a,e}t_{a,e} + (2500 + 1.88t_{a,e})\, w_{a,e} \qquad 2.3a$$

$$h_{a,i} = C_{p,a,in}t_{a,I} + (2500 + 1.88t_{a,i})\, w_{a,I} \qquad 2.3b$$

$$T_{a,e} = t_{a,e} + 273 \qquad 2.3c$$

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VIII, August 2025

The equations (2.0 – 2.3) can be solved to determine the value of $T_{a,e}$, $w_{a,e}$, and m_w. (Oyedepo and Kilanko, 2014)

The inlet air temperature after the cooling process can be calculated as:

$$T_{03} = Tb_{02} - \varepsilon.\ (Tb_{02}\ \text{-}\ Tw_{02}) \quad 2.4$$

Where Tb_{02} is the dry-bulb temperature, Tw_{02} is the corresponding wet-bulb temperature at the specified relative humidity, and ε is the cooling effectiveness of the cooler.

The cooling load associated with the evaporative cooling system results as:

$$\bar{Q}_{CL} = \dot{m}_a\ .c_{pa}\ (T_{02} - T_{03}) \quad 2.5$$

Where $\dot{m}_a$ is the air mass flow rate and c_{pa} is the specific heat of the dry air at constant pressure, determined as a function of the average temperature across the evaporative system T as (Oyedepo and Kilanko, 2014):

$$C_{pa} = 1.04841 - \frac{3.8371T}{10^4} + \frac{9.4537\ T^2}{10^7} - \frac{5.490031T^3}{10^{10}} + \frac{7.9298T^4}{10^{14}} \quad 2.6$$

The working fluid passing through the compressor is assumed to be an ideal mixture of air and water vapour. The total enthalpy of the atmospheric air is given as (Abam et al., 2012):

$$h = h_a + w \times h_v \cong C_{pa}T_a + wh_v \quad 2.7$$

where h_a is the enthalpy of dry air, and h_v is the enthalpy of water vapour.

The enthalpy of water vapour can be evaluated by (Jonsson and Yan, 2005):

$$h_v = 2501.3 + 1.8723T_j \quad 2.8$$

where j refers to state 04 or 05.

The total mass flow rate of the humid air is given by:

$$\dot{m}_{ha} = \dot{m}_{da} + w\dot{m}_{da} = (1+w)\dot{m}_{da} \quad 2.9$$

where, $\dot{m}_{ha}$ and $\dot{m}_{da}$ are the mass flow rates of humid air and dry air respectively. The compressor work for humid air between states 03 and 04 is calculated from the mass flow rate and enthalpy change across the compressor:

$$\dot{W}_C = \dot{m}_a(1+w) \times C_{pa}(T_{4s} - T_{03}) + w(h_{4s} - h_{03}) \quad 2.10$$

Mechanical Chiller Process

The specific humidity of the ambient air, $T_0 = T_2$, can be calculated as:

$$w = 0.622\,\frac{Pv}{P0\text{-}Pv} \quad (2.11)$$

Where P_0 is the ambient pressure, and $Pv = Psat * \phi$ is the saturated vapour pressure of the air at T_0.

The cooling load carried removed from the air at ambient temperature is given as(using the first law of thermodynamics):

$$Q_{mc} = \dot{m}_a(h_2 - h_3) - (w_2 - w_3)h_{w3}) \quad (2.12)$$

where h_2 and h_3 are the enthalpy of the air at the chiller inlet and outlet systems respectively.

The power needed to drive the mechanical chiller is given as :

$$W_{mc} = Q_{mc}\ /\ COP \quad (2.13)$$

Where COP is the coefficient of performance of the mechanical chiller, and its value is fixed (Santos and Andrade, 2012).

$$\dot{m}_a = \dot{m}_{dryair}\ (1 + w_2) \quad (2.14)$$

$$h_2 = (1.0029 + T_2.\ 5.4 \times 10^{-5}) + w_2.2500.9 + (1.856 + (T_2.2 \times 10^{-4})T_2) \quad (2.15)$$

$$h_3 = C_p.T_3.T_0 + w_3(2500.9 + 1.82T_3) \quad (2.16)$$

h_{w3} is the enthalpy of the water present in the air at T_3 (cooler outlet temperature), and w_3 is the specific humidity of the water present in the air at chiller outlet temperature T_3(Oyedepo and Kilanko, 2014).

The specific heat capacity of the air at T_3 is gotten from the equation:

$$C_{p,T3} = 1.048 - \frac{3.837T_{03}}{10^4} + \frac{9.4537\ T_{03}{}^2}{10^7} - \frac{5.4903T_{03}{}^3}{10^{10}} + \frac{7.9298T_{03}{}^4}{10^{14}} \quad (2,17)$$

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VIII, August 2025

Mechanical Chiller Compressor Process:

Compressor

Compressor outlet temperature T_{04} is given as:

$$T_{04} = T_{03} + \frac{T_{03}}{n_c}\left(r_p^{\frac{\gamma-1}{\gamma}} - 1\right) \qquad (2.18)$$

Where compressor efficiency, n_c and specific heat ratio γ are fixed values.

Specific heat capacity of air at T_{04} is given as :

$$C_{pa} = 1.04841 - \frac{3.8371 T_4}{10^4} + \frac{9.4537\ T_4{}^2}{10^7} - \frac{5.49031 T_4{}^3}{10^{10}} + \frac{7.9298 T_4{}^4}{10^{14}} \qquad (2.19)$$

Compressor work W_c, is given as:

$$W_c = \dot{m}_a (1+w_3)((C_{p,T4}.T_4) - (C_{p,T3}.T_3)) + w_3(h_4 - h_3) \qquad (2.20)$$

Combustion chamber equation

The mass of fuel flowing through the combustion chamber is

$$\dot{m}_f = Q_{in}/\ n_{combst}.LHV \qquad (2.21)$$

Turbine equation

The energy at the turbine input is given as :

$$Q_{in,T5} = C_{pg}\ (T_{05}-T_{04}) \qquad (2.22)$$

Turbine work, W_t is given as:

$$W_t = \dot{m}_a + \dot{m}_f(1+w_2)(C_{pg}(T_{05} - T_{06})) + w_2(h_{05}-h_{06}) \qquad (2.23)$$

The net work is given by:

$$W_{net} = W_t - W_c - W_{mc} \qquad (2.24)$$

And the power output is given as :

$$P_{out} = \dot{m}_a.\dot{W}_N \qquad (2.25)$$

For this cooling method, the gas turbine power output is decreased by the power consumption by mechanical chiller.

III. Results and Discussion

The result data used in this study is presented in this section. Table 1 presents the calculated data comparing parameters for a simple gas turbine, and ones fitted with evaporative cooling and mechanical chillers under same ambient temperature conditions, at a relative humidity of 30%. Figures 3.1-3.4 presented show a graphical comparison of calculated parameters comparing operational results between the simple gas turbine and select retrofitted versions (evaporative cooling, or evaporatoe, and mechanical chilling)

Performance at RH = 30% (Dry Conditions)

Simulation results show that evaporative cooling reduces increasing air density and mass flow rate at a better rate than mechanical chillers, without the extra energy drain from the system to power the chiller (Figures 3.1 and 3.3). Net work output improves by 34% at an ambient temperature of 300K, and thermal efficiency rises from 40.95% to 53.48%. Heat rate reduces from 87.9 to 67.3.

Mechanical chilling achieves greater cooling, but efficiency gains are reduced once chiller power consumption is deducted. Net work output increases only by 0.03% after deductions, and thermal efficiency goes up from 40.95% to 42.62%.

Table 1: Performance Gains at RH = 30% , Ambient temperature 300K

Parameter	**Baseline**	**Evap. Cooling**	**Mech. Chiller**
Net Power Output (MW)	31.19	42.03	32.24
Thermal Efficiency(%)	40.95	53.48	42.62
Heat Rate (kJ/kWh)	87.91	67.31	84.45

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VIII, August 2025

Performance at RH = 70% (Humid Conditions)

Evaporative cooling works less effectively in humid conditions. However, there is still a surprising higher net work gain, as well as thermal efficiency, comparative to that of mechanical chillers only as ambient temperatures increase(Figures 3.2 and 3.4). This concurs with results gotten from Carmona's study (2015) which showed that there was high potential for evaporative cooling in high temperature and relative humidity, areas, using Nigeria as a case study.

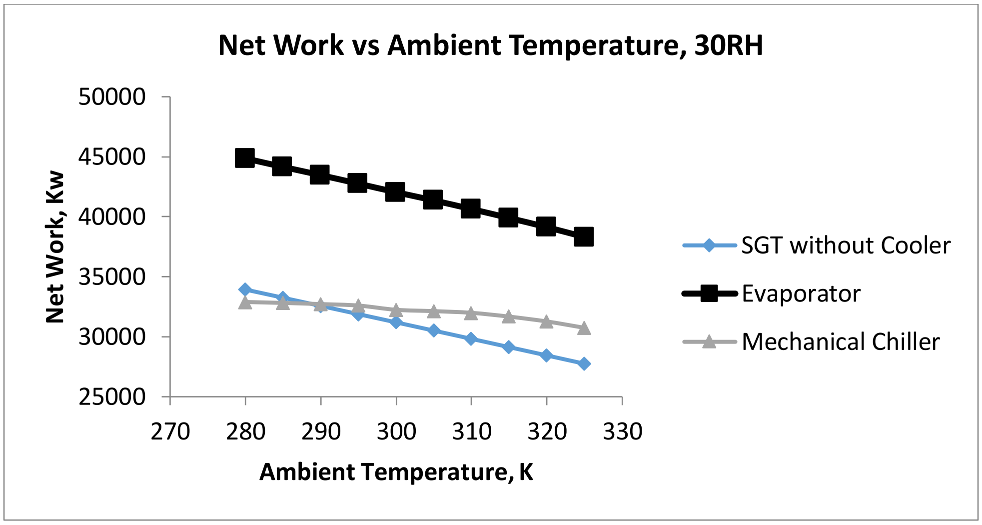


Figure 3.1- Graph of Net Work versus Ambient Temperature, RH 30%

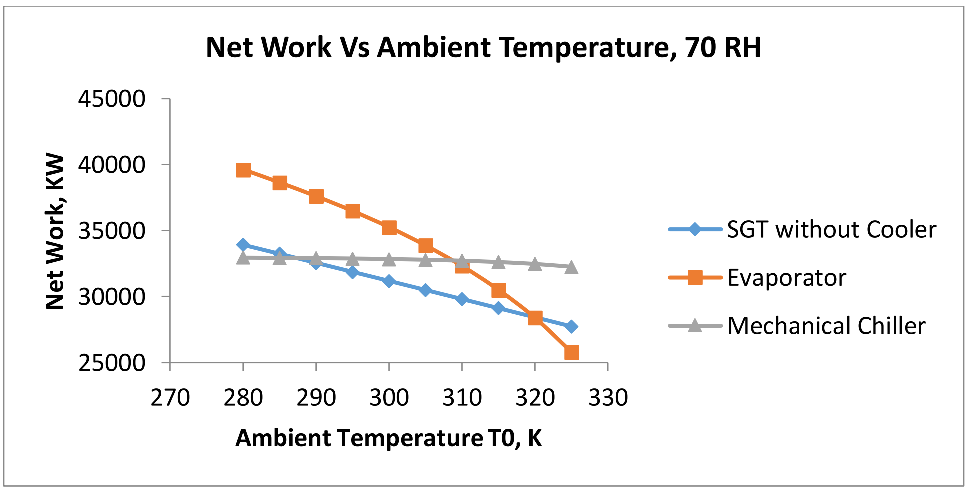


Figure 3.2- Graph of Net Work versus Ambient Temperature, RH 70%

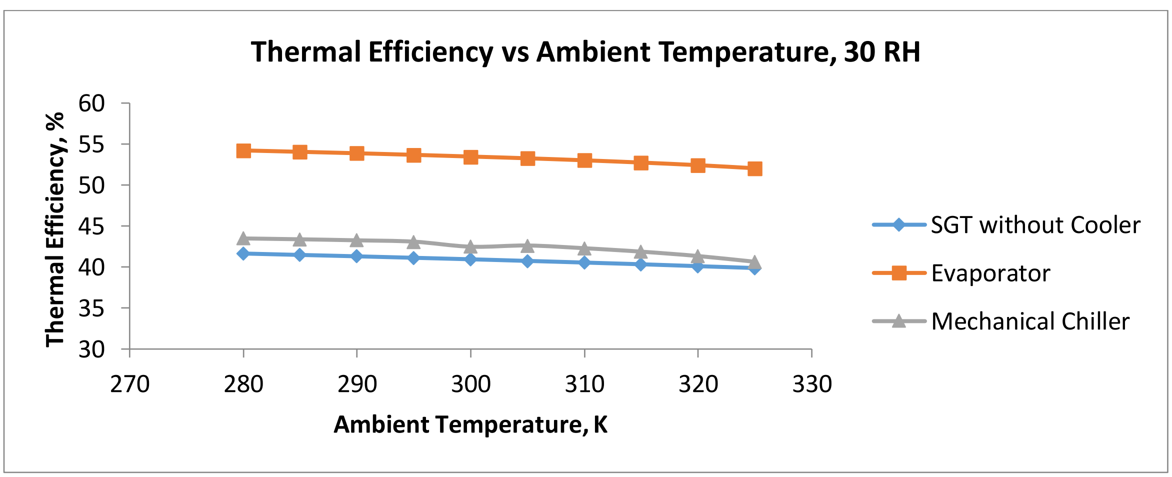


Figure 3.3- Graph of Thermal Efficiency versus Ambient Temperature, RH = 30%

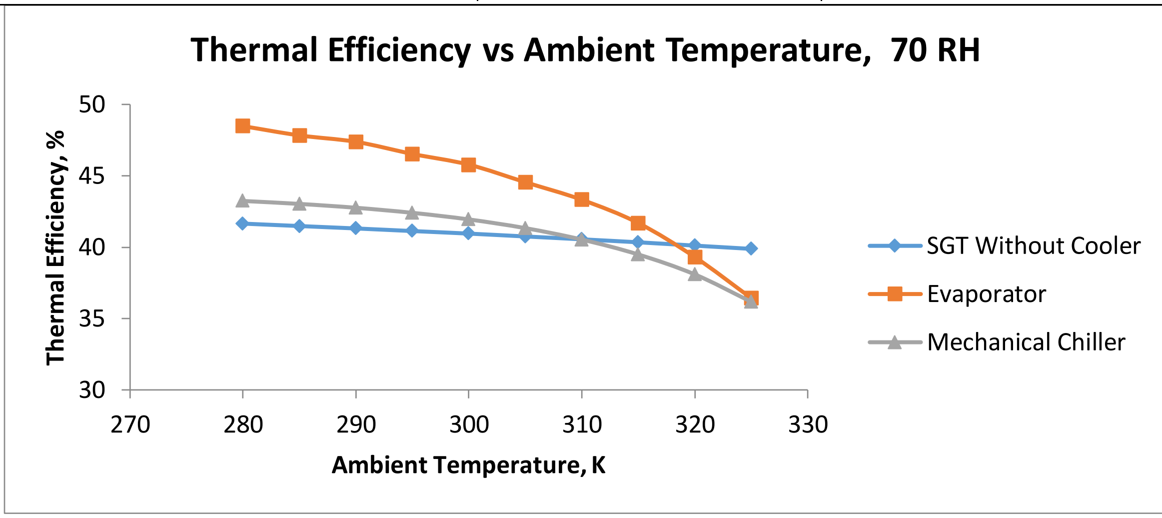


Figure 3.4- Graph of Thermal Efficiency versus Ambient Temperature, RH = 70%

Operational Considerations

Evaporative cooling has the advantages of lower capital cost, minimal power consumption, and simple maintenance. However, it is highly dependent on local humidity, with performance diminishing in coastal or rainy seasons. It still shows better cooling potential than mechanical chillers, contrary to popular opinion.

Mechanical chilling provides consistent performance regardless of humidity but carries higher capital and operational costs, plus parasitic power losses from the chiller system.

IV. Conclusion

The comparative analysis shows that evaporative cooling shows good performance in both areas with low and high relative humidity and ambient temperature. The Nigerian energy sector could take advantage of this information to retrofit our existing gas turbines, and improve power production with the equipment currently on ground. Other literature show that the cost of retrofit for evaporative cooling is significantly lesser than that for mechanical chillers, and that the power sector of the country should take advantage of these cooling technologies, and the associated prospective benefits.

Conflict of Interest

There is no conflict of interest associated with this work.

References

1. Ahmadi, P., Dincer, I., & Rosen, M. A. (2018). *Thermodynamic modeling of energy systems*. Springer.
2. Alhazmy, M. M., & Najjar, Y. S. H. (2004). Augmentation of gas turbine performance using air coolers. *Applied Thermal Engineering, 24*(2–3), 415–429. https://doi.org/10.1016/j.applthermaleng.2003.09.006
3. Ali, Zhiyan & Ali, Obed. (2024). Impact of Compressor Inlet-Air Cooling System on the Performance and Efficiency of Gas Turbine Unit: a Review. International Review of Mechanical Engineering (IREME). 18. 507. 10.15866/ireme.v18i10.25096.
4. Al-Ibrahim, A. M., & Varnham, A. (2010). A review of inlet air-cooling technologies for enhancing the performance of combustion turbines in Saudi Arabia. *Applied Thermal Engineering, 30*(14–15), 1879–1888. https://doi.org/10.1016/j.applthermaleng.2010.04.018
5. Carmona, J. (2015). Gas turbine evaporative cooling evaluation for Lagos, Nigeria. *Applied Thermal Engineering, 89*, 262–269. https://doi.org/10.1016/j.applthermaleng.2015.06.018
6. da Costa, R. C. , de Silva Jr., C. A. A. , Campos, J. C. C., Bohorquez, W. O. I., Brito, R. F., & Siqueira, A. M. (2021). A technical-economic analysis of turbine inlet air cooling for a heavy-duty gas turbine operating with blast-furnace gas. Research, Society and Development, 10(9), e59810915006. https://doi.org/10.33448/rsd-v10i9.15006
7. Ehyaei, M. A., Tahani, M., Ahmadi, P., & Esfandiari, M. (2014). Optimization of fog inlet air cooling system for combined cycle power plants using genetic algorithm. *Applied Thermal Engineering, 76*, 449–461. https://doi.org/10.1016/j.applthermaleng.2014.11.032
8. Goldborough, S. S., Johnson, M. V., Zhu, G. S., & Aggarwal, S. K. (2011). Gas-phase saturation and evaporative cooling effects during wet compression of a fuel aerosol under RCM conditions. *Combustion and Flame, 158*(1), 57–68. https://doi.org/10.1016/j.combustflame.2010.06.012
9. Ibrahim, T. K., Rahman, M. M., & Ahmed, N. (2011). Improvement of gas turbine performance based on inlet air cooling systems: A technical review. *International Journal of Physical Sciences, 6*(4), 620–627.

ISSN 2278-2540 | DOI: 10.51583/IJLTEMAS | Volume XIV, Issue VIII, August 2025

10. Johnson, R., & Cambron, R. (2006). Inlet air cooling for gas turbine plants. *ASME Journal of Engineering for Gas Turbines and Power, 128*(1), 15–22. https://doi.org/10.1115/1.1928310
11. Kakaras, E., Doukelis, A., & Karellas, S. (2004). Compressor intake-air cooling in gas turbine plants. *Energy, 29*(14), 2347–2358. https://doi.org/10.1016/j.energy.2004.03.013
12. Moran, M. J., Shapiro, H. N., Boettner, D. D., & Bailey, M. B. (2018). *Fundamentals of engineering thermodynamics* (8th ed.). Wiley.
13. Oyedepo, S. O., Fagbenle, R. O., Adefila, S. S., & Samuel, O. D. (2015). Performance evaluation of gas turbines. *International Journal of Energy Engineering, 5*(2), 13–22.
14. Ozgoli, H. A., Ghadamian, H., Roshandel, R., & Moghadasi, M. (2015). Alternative biomass fuels consideration: Exergy and power analysis for hybrid system includes PSOFC and GT integration. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 37*(18), 1962–1970. https://doi.org/10.1080/15567036.2011.560561
15. Zuniga, M. O. V. (2005). *Intake systems for industrial gas turbine* (Doctoral thesis). Cranfield University, United Kingdom.