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Thermodynamic Analysis of Gas Turbine in Al-Quds Power Plant

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Abstract

As a result of the high demand for electricity in Iraq and the expected shortage in the supply of electric power due to the high temperatures in the summer, the existing gas turbine plants at Al Quds Gas Plant have been upgraded with an intake air cooling system. This is the main objective of this study for the model of the Quds gas station (frame 9E) with a capacity of 123 MW, the management of the proposed Brayton cycle was compared with the basic case without the cooling system and with an entry air cooling system (evaporative and fogging system). In this paper the performance enhancement of gas turbine power plants by cooling the compressor intake air with an evaporative cooler is studied. This study investigated the effect of inlet air cooling system on the performance of an existing gas turbine power plant in Iraq. The results show that for each 5oC decrease of inlet air temperature, net output power increases around 5-10% and the thermal efficiency increases around 2-5%. It is shown that the amount of this increase is higher when the pressure ratio is high and turbine inlet temperature is low. The results of this study shows that retrofitting of the existing gas turbine plant with inlet air cooling system gives a better system performance and may prove to be an attractive investment opportunity to the Iraq government and stakeholders of the plant.

Keywords: *Gas turbine, evaporative, fogging, Brayton cycle, performance*

1. Introduction

Gas turbines are being used for producing power that equipped in electricity generation power plants, various industrial applications such as refineries and petrochemical plants [1]. In aircraft propulsion or drives for vehicles, gas turbines are chosen due to their large power-to-weight and power-to volume ratio. Furthermore, for certain operating conditions the cycle efficiency of gas turbines is high compared to piston engines. In the field of energy generation, gas turbines have often been chosen in the past when fast start and shut down on demand is required. This is especially needed for compensating peak loads over the daytime [2]. To increase the performance of gas turbine plants, the effect of several parameters has been studied by many researchers such as, Rahman et al. [3] the parametric study of thermodynamic performance on gas turbine power plant. The variation of operating conditions (compression ratio, turbine inlet and exhaust temperature, air to fuel ratio, isentropic compressor and turbine efficiency, and ambient temperature) on the performance of gas turbine. The results show that the compression ratio, ambient temperature, air to fuel ratio as well as the isentropic efficiencies are strongly influence on the thermal efficiency. In addition, the

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thermal efficiency and power output decreases linearly with increase of the ambient temperature and air to fuel ratio. Aram and Mohammad [4] the parametric study of a gas turbine cycle model power plant with intercooler compression process and regeneration turbine were proposed. The thermal efficiency, specific fuel consumption and net power output are simulating with respect to the temperature limits and compressor pressure ratio for a typical set of operating conditions. The power output and thermal efficiency are found to be increasing with the regenerative effectiveness, and the compressor and turbine efficiencies. The efficiency increased with increase the compression ratio to 5, then efficiency decreased with increased compression ratio, but in simple cycle the thermal efficiency always increases with increased in compression ratio. Barinaadaa and Vining [5] the thermodynamic analysis of a gas turbine power plant located in the equatorial rainforest of southern Nigeria. The variation of operating conditions (ambient temperature, compressor discharge temperature, turbine inlet temperature, exhaust temperature and fuel mass flow rate) on the performance of gas turbine (thermal efficiency, net power output, heat rate, specific fuel consumption and compressor work) were investigated using various thermodynamic relations and equations. The results show that a degree rise in ambient temperature could be responsible for the following: 1.37% reduction in the net power output, 1.48% increase in power drop, 1.49% reduction in thermal efficiency. Henry et al. [6] energy and exergy analyses were carried out on an active 42MW open cycle gas turbine power plant. Data from the power plant record book were employed in the investigation. The First and Second Laws of Thermodynamics were applied to each component of the gas power plant at ambient air temperature range of 21 - 330C. Results obtained from the analyses show that the energy and exergy efficiencies decrease with increase in ambient air temperature entering the compressor. It was also shown that 66.98% of fuel input and 54.53% of chemical exergy are both lost to the environment as heat from the combustion chamber in the energy and exergy analysis respectively. Wadhah et al. [7] this work aims to analyze the energy and exergy of a 55 MW Taza gas power station. The investigation demonstrated that the most significant misfortunes of the exergy happened in the combustion chamber, where was 66.5MW the most minimal misfortunes in the compressor 5MW while the misfortunes in the turbine 8.4MW. The thermal efficiency of the gas turbine power plant was 33.06%, while the exergy efficiency was 32.39%. Yousef and Ahmad [8] this system is a combination of a humidifier with a vapor compression or absorption cooling system for part of the total air i.e., the secondary air stream. The net power produced from the gas turbine on a hot day (45 °C) by using combined (indirect evaporative cooling system) with absorption chillers showed an increase in power and efficiency by 15% and 9%, respectively; its recovery period is suitable for all environmental conditions. For indirect evaporative cooling system combined with vapor compression mechanical chillers showed an increase in power and efficiency by about 7.81% and 2.24%, respectively. Jaber et al. [9] the influence of air-cooling intake on the gas turbine performance is presented. A comparison between using different cooling systems, i.e., evaporative and cooling coil, is perform, .at Power Station, Amman ,Jordan. The obtained results showed that the evaporative cooling system is capable of boosting the power and enhancing the efficiency of the studied gas turbine unit in a way much cheaper than cooling coil system due to its high-power consumption required to run the vapor-compression refrigeration unit. Hassan et al. [10] a gas turbine cycle with fog cooling and steam injection, and integrated with biomass gasification, is proposed and analyzed with energy, exergy and exeroeconomic analyses. The thermodynamic analyses show that increasing the compressor pressure ratio and the gas turbine inlet temperature raises the energy and exergy efficiencies. On the component level, the gas turbine is determined to have the highest exergy efficiency and the combustor the lowest. Bhargava and Meher [11] the results of a comprehensive parametric analysis on the effects of inlet fogging on a wide range of existing gas turbines are presented. Both evaporative and overspray fogging conditions have been analyzed. The results show that the performance parameters indicative of inlet fogging effects have a definitive correlation with the key gas turbine design parameters. In addition, this study indicates that the aeroderivative gas turbines, in comparison to the heavy-duty industrial machines, have higher performance improvement due to inlet fogging effects. Plausible reasons for the observed trends are discussed. Sepehr and Mojtaba [12] tthe effects of evaporative cooling on gas turbine performance were studied in this paper. Then, the effects of both evaporative cooling in inlet duct, and wet compression in compressor, on the power output, turbine exhaust temperature, and cycle efficiency of 16 models of gas turbines categorized in four A–D classes of power output, were investigated. The results of this analysis for saturated inlet fogging as well as 1% and 2% overspray are reported and the prediction equations for the amount of actual increased net power output of various gas turbine nominal power output is proposed. Hayder et al. [13] this research focuses on using a fogging air intake cooling system to improve the performance of the gas turbine in the weather conditions of Karbala city. The results show there was a drop in inlet air temperature in the case of existence the cooling system when the ambient temperature in the range of (25 to 60) ℃. The utilizing of air-cooling technique with the gas turbine causes a gain in net power and thermal efficiency and reduction in the consumption of fuel. In addition, the heat rate reduces by 7% compared to not adding the system. As a result of the high demand for electricity in Iraq and the expected shortage in the supply of electric power due to the high temperatures in the summer, the existing gas turbine plants at Al Quds Gas Plant have been upgraded with an intake air cooling system. This is the main objective of this study for the model of the Qudus gas station (frame 9E) with a capacity of 123 MW, the management of the proposed Brayton cycle was compared with the basic case without the cooling system and with an entry air cooling system (evaporative and fogging system).

2. Frame 9E gas turbine

Formerly known as the Frame 9E, GE Gas Power's 9E gas turbine can help decrease costs and increase revenue for your plant. 9E gas turbines can use more than 52 types of fuel— almost the entire fuel spectrum—and can even switch fuels while running under full load. Our 9E turbines operate on fuels with contaminants, natural gas, light and heavy distillate oil, naphtha, crude, residual oil, syngas, and steel mill/blast furnace gases [GE 14]. AL-Quds gas station operates on 10 turbine of frame 9E for electricity production, as shown the figure (1).

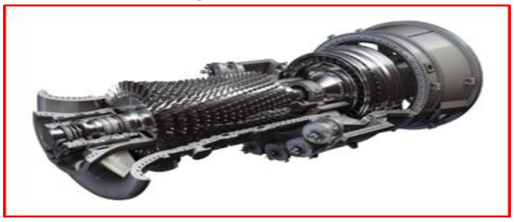

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Table (1): Illustrates the details of the frame 9E

model	PG9171 (E)
Design output power	123 MW
Fuel	Dual type (gas and light crowd oil)
Rotor	Single shaft
RPM	3000
Load condition	base
Design RH	30%
Frequency	50 HZ
Design compression ratio	12
Design temperature	-6 to 55 ^{0}c
Combustors No.	14

3. Gas Turbine Cycle

The Brayton cycle is a thermodynamic cycle named after George Bailey Brayton that describes the workings of a constant pressure heat engine, although it was originally proposed and patented by Englishman John Barber in 1791 [15,16]. It is also sometimes known as the Joule cycle. schematic diagram is shown in Figure (2) open gas turbine cycle without cooling system and figure (3) with cooling system along with its T-S and P-V representation in Figure (4 and 5) [17].

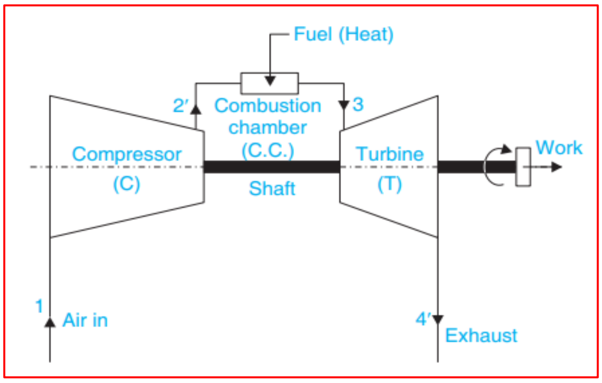

Figure (2) Open cycle gas turbine

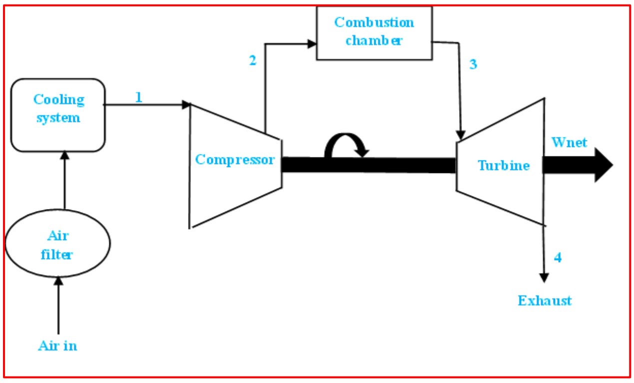

Figure (3) Open cycle gas turbine with cooling system

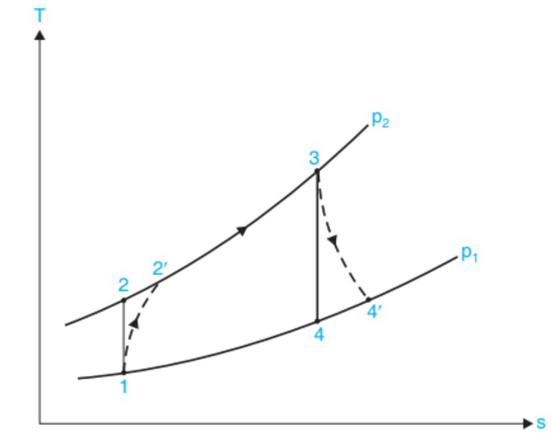

Figure (4) T-S diagram of gas turbine cycle

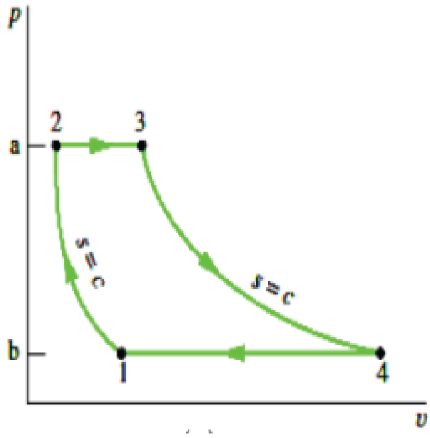

Figure (5) P-V diagram of gas turbine cycle

3.1 Data Collection

Operating data for a gas turbine unit were collected from the daily turbine control log sheet for a period of one year (2022) as shown figure (6). The daily average operating variables were statistically analyzed and mean values were computed for the period of January to December, followed by an overall average. summary of the operating parameters of the frame 9E unit for AL-Quds gas turbine used for this study is presented in Table 1. The analysis of the plant was divided into different control volumes and performance of the plant was estimated using component-wise modeling. Mass and energy conservation laws were applied to each component and the performance of the plant was determined for the simple system (without inlet air cooling) and for the cooled system (with evaporative cooler and fogging). Table (2): Summary of operating data for the frame 9E unit for AL-Quds gas turbine (123 MW)

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No	Operating Parameters	Value	Unit
1	Temperature of inlet air to compressor (T1)	25	^{0}C
2	Pressure of inlet air to compressor(P1)	1	bar
3	Outlet temperature of air from compressor(T2)	354	^{0}C
4	Outlet pressure of air from compressor (P2)	10	bar
5	Fuel-gas (natural gas) mass flow rate (mf)	7.3	Kg/s
6	Exhaust gas temperature	441	C^0
7	Load	84.6	MW

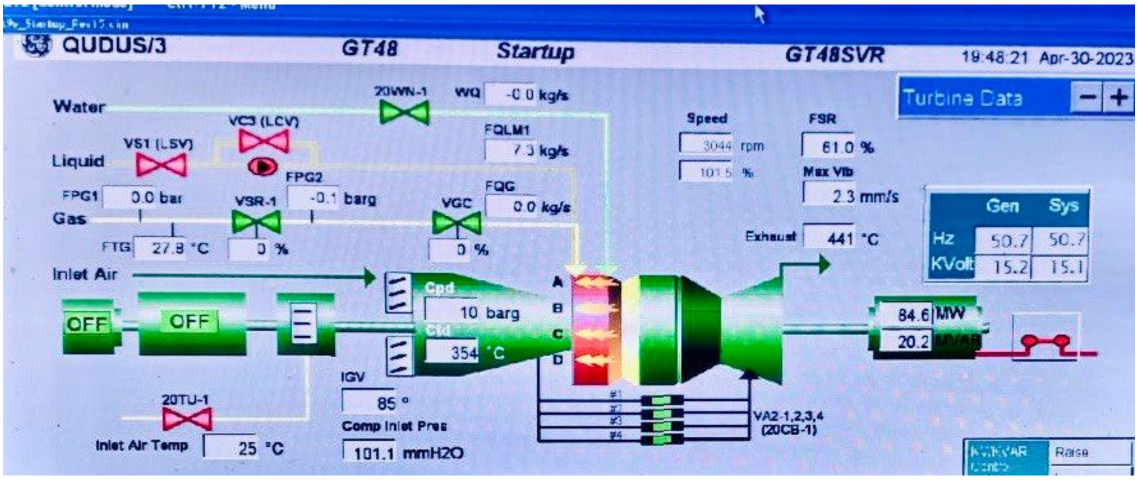

Figure (6) log sheet for a period of one year(2022)

3.2 THERMODYNAMIC MODELING OF GAS TURBINE

The gas turbine plants consist of four components including the compressor, combustion chamber, turbine and generator .The compressor pressure ratio can be defined as: [18]

$$r_P = \frac{P_2}{P_1} \qquad (1)$$

where, p1 and p2 are compressor inlet and outlet air pressure respectively.

The temperature of the air coming out from the compressor is calculated following as:[18]

$$\frac{T_2^-}{T_1} = \left[\frac{1}{r_P}\right]^{\frac{K}{K-1}} \qquad (2)$$

where, T1 and T2 are compressor inlet and outlet air temperature respectively.

The magnitude of work of the compressor is calculated following as:[18]

$$W_C = (T_2^- - T_1) \qquad (3)$$

The isentropic efficiency for compressor is expressed as:[18]

$$\eta_C = \frac{T_2^- - T_1}{T_2 - T_1} \qquad (4)$$

The temperature of the inlet turbine is calculated following as:[18]

$$\frac{T_3}{T_4^-} = r_P^{\frac{K-1}{K}} \qquad (5)$$

where, T3 and T4 are turbine inlet and outlet air temperature respectively.

The magnitude of work of the turbine is calculated following as:[19]

$$W_T = (T_3 - T_4^-) \qquad (6)$$

The isentropic efficiency for turbine is expressed as:[19]

$$\eta_C = \frac{T_3 - T_4}{T_3 - T_4^-} \qquad (7)$$

The network rate of the cycle is given by:[19]

$$W_{net} = W_T - W_C \qquad (8)$$

The heat added of the cycle is given by:[19]

$$Q_{add} = (T_3 - T_2) \qquad (9)$$

The cycle thermal efficiency is given by:[19]

$$\eta_{th} = \frac{W_{net}}{Q_{add}} \qquad (10)$$

Or

$$\eta_{th} = 1 - \frac{1}{r_P^{\frac{k-1}{k}}} \qquad (11)$$

Defining the cooling effectiveness of evaporative cooling system as:[12]

$$CE = \frac{T_{amb} - T_e}{T_{amb} - T_{wb}} \qquad (12)$$

4. Results and Discussion

From this paper, conducted a case study for one of the gas powers plants in Iraq, which namely the Quds Thermal Power Plant. In this study, thermodynamics analysis was investigated to better understand the behavior and performance of the power plant which indicated above. As a requirement research data collection was gathered from the Quds power plant in a form which called a log sheet for the full year (2022). This data is represented in three cases: one of them the station works without any cooling system, and others with systematic cooling (e.g., evaporative cooling system and Fogging cooling system). From the findings and data collected, will show the effect of the station's operating conditions (e.g., ambient temperature) on the overall performance and thermal

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efficiency and turbine efficiency, and compressor efficiency during the annual operating average of the station.

Based on Figure 1, revealed the relationship between compressor work in M watts and the number of months for the full year (2022), with three systematic proposed in the current study one of them that without a cooling system and with two different cooling systems (e.g., evaporative, fogging). From the figure, the compressor work increases with deteriorating operating conditions (outside standard operating conditions) during peak operating months with rising temperatures. Also, from the curve it displays that the generating units that don't work with a cooling system increase compressor work and this is an indicator that the compressor is one of the mechanical parts that has negative work, the contrary we find that compressor work in generating units that operate with a cooling system decreases work, due to decrease in inlet temperature that entered in the compressor. In the generating units when comparing compressor work between a generating unit that operates without a cooling system and that one works with an evaporative cooling system, the reduction in compressor work value ranges from (-0.088%) during December to (-0.136%) during July. also compared compressor work between a unit that works with the fogging cooling system and one that works with an evaporative cooling system. The reduction in work of compressor ranges from (-0.072%) during December to (-0.29%) during July. So, the unit generating that works with fogging cooling systems is considered the lowest compressor work among other systems. Figure (2) shows turbine work and the number of months for the full year (2022) with the three-systematics suggested through the current study in case of the absence of cooling systems and with their presence. From the figure, it can be seen that turbine work increases with better-quality operating conditions (inlet temperature of the station that is suctioned from the compressor). The generating unit that works with fogging cooling system generates good work than other units whether they operate without a cooling system or with the other one that works with the evaporative cooling system. From the calculated results, the generating unit that works with the evaporative cooling system superiors the other one that does not work with the cooling system by (2.87%) in July month which is considered one of the worst months during the operational year of the station. But when comparing the unit that operates with an evaporative cooling system with the other one that operates with fogging cooling system, find the latter superiors by (6.52%) in July month, also where these systems start to work.

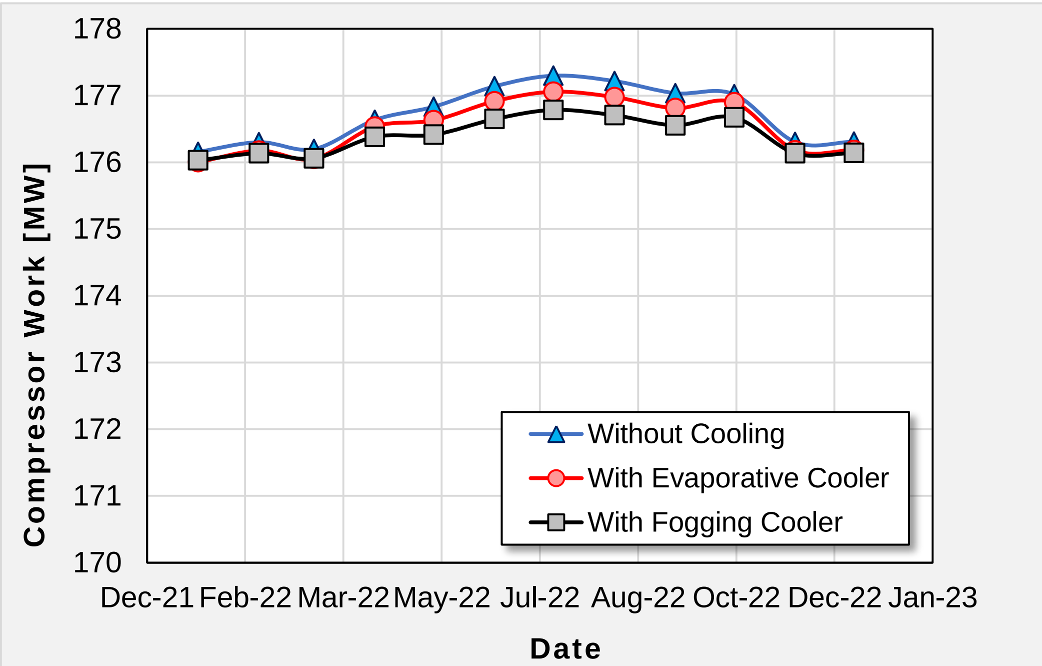

Figure (1). Shows compressor work in M watts and the number of months for the full year (2022)

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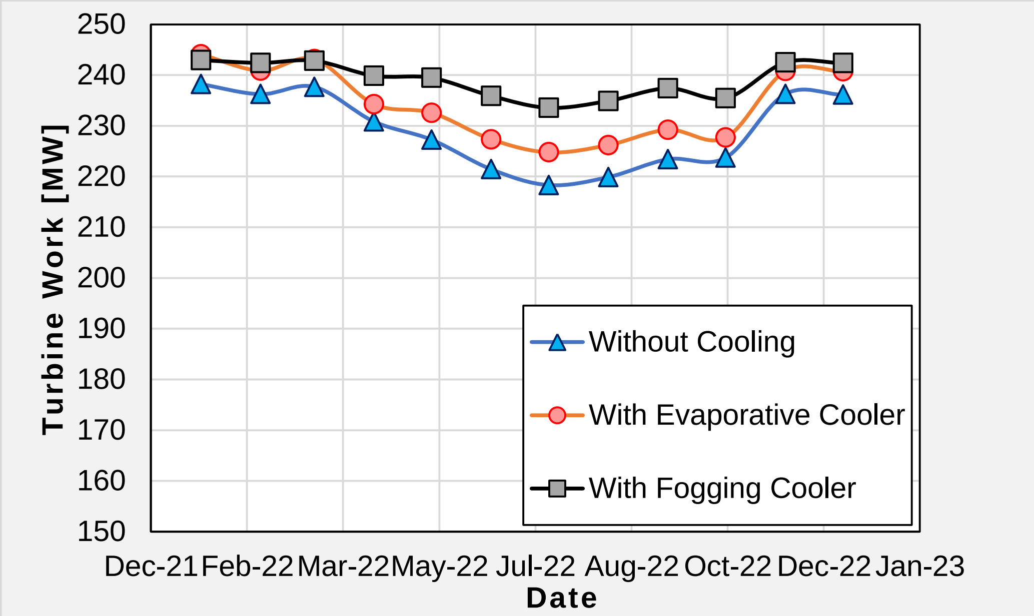

Figure (2): shows turbine work and the number of months for the full year.(2022)

Figure (3): It shows the generated load in Mega Watts and the number of months in the full year (2022) and the comparison with three systematics throughout the present case study. From the results got, the peak generated load for the gas power plant is when the generating unit is coupled to a fog cooling system, followed by a lower performance when working with an evaporative cooling system. while the worst generation among the three systems is when the generating unit works without a cooling system through the months that are highest in terms of high temperatures. From the results, it can be seen that when comparing a generating unit working with an evaporative cooling system and another that does not operate with a cooling system, an increase in performance during July by (8.17%). Likewise, when comparing two generating units, one of which works with an evaporative cooling system and the other with a fog cooling system, the latter attains an increase in generated load by. (17-32%)

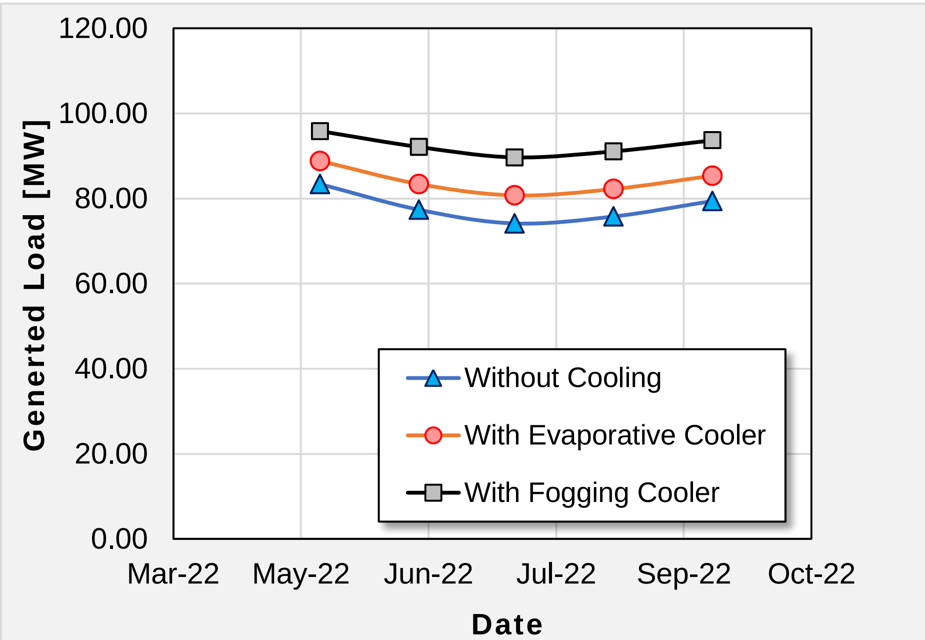

Figure (3): shows the generated load in Mega Watts and the number of months in the full year **(2022)**.

Figure (4): It illustrates the thermal efficiency and the number of months in the full year **(2022)** and the comparison with three systematics during the current case study. Mainly, the thermal efficiency of a gas turbine plant depends on the pressure ratio and ambient temperature. So, from the results, the highest efficiency for the gas power plant is when the generating unit is connected to a fogging cooling system, then followed by a lower efficiency when working with an evaporative cooling system. but the worst generation among the three systems is when the generating unit operates without a cooling system through the months that are highest in terms of high temperatures which effects on pressure

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ratio. From the results, it can be seen that when comparing a generating unit working with an evaporative cooling system and another that does not operate with a cooling system, an increase in performance during July by **(12.2 %)**. Likewise, when comparing two generating units, one of which works with an evaporative cooling system and the other with a fog cooling system, the latter attains an increase in generated load by **(24.09 %)**.

Figure (5): depicts the curve between the inlet temperature to the gas turbine plant with the number of months during the full year 2022. with the use of three systematic. To enable us to get a pointer of the behavior and effect of inlet temperatures on the gas power plant throughout the months for one year. Moreover, determine which months witness an increase in temperatures and monitor the effect of this increase on the overall performance of the gas power plant through the curve. It can be seen that most months are hot between me June and Jul. From the results, the generating unit that works with a cooling system by fog, there is a decrease in temperature index than the generating unit that does not work with a cooling system. Also, the cooling system that works with fog outperforms the system that works with evaporation by lowering temperatures during the operation of these systems during the months with higher temperatures.

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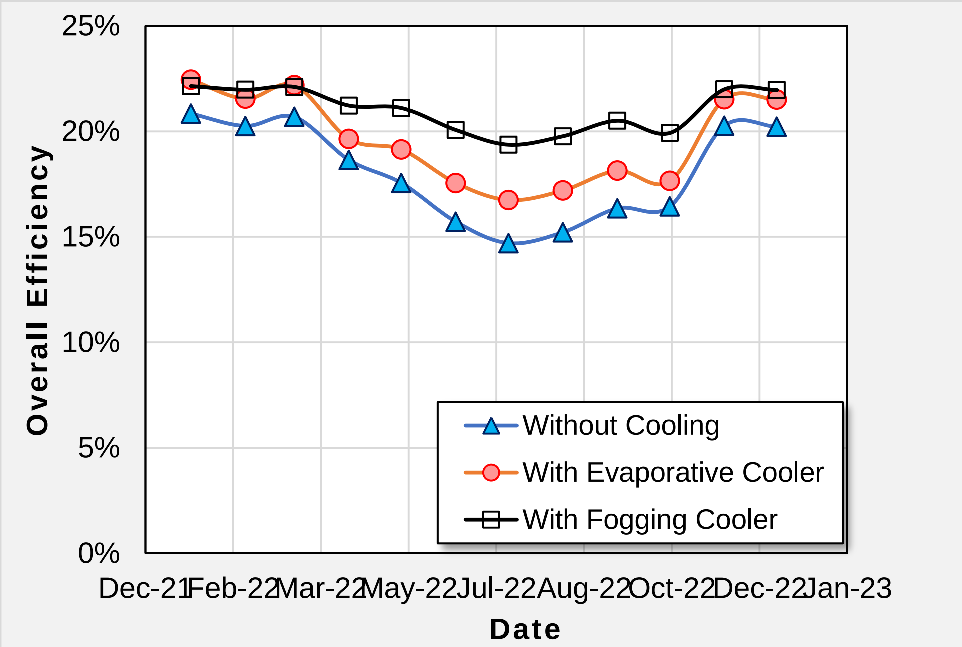

Figure (4): It illustrates the thermal efficiency and the number of months in the full year **(2022).**

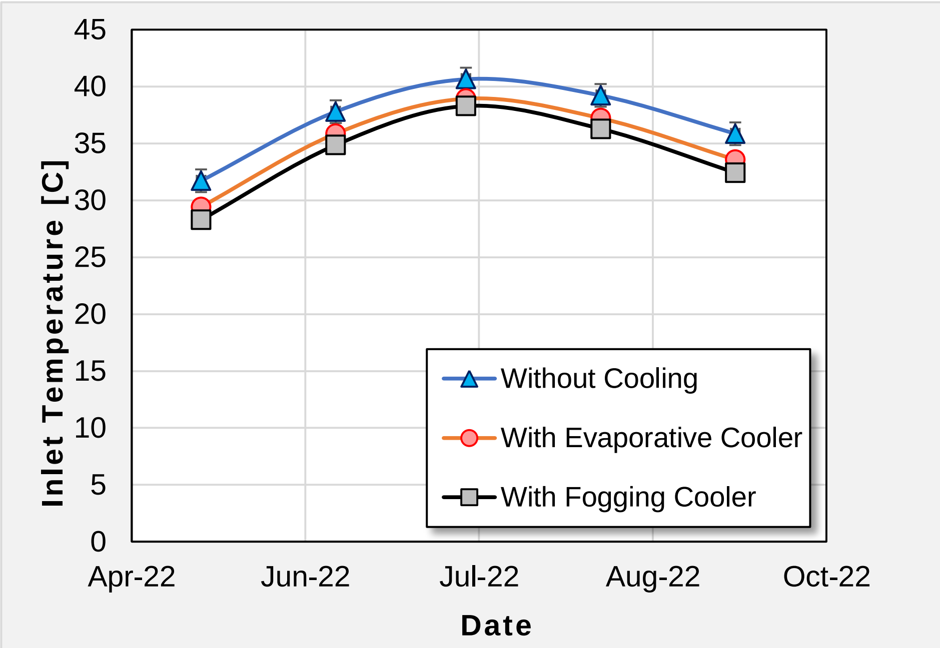

Figure (5): depicts the curve between the inlet temperature to the gas turbine plant with the number of months during the full year 2022.

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5. Conclusion

1. the reduction in compressor work value ranges from (-0.088%) during December to (-0.136%) during July. also compared compressor work between a unit that works with the fogging cooling system and one that works with an evaporative cooling system. The reduction in work of compressor ranges from (-0.072%) during December to (-0.29%) during July.
2. generating unit working with an evaporative cooling system and another that does not operate with a cooling system, an increase in performance during July by (8.17%). Likewise, when comparing two generating units, one of which works with an evaporative cooling system and the other with a fog cooling system, the latter attains an increase in generated load by (17.32%).
3. an evaporative cooling system and another that does not operate with a cooling system, an increase in performance during July by (12.2 %). Likewise, when comparing two generating units, one of which works with an evaporative cooling system and the other with a fog cooling system, the latter attains an increase in generated load by (24.09 %).
4. the generating unit that works with a cooling system by fog, there is a decrease in temperature index than the generating unit that does not work with a cooling system. Also, the cooling system that works with fog outperforms the system that works with evaporation by lowering temperatures during the operation of these systems during the months with higher temperatures.

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