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GAS TURBINE SUITABLE FOR THE AMBIENT CONDITIONS PREVAILING IN ARAB GULF COUNTRIES - A PROGNOSTIC ANALYSIS

Wissam Huzam Salman Alaabidy[1]*, Antipov Y. A.[1], Majid Sabbar Salih Al-Rubaiawi[2], Mikhail Frolov[1]

[1] Department of Energy Engineering, Peoples' Friendship University of Russia (RUDN). Moscow, Russia
[2] Shiite Endowment Office

** 1032204101@pfur.ru*

The present study conducted a prognostic analysis with the aim of understanding the problems associated with the operation of gas turbines in hot climatic regions like the Middle Eastern region. In addition to the hot and dry climatic condition, the region experiences frequent dust storms which can result in operational problems, shorter life span and very high maintenance costs, making air filtration a mandatory operation. Due to this condition and taking into consideration the high humidity of the coastline region, for better effective operation, longer useful life and reduced operating cost the gas turbines have to be located away from the coastline region. To get better power output from the gas turbines, the ambient air has to be cooled. Among the different options available for cooling, evaporative cooling system was found to be more suitable and cost effective for the region. Analysing the performance of the gas turbine, it was found that adopting the cooling system will result in enhancing the output power up to 7.12%.

Keywords: gas turbine, ambient conditions, biobased fuels, power generation

1 INTRODUCTION

Taking into account the current population growth, it is estimated that the global population will reach an alarming count of 10.4 billion by 2050 [1,2]. This in turn will put huge pressure on the energy sector, especially in the developing countries (Fernandez et al., 2021). Studies reveal that the global energy demand is increasing every year by 2.9% since 2010. Presently, 73% of the energy demand is supplied by fossil fuel resources [4]. Fossil fuels still dominate the energy sector worldwide[5], but their use is reducing slowly due to the implementation of new legislative regulations globally for controlling its use to mitigate the environmental effects caused by them[6]. Though using fossil fuel based technology (FFBT) for energy production raises environmental concerns from their emissions [7], but cannot be completely ruled out as they are proven sources presently available for effective economic progress[8]. This is one of the factors that drive economically developing countries towards adopting FFBT to meet their energy requirements.

Presently, more researches are being diverted globally on the use of alternative biobased fuels and very little works are being concentrated on improving technologies running with fossil fuels [9]. It should be noted that the fossil fuels still hold a prominent share in meeting the global energy demand and will continue for many more years. Thus, making a sudden step back is practically difficult [10]. Thus, researches on improving the efficient use of fossil fuels and resulting increase in its availability period and the reduction of the environmental effects are still significant. Taking into account the positive drive of the FFBT, the effective way to compact the environmental concerns is by choosing lesser polluting FFBT options and increasing their efficiency on energy production. This can bring twin benefits of allowing faster economic progress in developing countries with reduced environmental effects.

Among the different fossil fuels, natural gas is considered to be more environment friendly [11] as a result, natural gas fuelled gas turbines (NGGT) are being widely considered instead of steam turbines fuelled by coal and petro-fuel [12]. This increased use of natural gas instead of coal have led to huge reductions in CO_2, NO_x, and SO_2 emissions globally[13]. Using natural gas instead of coal can result in nearly 50% reduction of CO_2[14]. In addition to the reduced environmental effects, they are economical and have better thermal efficiencies than the other FFBT[12]. The energy sector of the economically developing countries have to tackle two major problems, the ongoing variations in the energy prices and the steadily increasing energy demand[15]. Among the different energy sources, electricity is considered to be very important by the human society today. Due to the cost effectiveness, simplicity in construction and operation and the ability to respond quickly to varying load requirements, gas turbines are being widely considered for electric power generation[16]. Though they are being widely considered and recommended, both its thermal efficiency and the quantity of power produced is highly dependent on the ambient environmental conditions[17]. The important factors that affect the performance of gas turbine used for power generation (GTPG) are, the geographical location [18], inlet air temperature [19]which decides the quantity of work by the compressor [20], ambient temperature, air density [21], air pressure [22], relative humidity [23]and fuel [24].

A variety of fuels can be used in gas turbines with each having its own power output performances. Generally, it could be stated that as the hydrogen to carbon ratio in fuels increases, so will be the increase in thermal efficiency, shaft power and reduction in CO_2 emission [25]. Apart from fuel, all the factors that affect the performance of gas turbines are mainly connected to geographic location based climatic parameters. This is due to the fact that they are basically a constant volumetric flow rate machines which requires a constant supply of high air flow for combustion.

As the air required for combustion is taken from the surrounding environment, the ambient environment and the weather conditions affect its performance [26]. Among all the factors, those which affect the volumetric efficiency [26] such as density and mass flow rate of the air entering the gas turbine affects its performance the most [27]. Thus, the parameters such as inlet temperature, ambient temperature and relative humidity have a direct influence on the operating performance (power output and thermal efficiency) of the gas turbines [28]. Among the factors affecting the density and mass flow rate, inlet air temperature affects the GTPG performance the most[19]. Under ISO conditions, the typical thermal efficiency of GTPG is 30% and studies have found that for every degree rise in the inlet air temperature above the ISO condition, there will be approximately a reduction of 0.64% in the total power output [21] and 0.18% in thermal efficiency [29]. Thus, in hot climatic regions and summer seasons when electric power demand is typically higher, both the quantity of power produced[30] and the production efficiency [31]of GTPG will be highly affected. Thus leading to increased production cost and pollution produced per kW of electric power generated [32].

Taking these factors into consideration, it is evident that both the thermal efficiency and power output will be highly affected when GTPG are being operated in hot climatic regions such as the countries of the middle east. In addition to the above parameters, GTPG operating in the middle east region will face problems related to higher filtration requirements for the air entering the GTPG due to the general dusty environment prevailing in the region[33]. Improper air filtration can affect the life, performance and frequent higher maintenance requirements for the GTPG. There are many studies that explain the problems associated with the use of gas turbines in hot climatic regions, providing different solutions for tackling each problem. The present study performs a theoretical prognostic analysis of the problems faced and solutions offered for improving the performance of GTPG operating in hot climatic conditions based on published research outcomes. As ambient temperature is the most important parameter that affects the performance of the GTPG, the present study tries to analyse to what extend ambient temperature affects the performance of GTPG, the different options available for reducing the temperature of the air entering the GTPG and select a suitable cooling system for GTPG operating in hot climatic regions like the Middle East. The study further analyses the performance of GTPG based on the highest average temperatures reported in published literatures.

2 EFFECT OF AMBIENT AND INLET AIR TEMPERATURE ON THE PERFORMANCE OF GTPG

2.1 Importance of cooling compressor air inlet temperature of GTPG operating in hot climatic conditions

Gas turbines are constant-volume engines and their shaft power is proportional to the mass flow rate of air. As the mass flow rate of air increases, the power produced and the fuel consumed increases. Though the fuel consumption increases with the increase of air mass flow rate, when compared with the power output the increased fuel consumption is smaller [34]. As the air temperature increases the density of air decreases, thus reducing the mass flow rate of air which in turn increases the work of the compressor [35]. By cooling the inlet air, its density is increased at constant pressure, resulting in higher mass flow rate and thereby the output power [36]. The power output of the GTPG is rated at 15 °C and temperatures above 15 °C results in the reduction of both thermal efficiency and power output [37]. It was found by Zeitoun[38] that a GTPG delivering 84.4 MW power at 15 °C dropped down to 69 MW at 450C. Further El-Shazly et al. [37] observed that by reducing the inlet air temperature by 10 ºC from 400C can result in output power enhancement of 10%. In addition to power and thermal efficiency enhancement, GTPG operating with lower intel temperature result in better heat rate and enhanced turbine life. Studies have shown that for every 0C rise in temperature above 15 °C, the GTPG power output reduces by 0.77% [35], thermal efficiency by 0.1% [39] and the air mass flow rate by 0.36% [40]. This highlights the importance of cooling the inlet air when the GTPG is operating in conditions having high ambient temperature. Thus, for better performance of the GTPG, the temperature of the inlet air has to be 15 °C or brought down as close as possible.

2.2 Technological options available for cooling compressor air inlet temperature

Many studies have been conducted and many options are being proposed on the enhancement of GTPG power output by cooling the inlet air temperature (Table 1). The technological options available for cooling the inlet air temperature for GTPG can be broadly classified as systems that lower temperature only and those lower the temperature associated with the increase in humidity (Figure 1). Among the systems listed in figure 1, the methods can be grouped as systems that cools the incoming air by absorbing the latent heat of evaporation commonly called as evaporative cooling systems [41–43], using high pressure fogging system [44,45], adopting absorption chiller cooling systems that cools the incoming air using heat exchangers [46,47], using mechanical refrigerate cooling system [47,48] and adopting thermal storage systems [49]. Each system has its own advantage and disadvantages (Figure 2) [17] and a particular system has to be selected taking into consideration the economics, technical requirements and the extend of its suitability in handling the ambient conditions prevailing in the area.

Table 1. Performance compression of studies using different cooling systems for GTPC

Cooling method Adopted	Ambient temperature (°C)	Temperature reduction obtained (°C)	Power output increased (%)	Thermal efficiency increased (%)	Reference
Media evaporative cooling system	48.8	13.54	9.83		[50]
	38	19	14.60		[51]
	20-40	5 - 25	11.80	1.5 to 5	[29]
	34	19	8.40	2.3	[52]
	31	5	5-10	2-5	[53]
Fogging system/spraying system	48.8	15.08	11.00		[50]
	40	15	7.70	0.37	[15]
	32	18	7.00	2.70	[54]
	42	16	15.50	3	[17]
	30 - 40	5.54 -15.77	3.97 - 11.15	0.11-1.47	[55]
mechanical refrigeration/Chiller cooling	34.2	19.2	11.3		[40]
	48.8	26.7	19.70		[50]
	50	25	11.00		[15]
	30	15	6–8		[56]
	34	19	12.70	5.3	[52]
	25	10	1.14	1.14	[57]
	43.33	35.33	14.90		[48]

(i) Evaporative cooling systems

In evaporative cooling both high pressure fogging and cooling using media are considered to be better option than the others, especially for GTPG operating in hot and dry conditions[51]. The temperature deduction of the air using evaporative coolers is achieved by the thermodynamic process called adiabatic saturation[58]. The thermal energy of the air is consumed by the water causing it to evaporate, resulting in the decrease of air temperature and increase of its humidity[59]. Thus, using evaporative cooling system, the temperature of the inlet air is dropped to a value very close to the wet bulb temperature[60]. Thus, wet-bulb depression*[61]* is a deciding factor on the amount of temperature reduction and thereby the performance of the GTPG[60]. Taking the general performance into consideration, the effectiveness of evaporative cooling method using media is in the range between 0.85-0.9, while high pressure fogging system is in the range between 0.97-1[62]. Thus, among the evaporative cooling methods, cooling using high pressure fogging system is being widely practiced [63]. In addition to its effectiveness, its simple design, easiness to install, operate and cost effectiveness in power output enhancement [64] have enhanced its wider acceptance. The effectiveness of the fogging system in reducing the temperature of the inlet air can be further enhanced by using cold water [65]. Thus, the temperature of the water used for fogging also influences the cooling process. In addition to this to achieve faster reduction in temperature by absorbing the latent heat of vaporisation from incoming air, the droplet diameter should be between 30 - 50 µm [66,67]. Based on these results it can be said that fogging system can be more effective to increase the power output of gas turbines in dry climatic regions as these regions are characterised with higher ambient temperature and lower relative humidity. The basic disadvantage of this system is that it consumes huge amount of water and can be a problem in places having water availability problems. In evaporative cooling system using media, the air to be cooled is passed through pads of fibers soaked with water resulting in the decrease of temperature and increase of humidity [29]. The media evaporative cooling system consumes only about 0.6 to 1.2 m^3 of water for each MW of power generation and can result in the up to 14% increased power output. The water consumption of media evaporative cooling system is about 10.15% lower than that of high pressure fogging system[50]. But as there is pressure drop while the air passes through the media and the media needs regular replacements increasing the operation cost of the system[59].

(ii) Mechanical systems- Absorption chiller and refrigeration cooling systems

Mechanical compression and absorption cooling systems are generally considered as a second option next to evaporative cooling systems as they bring about change in only temperature of the incoming air[68]. This is due to the fact that mechanical compression and absorption cooling systems do not add moisture to the air and thus the associated negative effects caused such as erosion, corrosion etc., on different parts of the turbine is avoided[69]. Both the systems are capable of producing better cooling effect than evaporative cooling systems, but are associated with parasitic losses in terms of more electricity consumptions for their operation[70]. In the study conducted by Santos and Andrade[68] found that absorption chillers are better than mechanical compression systems in providing higher energy increments at lower cost. There have been a lot of studies on improving both mechanical compression and absorption cooling systems resulting in the development of mechanical chillers having coefficient of performance above 6.0 [71].

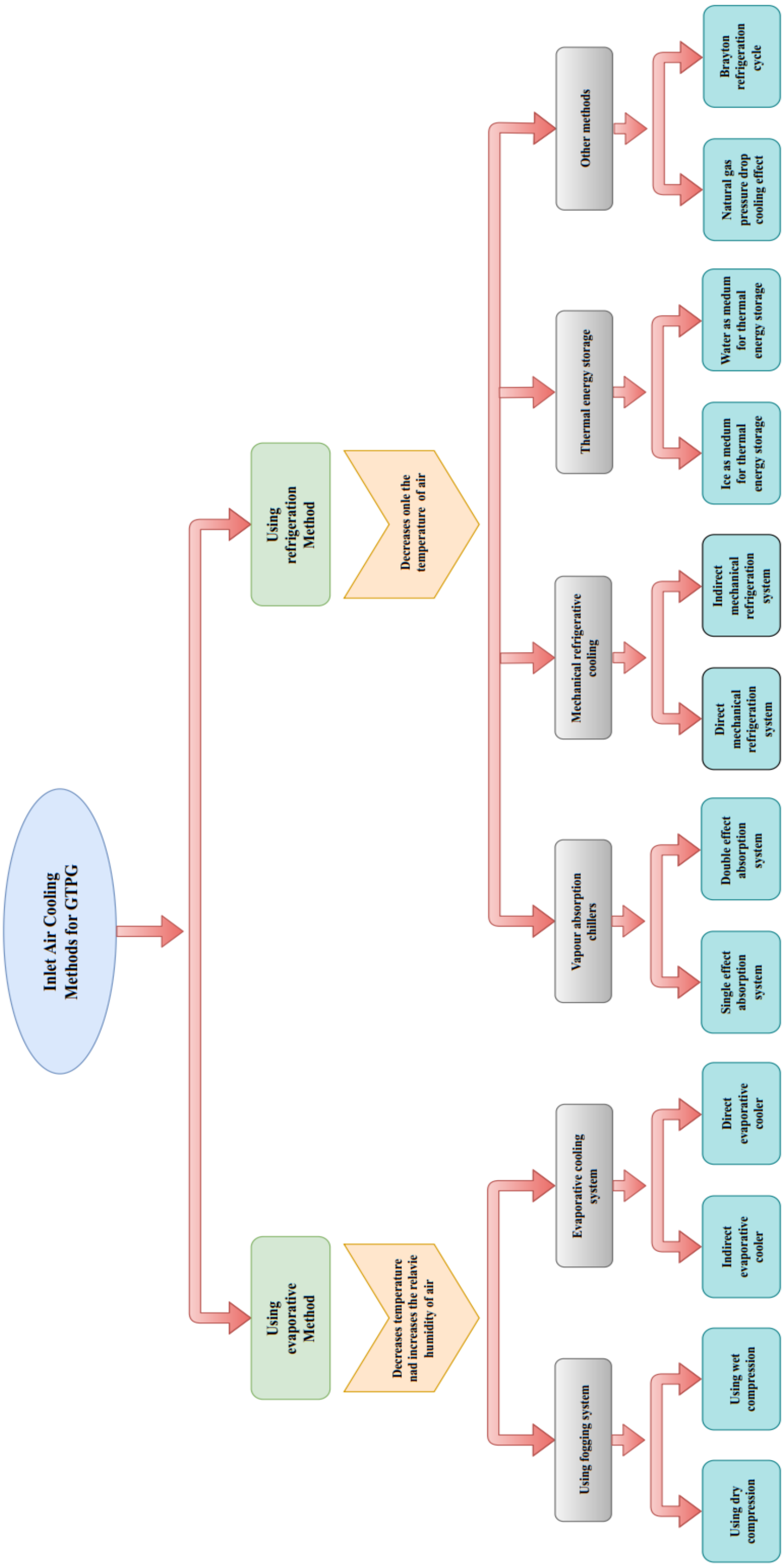


Figure 1 Different inlet air cooling methods available for GTPG. Source [17]

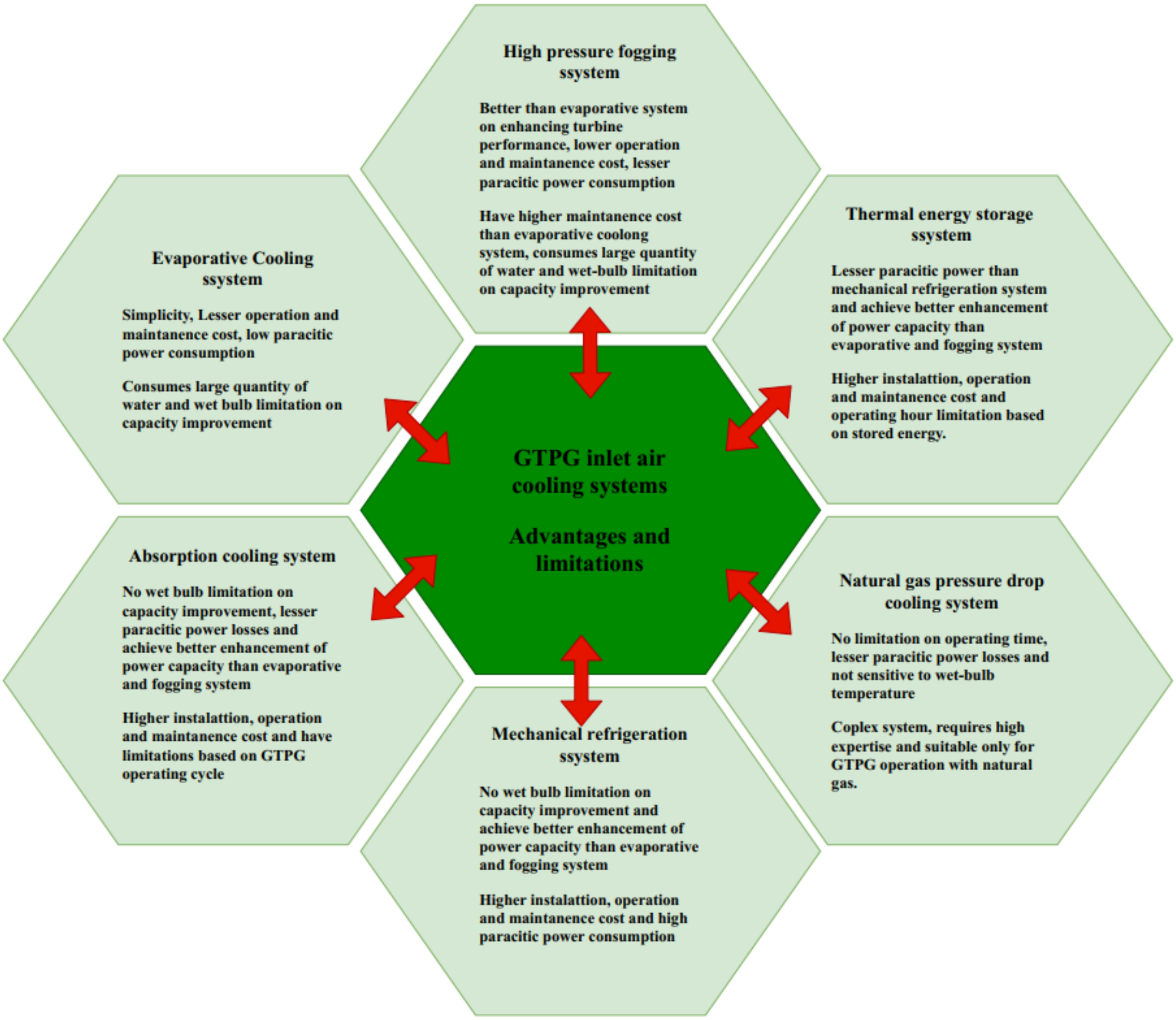


Figure 2. Comparison of different inlet air cooling methods for GTPG. Source [17]

The working of the absorption chiller is similar to the traditional vapour compression system apart from the change of the compressor with a chemical cycle between an absorber, pump, and regenerator[72]. The commonly used refrigerants in absorption chillers are ammonia with water absorbent and water with lithium bromide absorbent[73], out of these water with lithium bromide absorbent was found to be better than are ammonia with water absorbent[74]. Absorption chillers are capable of reducing the temperature of the incoming air by 16.7% to 26.7% more than evaporative cooling systems, increase the power output by 15% to 20% and the thermal efficiency by 1-2% [50] and decrease the electricity production cost by 2.97% - 5.04%[32] regardless to the prevailing ambient conditions. The power output produced is 40% to 55% more than that of high pressure fogging system [50], but the system is more complex [75] and consumes more energy than cooling system using high pressure fogging system [50]. Thus, making the operating cost much higher than the evaporative cooling systems [76]. In fact the payback period of evaporative cooling system is just 41.1% of absorption chiller system [77].

(iii) Thermal storage systems

In this system thermal energy is stored and is used for cooling the incoming air based on requirement [78]. The storage system is either sensible or latent heat type, with the latent type changing its phase while rejecting the stored energy to the incoming air. The latent type of system can store more energy than the sensible system[79]. The commonly used sensible thermal energy storage medium is water and ice as latent thermal energy storage medium[80], in addition glycol chiller and encapsulated phase change materials are also being widely used[81]. In the study conducted by Sanaye et al[79] found that using the thermal energy stored in the ice was effective in increasing the power output by 3.9-25.7%, the thermal efficiency by 2.1-5.2%, but the payback period increased from 4 to 7.7 years. The increase payback period is due to the increased installation cost of the system.

3 EFFECT OF RELATIVE HUMIDITY

The relative humidity is a parameter often neglected by researches while evaluating the performance of GTPG as it is considered not to produce any significant effect [82,83]. The thermodynamic property of the working medium (air-water vapour mixture) changes with the change in relative humidity, which in turn will affect the engine performance[84]. In the study conducted by Alasfour et al.[85] found that both temperature and relative humidity are important parameters while determining the exergetic performance of GTPG. The relative humidity play a major role in accurately estimating the performance of GTPG when the ambient temperature is greater than 300C and relative humidity is above 70%[86,87]. Especially while calculating the excess air requirement for the GTPG. The study conducted by Lugo-Leyte et al.[88] neglecting relative humidity can result in estimating excess air requirement over 5% of what is actually required. An efficiency reduction of 6.28% was observed in the study conducted by AL-Salman et al.[60] when the realative humidity of air was increased fron 10 to 60% at constant ambient temperature.

Relative humidity also plays a major role in cooling air while using evaporative cooling systems. The extent of cooling depends on the relative humidity, under same temperature air having lower humidity will be cooled more than air with higher humidity. It was observed by Barakat et al [17] that the temperature drop decreased by 22.8% when the relative humidity changed from 20 to 80%. Moreover, higher humidity results in increased heat consumption in the combustion chamber of GTPG. This is due to the high specific heat of water[23].

4 AMBIENT CONDITIONS PREVAILING IN THE MIDDLE EAST REGION

The Middle Eastern region is composed of 18 countries[89], generally having desert type (arid) climate with the day temperatures during summers (July and August) going above 490C and nights temperatures going very low and sometimes even below 00C. The dry climatic conditions are associated with low relative humidity[90]. The monthly average temperature both during the day and night from the years 2015-2022 is portrayed in Figure 3 [91]. It is clear from the data that the cooling load on the cooling system of GTPG will be low during the months of November, December, January and February, moderate during March, April and May and high during the months from June to September. It could also be seen that the cooling system need not be operated during the nights from January to April and October to December. As the climate generally remains dry the relative humidity apart from the coastal regions is dry with average values in the range between 20 to 40% and the coastal areas as high as 60%[36,55,92].

Dust storms are common, as much as 38 dust storms a year[93]. In fact about 20% of the global dust emissions is from the Middle Eastern region[94] from the dust storms originating from the deserts of Iran, Iraq and Arabian Peninsula[95], with its frequency more in summer than in winter[96]. It was found by Mohammadpour et al.[97] that between 2003–2012 there were 155 dust storm events with majority of them occurring during the months of April and May. The majority of the dust particles have diameter in the range 0.1–10 μm, distributed vertically to a height of 1000m and requiring a minimum time of 14 hours to settle[98]. This highlights the importance of filtering the air entering the GTPT prior to cooling.

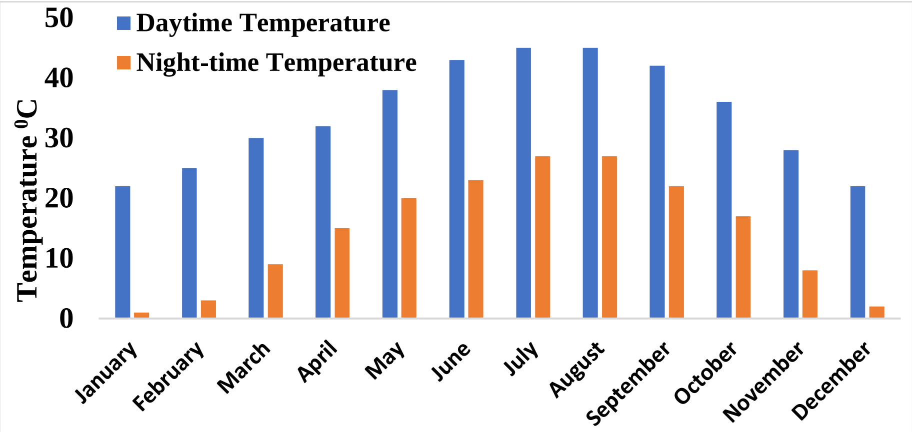


Figure 3. Average day and night temperature in the Middle Eastern Region

5 FILTRATION AND FILTER REQUIREMENTS FOR AIR ENTERING THE GAS TURBINE

The volume and quality of air entering the GTPG is an important factor that decides its life and operating performance. Thus, the air entering the GTPG should be properly filtered and the filter used should not affect the mass flow rate of air required by the GTPG. While selecting filter for GTPG, the air resistance and pressure drop induced by the filter, its dust holding capacity and efficiency of filtration has to be taken into consideration[99]. Taking the results of Parolari et al. [98] into consideration, the filter selected should be able to filter out particles having diameters of 0.1 μm, but as per Schroth and Cagna[100] filters used for GTPG should be able to filter out particles sizes in the range of 0.01 μm to 3 mm. In addition to this the middle easter region experiences frequent dust storms which can result in filters getting loaded fast, requiring frequent cleaning[101]. Thus, to avoid frequent stopping of the GTPG for cleaning the filters, self-cleaning filters are more suitable for GTPG operating in desert areas like the Middle Eastern region. This prevent frequent shout downs and save a considerable cost of labour required for cleaning required in the case of non-self-cleaning filters[102,103]. More over due to the complex and harsh conditions prevailing in the desert type climate, often the filters used don’t get in actual the useful life prescribed by the manufacturer[104]. Thus, for efficient operation and longer life of the GTPG operating in Middle Eastern region, filtration of the incoming air is very essential and filter has to be selected by properly evaluating the information provided by the filter manufacturer, the prevailing operating conditions and taking into account the investment and maintenance cost required[105].

6 SUITABLE LOCATION AND COOLING SYSTEM FOR GAS TURBINES OPERATING IN HOT REGIONS

In the Middle Eastern region, the coastline regions have hot and humid climate and as we move away from the coastal region, the climate is hot and dry. If GTPG is installed in the coastal region, only the temperature of the inlet air needs to be reduced to increase the power output and thermal efficiency. As the wet bulb depression is small, evaporative cooling system cannot be that effective as absorption chiller and refrigeration cooling systems. But the absorption chiller and refrigeration cooling systems are more complex, requires high technical expertise, have higher parasitic power consumption and very high installation and operating cost than the evaporative cooling system. Moreover, GTPG operating under high humid conditions are reported to have higher pressure losses in the intake system. This will be further worsened with frequent dust storms[106,107]. In addition to this desert regions near the coastal lines along with high humidity also experiences dense fog, which can result in collection of dust in the form of cake on the filters decreasing its effectiveness [101]. Thus, in desert regions like the Middle East, coastline locations for GTPG should be avoided.

Evaporative cooling systems (both media and fog) are considered as the most economical solutions for hot and dry areas than the expensive absorption and vapour compression chiller methods[59]. Evaporative cooling systems can be adapted for GTPG in the Middle East if they are installed away from the coastline region. In the evaporative cooling system, sensible heat of the air exchanged for the latent heat of evaporation from water is adiabatic[108], which is considered as preferred solution for enhancing the GTPG power output by about 12% in regions having desert type of climate [109]. Thus, adopting evaporative cooling system is the most cost-effective method to enhance the power output of GTPG in regions like the Middle East having a hot-dry desert type of climate[110].

7 CASE STUDY: PERFORMANCE ANALYSIS OF GTPG OPERATING IN MIDDLE EASTERN REGION

A theoretical performance analysis of GTPG was done taking into account its operation in hot ambient temperature conditions of the Middle Eastern region. Performance of the GTPG was compared both with and without cooling the inlet air to the compressor. As there is considerable variation between the day and night temperature, the performance of the GTPG was studied for both monthly average temperature and the temperature variations in a day. Since the region faces high temperatures during the months June, July and August, average temperatures of the same was considered for the study. The monthly average ambient dry bulb and wet bulb temperatures of the cities Baghdad, Mosul and Basrah, reported by Mohammad[111] and the average temperature variations for every three hours in Ghazvin city in Iran reported by Ehyaei et al [32] was used. The basic system configuration of the GTPG is portrayed in figure 4, the technical specifications and operating data at ISO condition of the GTPG as detailed in table 2 [53].

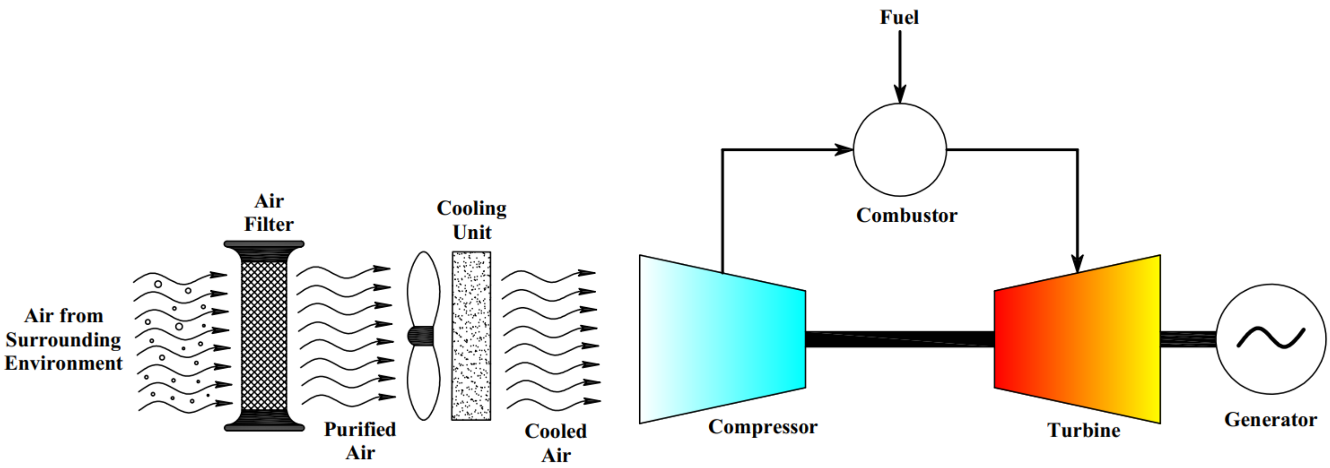


Figure 4. The Gas turbine configuration considered for the study [24]

Table 2. Technical specification of the GTPG considered for the study

Parameter	Value	
Pressure ratio	12.1	
Pressure of air interring the compressor	101.3	kPa
Mass flow rate of air	125.2	kJ·kg-1
Turbine inlet temperature	1219	K

Parameter	Value	
Isentropic efficiency of compressor	85	%
Isentropic efficiency of turbine	86.8	%
Combustion efficiency	99	%
Combustion chamber pressure loss	1.17	%
Fuel	Natural Gas	
Calorific value of fuel used	48235.6	kJ·kg-1

7.1 Thermodynamic Model of a single shaft simple GTPG

While analysing the performance of the selected GTPG the following assumptions were taken into consideration:

a) It was assumed that the air is entering into the cooling unit was at ambient temperature [112].
b) The ambient pressure (Pa = 101.3 kPa) and it was assumed that the pressure of the air leaving the cooling system was same as the ambient pressure (Pa = Pi) [53,68].
c) The cooling process was adiabatic with no water loss while being injected and had an effectiveness of 90% [113].
d) In the fogging chamber all the fog droplets were evaporated and the air from the fog chamber inters the compressor unit in saturated condition [114,115].
e) The air and the products of combustion behaves like ideal gases [52]

The equations used for calculating the performance of the selected GTPG was as follows.

Temperature of the air coming out of the cooling unit [17,52,114,116].

$$t_o = t_i - (t_i - t_{wb})\eta_c \tag{1}$$

The cooling load of the cooling unit[52,68,116].

$$q_{cl} = m_{air}\, C_{dap}\, (t_i - t_o) \tag{2}$$

Pressure of the air while leaving the compressor [9,49,52,53,68,112].

$$P_1 = rP_i \tag{3}$$

Considering the polytropic relations for gas ideal and isentropic efficiency of compressor, the temperature of air coming out of the compressor (t_1) was be obtained by [49,52,53,68]:

$$t_1 = \frac{t_o}{\eta_{comp}}\left[\left(\frac{P_1}{P_i}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] + t_o \tag{4}$$

By applying the first law of thermodynamics, the work done by the compressor was calculated [35,52,53,57,68,112].

$$W_{comp} = m_{air}\, C_{dap}\, (t_1 - t_o) \tag{5}$$

The discharge pressure from the combustion chamber was calculated based on the pre-defined combustor pressure drop (P_{cpd})[9,52,53,68,116].

$$P_2 = P_1 - P_{cpd} \tag{6}$$

Using energy balance in the combustion chamber, the heat delivered by combustion chamber was calculated as follows[35,52,53,57,68,112].

$$q_{in} = C_{flue\ gas}\, (t_2 - t_1) \tag{7}$$

The mass flow rate of the natural gas used for combustion by the gas turbine was calculated based on the calorific value of the fuel gas used[52,53,68].

$$m_f = \frac{q_{in}/_{CV_f}}{\eta_{compustor}} \tag{8}$$

The turbine discharge temperature was calculated as follows[35,49,52,53,68]

$$t_3 = t_2 - \eta_t t_1 \left[1 - \left(\frac{1}{P_2/P_a} \right)^{\frac{\gamma-1}{\gamma}} \right] \quad (9)$$

The turbine power was calculated using the following equation[35,49,52,53,57,68].

$$W_t = m_t \, C_{flue\ gas} \, (t_2 - t_3) \quad (10)$$

Where,

$$m_t = m_{air} + m_f \quad (11)$$

net power obtained from the gas turbine is given by [11,49,52,53,68,116].

$$W_{net} = W_t - W_{comp} \quad (12)$$

The specific fuel consumption was determined by [17,49,52,53,68,117].

$$T_{sfc} = \frac{3600\, m_f}{W_{net}} \quad (13)$$

The thermal efficiency of the gas turbine was determined by the following equation [52,53,55,57,68,116].

$$\eta_{TH} = \frac{W_{net}}{m_f CV_f} \quad (14)$$

7.2 Results

(i) Cooling effect

The reduction in temperature induced by the cooling system is portrayed in figure 5 and 6. Considering the monthly average temperatures (figure 5), it is clear that the wet bult temperature (Twb) of the region is above the ISO rating of 15⁰C. Thus, using the evaporative cooling system (both media and high-pressure fogging system) the temperature cannot be bought below Twb on normal conditions during the summer months (June to August). As a result, power loss from the manufacturer rating cannot be avoided. The GTPG has to be operated with an air inlet temperature in the range between 22.5 to 27.35⁰C. Thus, based on the finding of Al-Ansary et al.[21] operating GTPG will be associated with a power output loss in the range between 4.8-7.9% with the cooling system in use. Taking into consideration the average temperature variations in a day (figure 6) it was found that the GTPG can deliver the rated power (for a duration 9-12 hours) during the nights and early hours of the morning.

The present study temperature drops were calculated assuming the effectiveness of cooling system as 90%, while Barakat et al.[17] reported 5% higher and Hamedani et al.[94] 10% lesser effectiveness than what was assumed in the present study. The finding of the present study, that evaporative cooling system while operating in high temperature conditions not able to lower the temperature below Twb and thus unable to attain the ISO rated temperature was supported by the findings of Marzouk and Hanafi[118] in a study conducted in south-eastern Egypt, Zeitoun[38] in Riyadh, Sh.Alnasur and Al-Furaiji[119] in Baghdad and Dinc et al.[120] in Kuwait.

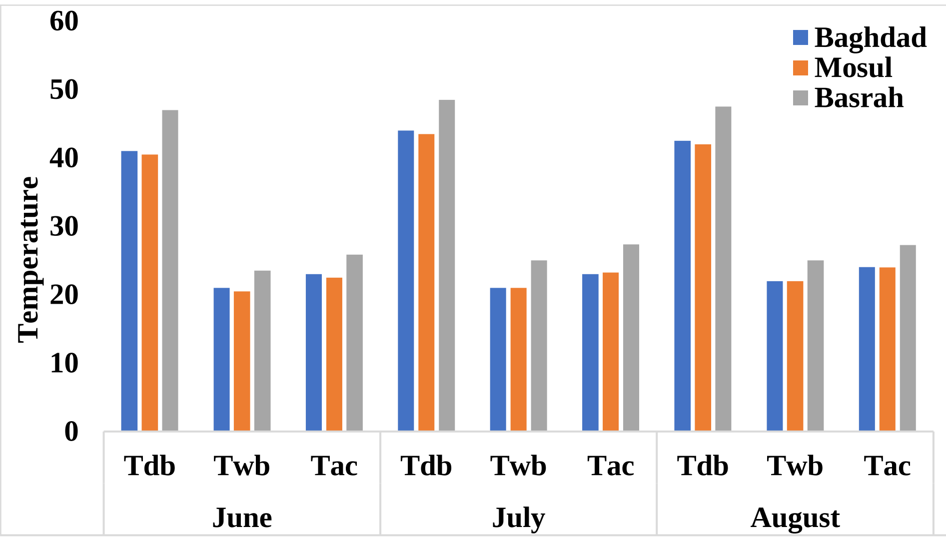


Figure 5. Dry bulb (Tdb), wet bulb (Twb) and the temperature after cooling (Tac) of monthly average temperatures

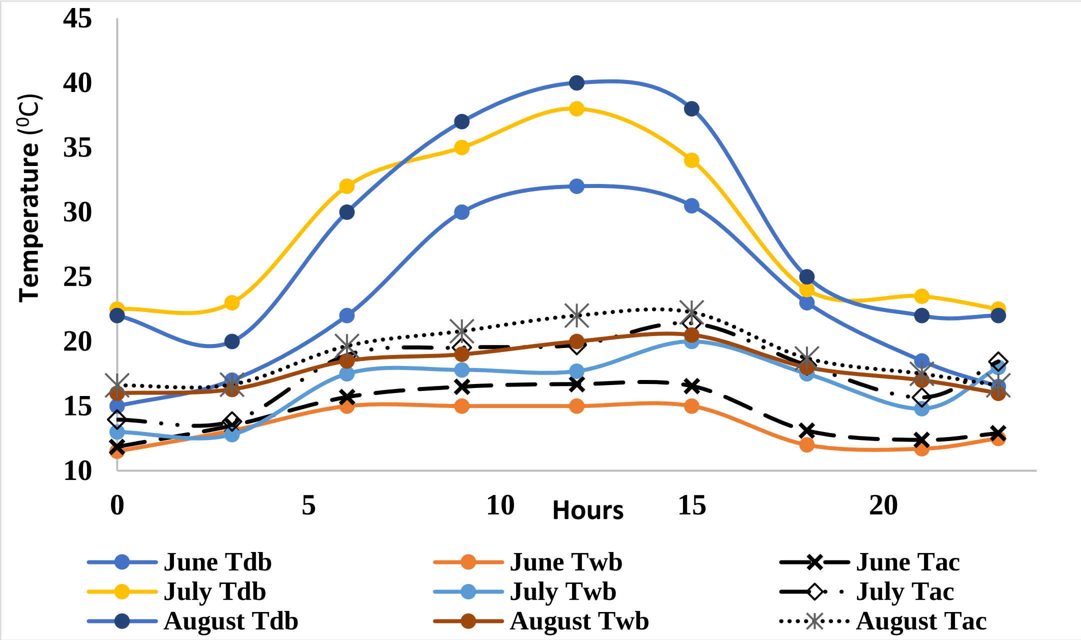


Figure 6. Dry bulb (Tdb), wet bulb (Twb) and the temperature after cooling (Tac) of average temperatures during a day

(ii) Performance of GTPG

The change in output power of the GTPG with and without reduction in temperature induced by the cooling system is detailed in figure 7 and 8. Taking into consideration the monthly average temperatures (figure 7), the power loss in the GTPG without cooling ranged between 35 to 46 % and with cooling a power gain of 7.12% was observed. While based on the temperature changes in a day, it was found that the maximum losses accrued during the mid-day hours. The losses ranged between 20 to 32% without cooling, which was reduced to 4.6 to 7.9% by employing the cooling system. Considering the losses month wise, it was found that the losses were higher during July and August than June. The change in thermal efficiency and specific fuel consumption of the GTPG with respect to its operation at ISO rated parameters is given in figure 9. It is clear from the figure that as the temperature increases there is a considerable decrease in thermal efficiency and increase in the specific fuel consumption. It was also found that cooling the inlet air temperature bought great improvements on both thermal efficiency and specific fuel consumption.

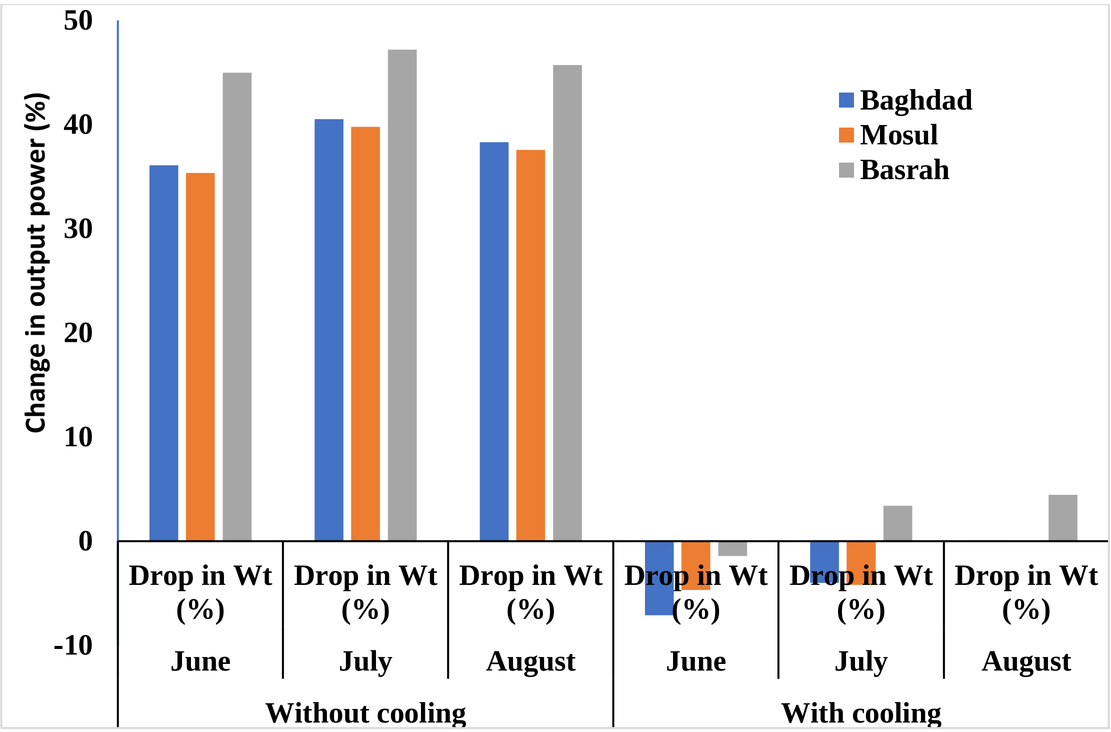


Figure 7. Change in output power for monthly average temperatures

While operating GTPG in hot climatic conditions Punwani [121] experienced 30% reduction in output power and 5% in thermal efficiency. Karakas et al[82] reported that there will be 10% reduction in output power for every 100C increase ambient temperature. Chacartegui et al. [122] experienced 7% output power reduction while operating the GTPG at 250C, which further increased to 15% when the temperature increased to 360C. Hamedani et al.[94] experienced 12.5% reduction in power output and 2% reduction in thermal efficiency and Marzouk and Hanafi[118] experienced 20% reduction in power output and 2% reduction in thermal efficiency while operating their respective GTPG at 400C. While the study conducted by Dinc et al.[120] resulted in reduction of power output by 21.3%, thermal efficiency by 3.6% and increased SFC by 9.31% while operating the GTPG at 550C. The results of these studies support the power reduction outcomes of the present study. With regard to the improvements in power output as the result of cooling the incoming air, Oyedepo and Kilanko[53] using evaporative cooler obtained 5-10% and 2-5% and Marzouk and Hanafi[118] 6.84% and 2% enhancement is power output and thermal efficiency respectively.

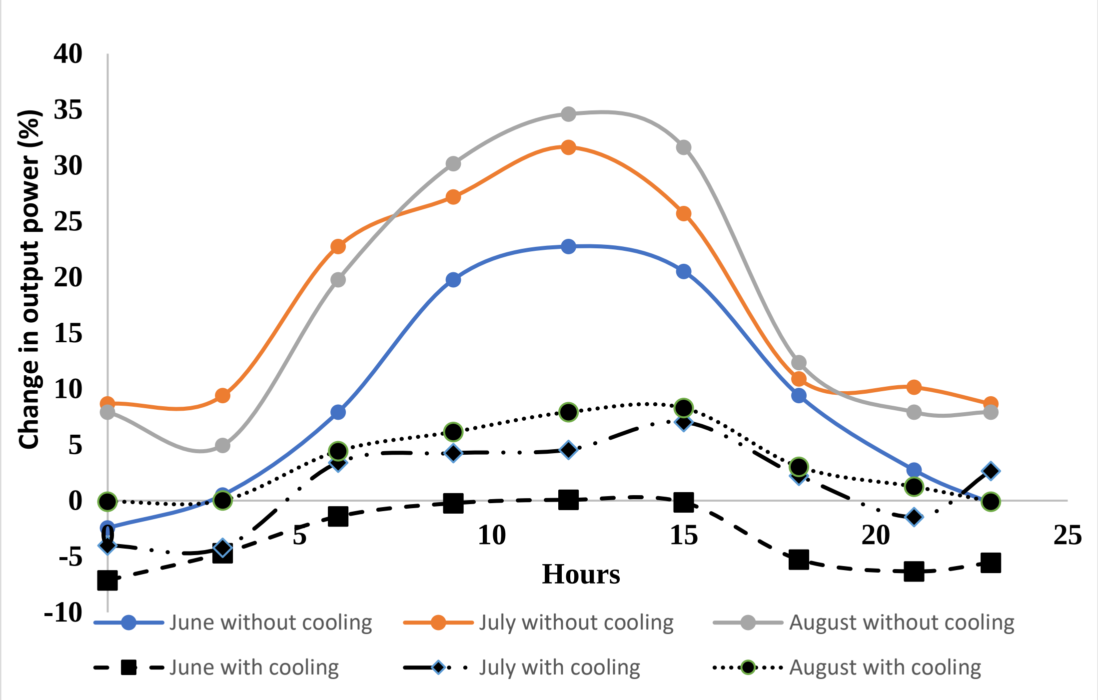
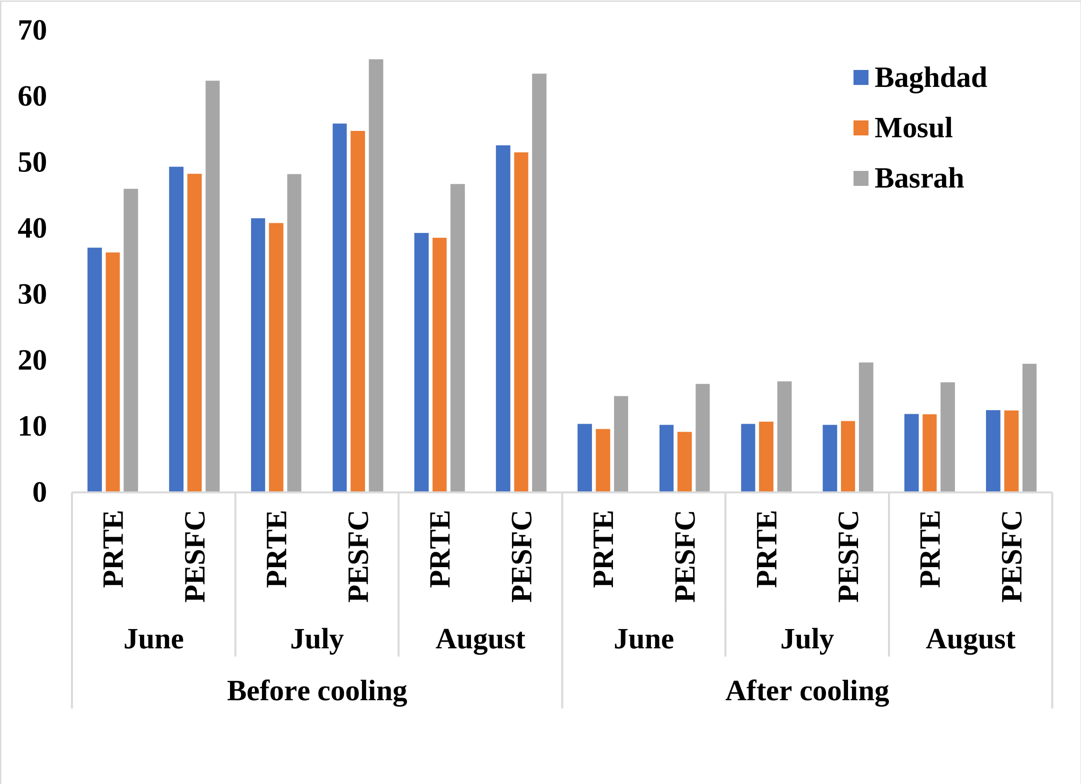


Figure 8. Change in output power for average temperatures during a day



Percentage reduction in Thermal efficiency (PRTE), Percentage excess specific fuel consumption (PESFC)
Figure 9. Change in thermal efficiency and specific fuel consumption for monthly average temperatures

8 CONCLUSION

The following conclusions were derived from the present study.

- Taking into consideration the climatic conditions prevailing in the Middle Eastern region, evaporative cooling system (either media or high-pressure fogging) was found to be more suitable method as it has twin benefits of both reducing the temperature and increasing the relative humidity.
- As the area experiences frequent sand storms air filtration is essential for both effective functioning and longer life of the GTPG.
- Installing the GTPG near the coastline areas is not advisable as high humidity of the coastline areas in association with the temperature drops during the nights will result in hard pasted layer of dust adhering on to the filter, thereby affecting its performance, useful life and increased maintenance.
- Evaluating the performance of the cooling system, due to the limitations offered by the wet bulb temperature, it was found that the ISO rated temperature cannot be attained for ambient temperatures above 230C. Thus, power loss cannot be avoided but can only be reduced during the day time. As the nights and the early morning hours of the day are generally associated with lower temperatures, rated output power from the GTPG can be obtained for about 9–12-hour duration in a day. Adopting the cooling system, a power gain of 7.12% can be obtained while considering of what is obtained without cooling.

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10 NOMENCLATURE

t_i	Temperature of air coming into the cooling unit, K
t_o	Temperature of air coming out of the cooling unit, K
t_{wb}	wet bulb temperature of the inlet air, K
t_1	Temperature of air coming out of the compressor, K
t_2	Temperature of air entering the turbine, K
t_3	Turbine discharge temperature, K
P_a	Ambient air pressure, Pa

P_i	Pressure of the air entering the compressor, Pa
P_1	Pressure of the air leaving out of the compressor, Pa
P_2	Discharge pressure from the combustion chamber, Pa
r	Compression ratio of the compressor
P_{cpd}	Combustor pressure drop, Pa
m_{air}	Mass flow rate of air, $kJ \cdot kg^{-1}$
m_f	Mass flow rate of fuel gas, $kJ \cdot kg^{-1}$
m_t	Total mass flow rate $kJ \cdot kg^{-1}$
C_{dap}	Specific heat of dry air at constant pressure, $kJ \cdot kg^{-1}$
$C_{flue\ gas}$	Specific heat of flue gas $kJ \cdot kg^{-1}$
γ	Specific heat ratio
CV_f	Calorific value of fuel gas, kJ/kg
q_{cl}	Cooling load on the cooling unit, $kJ \cdot kg^{-1}$
q_{in}	Heat delivered by combustion chamber, kJ/s
W_{comp}	Work done by the compressor $kJ \cdot kg^{-1}$
η_c	Effectiveness of the cooling system, %
η_{comp}	Isentropic efficiency of compressor, %
$\eta_{combustor}$	Combustion chamber efficiency, %
η_t	Turbine isentropic efficiency, %
η_{TH}	Thermal efficiency of turbine, %
W_t	Turbine power, MW
W_{net}	Net power from the turbine, MW
T_{sfc}	Turbine specific fuel consumption $kJ \cdot kg^{-1}$

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