Enhancement of Marib Gas Turbine Power Station Using Air Cooling Fogging System

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Abstract

Energy crises is one of the major causes for the economic decline in Yemen since large portion of the invested capital is spent on standalone small-scale low efficiency electrical generators. This goes not only for the industrial sector, but also for the simple citizens to provide some of their basic electrical requirements. The establishment of Marib gas turbine (GT) station as the first gas turbine based plant in Yemen in 2009 has slightly reduced the gap between power requirement and consumption. Marib power plant consists of three GT units of 163 MWe nominal net output per unit with additional 400 MWe in the second phase of the project. However, its high potential is wasted by using the simple GT cycle without any enhancement method such as combined or even recuperative cycles. Additional to the high altitude of its location that dropped significantly its efficiency down to 29 %. Thus, around 71 % of the fuel thermal power is discharged to the ambient as a waste. This study investigates one of the enhancement methods for Marib GT plant without any major modification on the current configuration of the station. The study showed that the rise in ambient temperature in summer could cause a power output degradation up to 0.6 % per 1°C. Thus, the addition of fogging inlet air cooling system was found to be one of the simplest and economical solutions. A mathematical model is developed to determine the impact of ambient conditions (i.e. temperature and humidity), on turbine performance. The developed mathematical model is verified with on-site operation data from Marib power plant. The results showed that Marib gas turbine power plants have excellent potential for fog operation with Evaporative Cooling Potential of 11.5 - 24 ºC. The results also showed a significant enhancement in turbine performance after using the fogging system with additional output power boost up to 30 MWe.

Keywords: Gas turbine enhancement, Fogging cooling system, Marib power station, Central power generation.

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1. Introduction

Electricity sector in Yemen until recently was relaying on diesel generators for total coverage of base-load requirement for many major cities. Steam power plants in Ra'as Katib (150 MWe), Mokha (160 MWe) and Al-Hiswah in Aden (166 MWe), all covered a limited grid that was not enough to support a national scale grid with a stable base-load supply. Moreover, the fast growth of population especially major cities demanded more reliable base load generation technology such as gas turbine power plants. Currently, the estimated electrical demand is about 2GWe, and the actual production is less than 1 GWe [1]. Thus, putting the operational central and distributed generation plants in a continuous overload status, with a regular blackouts in most of the cities. Marib power station was established in 2009 based on simple gas turbine cycle with 3 units of 163 MWe each and a plan to add more units in the future.

Gas turbine technology presents the highest power density among conventional power generation technologies with lowest space requirement. Other advantages is the relatively lower cost and can be quickly put into commission. However, main drawback is the low thermal efficiency for the simple cycle in the range of 22-35 %. Therefore, so many technologies have been investigated to enhance cycle efficiency. Some of the techniques used to enhance gas turbine system efficiency are turbine inlet temperature elevation, waste heat recovery (regeneration and combined cycles), reducing air inlet temperature, re-heating, and multiple compressors with intercooling and water or steam injection [2]. Adding water or steam to the gas turbine working fluid is one of the low cost, performance augmentation solutions, and it was widely studied since it does not require a major modification on the system. The benefits of water or steam addition, also known as the humidified gas turbine, vary for the different applications based on the addition purpose for each application. Different humidified gas turbine technologies have been reviewed by [3]. Three main techniques can be implemented for water injection:

1.1 Water spray before the compressor and also between compressor stages

This technique is mainly to enhance the compressor performance by dropping air temperature.

1.2 Water injection after the compressor

In case of recuperated gas turbine, injecting water increases the mass flow through the recuperator, thus, increasing the heat recovery rate from the turbine exhaust.

1.3 Water injection at the combustion chamber

This technique is used to control TIT and NOx emissions since water observes more thermal power from the combustor for evaporation compared to steam injection. In second and third techniques, mass flow through the turbine is increased by water injection, resulting in more turbine power with low power consumed in water external compression. Whereas in first technique, gas turbine compressor is used to compress water vapor resulting in more compression power consumption. However, water injection after the compressor require a modification on the engine by adding more volume to allow water to evaporate [4]. Steam injection is an old technology and it was implemented in the 1960's for NOx emissions control [5]. Nonetheless, the noticeable enhancement in gas turbine efficiency and output power has led to use this technology in the small and medium industrial combined cycle plants. Since in these systems, HRSG efficiency drops at partial load operation. Thus, the steam generated by HRSG can be injected to the gas turbine to maintain its maximum efficiency [3]. The use of steam injection in biomass fueled EFGT was also proposed by [6]. The evaporative gas turbine (EvGT), also known as humid air turbine (HAT) has a humidification tower that is the key component in the cycle. Heat and mass transfer occurs between the pressurized air that passes through the tower and a circulated hot water resulting in a saturated heated humid air out of the tower. A pilot EvGT plant was developed in the Lund Institute of Technology [7].

Studies showed that fogging air cooling can provide better economical value compared to the conventional compression system, studied [8, 9, 10]. Many recent studies covered the technical aspects [11, 12] and techno-economical aspects [13, 14] of the fogging air cooling technology for gas turbine applications.

2. Marib power plant description

The power plant is located at Safer, 60 km East of Marib town which is about 200 km East of the capital Sana'a. The plant is located at 1100 m above mean sea level. The site of the station is only 3 km away from the existing well- heads of the gas field of the Safer Company. The Siemens Power Group is the main contractor and has handled the overall project management. Marib gas turbine power station consists of three Siemens gas turbine generating units that operate in open cycle, V94.2 Siemens model with 300 MW ±20 % total turbine power at design condition and net electrical output power of 163 MWe. Space provision has been kept for the addition of seven gas turbines in future and subsequent conversion to combined cycle plant by addition of heat recovery steam generators and steam turbine generators. Each gas turbine unit is designed to fire both gas and liquid fuel systems and equipment has been designed in accordance with the applicable codes, standards and regulations. Main fuel for the gas turbines is natural gas (NG), supplied through a gas pipeline from the gas field of the Safer Company. The pressure inside the pipeline is 60 bar, the gas pressure is reduced by valve regulation until 20 bar which is the suited pressure for the combustion. Distillate oil is maintained as backup fuel supplied by road tankers. The power plant consists of: air intake system (filters and silencer); 16 stage axial-flow compressor with variable-pitch inlet guide vanes; two walk-in combustion chambers for hot gas-path inspection with hybrid burners for premix and diffusion mode operation with natural gas, fuel oil; four stage turbine; and exhaust system (ducting and 30.6 m height stack). All blades are removable with rotor in place .Combustion chambers are lined with individually replaceable ceramic tiles .Optional fast inlet guide vanes for peak load operation and frequency stabilization. A schematic drawing of the turbine components is shown in Fig (1).

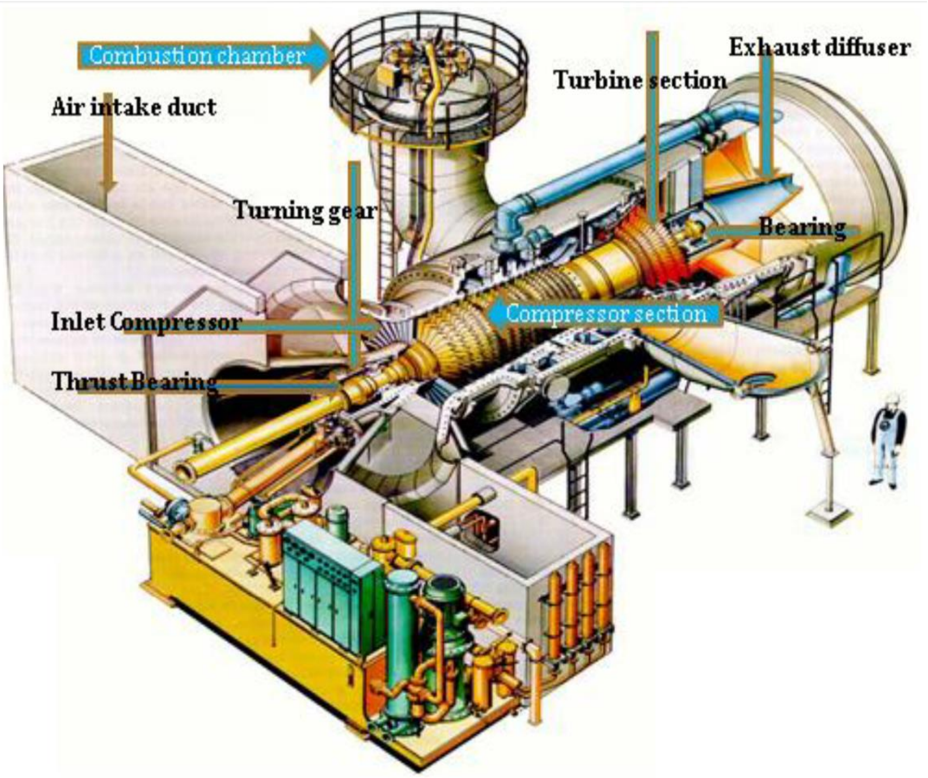

Figure (1): Gas turbine SGT-2000E series

Table[1] summarizes the actual operation parameters as taken from the site compared to the design parameters of the gas turbine units in Marib power plant. It can be clearly notices from the on-site date the dramatic power de-rating compared to the design conditions. This is mainly due to the high altitude of the site (1100 m above sea level) and the hot desert climate conditions.

Table(1): Gas turbine design and actual operation parameters.

Variable	Design conditions*	Actual conditions (summer)
Grid frequency [HZ]	50	50
Power output [MW]	163	113
Efficiency [%]	34.7	29.6
Pressure ratio	11	11
Air mass flow [kg/s]	500	455
Exhaust temperature [°C]	541	415
Exhaust mass flow [kg/s]	509	464

*** Gross values, standard design, ISO conditions, natural gas fuel [15].**

3. Fogging system design

The main objective of cooling the input air to the turbine system is to increase air density, thus, overcoming the volumetric limitation of the compressor and increasing air mass flow rate. Moreover, reducing air temperature reduces entropy and helps in enhancing the thermodynamic cycle efficiency. Conventional refrigeration compression or absorption systems has a good control with extreme low air temperature however, it can be used for small scales such as in micro gas turbines. Some of the downsides for such systems is the high operation and maintenance cost. For larger scale gas turbines, conventional cooling can also be used indirectly with cooled water chillers. However, high initial, operation and maintenance cost make such systems less attractive compared to water evaporative systems especially for large-scale systems with tremendous air flow rates. For the dry desert condition in Marib city with dry/wet bulb temperatures of 41/27 °C, water evaporative based cooling systems are preferred since they drop air temperature close to wet bulb temperature with very low operation required power. Moreover, additional water mass is added to the flow resulting in more system power output. Using humidification tower to increase air humidity in the range of 85 %-95 % is one of the earliest attempts. Fogging system is another approach for gas turbine air cooling that shares similar methodology but provides higher humidity/water mass content, and yet at much lower initial and operation expenses.

Water is atomized via high-pressure water injectors to form water droplets in micron size, thus, providing extreme evaporation surface area for instant evaporation. Dry air condition (i.e. low relative humidity) provides very low water vapor partial pressure resulting in an instant water vaporization. The increment in water content elevates partial pressure of water vapor until it exceeds the evaporation limit in a point known as air saturation. Additional water droplets after the air saturation remains floating in the form of mist or fog. Absolute humidity ratio (ω) in the form of kg water/ kg dry air is calculated using Eq. (1):

$$\omega = 0.622\, P_v / P - P_v \qquad (1)$$

Sometimes, poor water atomization and distribution results in fog forming even without reaching air saturation duo to poor water/air mixing and large water droplet size. This known as the evaporation effectiveness (ε) and with high effectiveness ($\varepsilon = 1$), air temperature can be dropped down to the wet bulb temperature as illustrated in Eq. (2):

$$T_{out} = T_{air} - \left(T_{air} - T_{wb}\right) X\, \varepsilon \qquad (2)$$

Thermal power absorbed by the air stream is consumed in the form of water latent heat of evaporation. Water mass flow rate is calculated using Eq. (3):

$$\dot{m}_w = \dot{m}_a\left(\omega_2 - \omega_1\right) \qquad (3)$$

Based on actual onsite readings, ambient conditions change in Marib in summer significantly throughout the day. In Marib city area, ambient temperature goes above 40 °C in summer. Figure 2 illustrates a sample of temperature and humidity profile in Marib area in summer. A significant increment in temperature that can reach up to 17 degrees difference. The high temperature level above 35 °C extends for more than 10 hours through the day, and hence it affects directly air density that in turn is directly proportional to air mass flow rate drawn by the compressor.

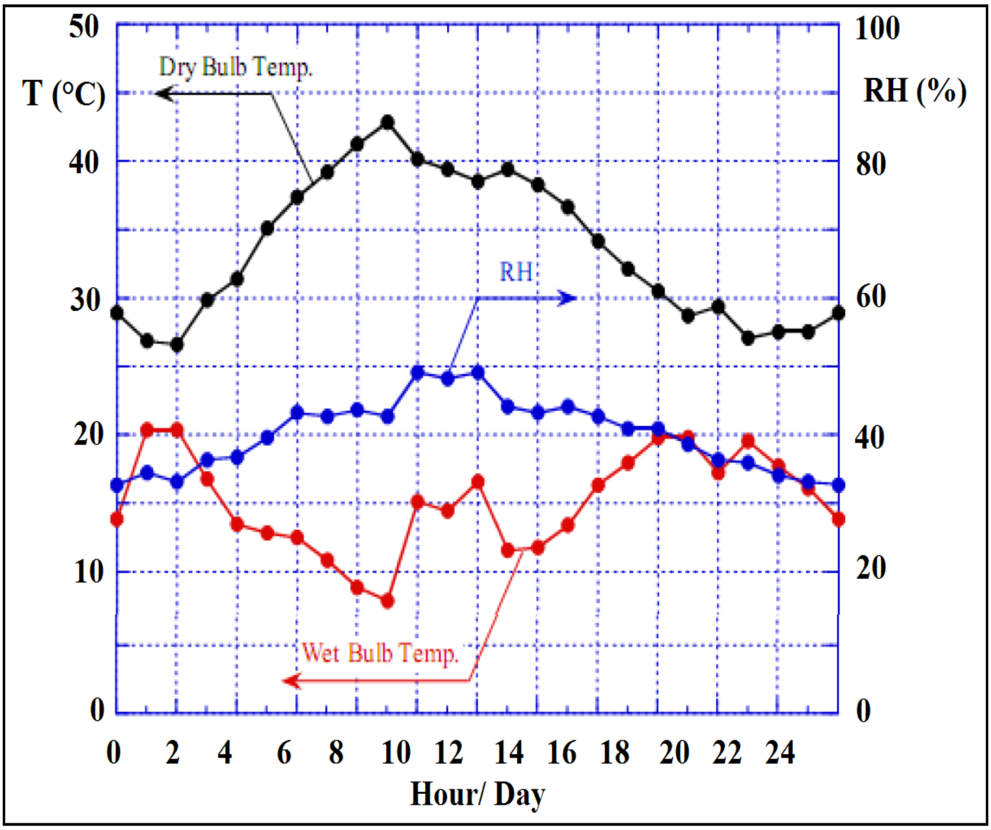

Figure (2): Temperature and humidification profiles in Marib area in summer

Figure (3): shows that ambient temperature is almost linearly proportional to air density resulting in about 0.06 kg/m^3 density drop through the day. Consequently, air mass flow rate through the compressor drops from about 480 kg/s down to 455 kg/s merely by the density drop effect since the volumetric flow remains constant at constant compressor rotating speed.

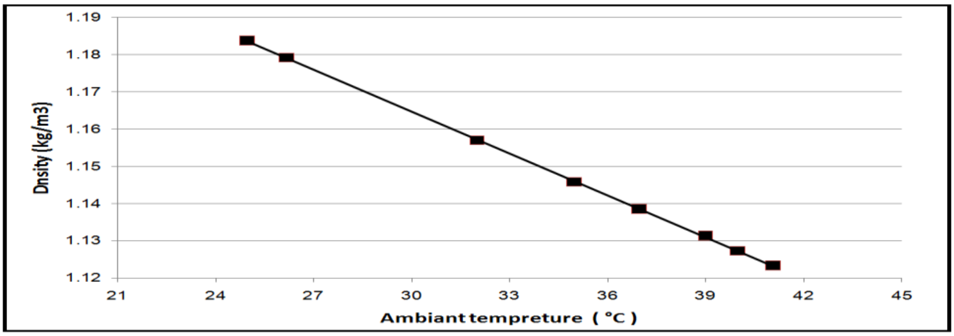

Figure (3): Effect of ambient temperature on air density

In order to calculate absolute humidity ratio before and after the process, psychrometric chart is used. Figure 4 illustrates a sample calculation on the psychrometric chart for 40 °C air temperature and a drop in air temperature after the process down to around 27 °C.

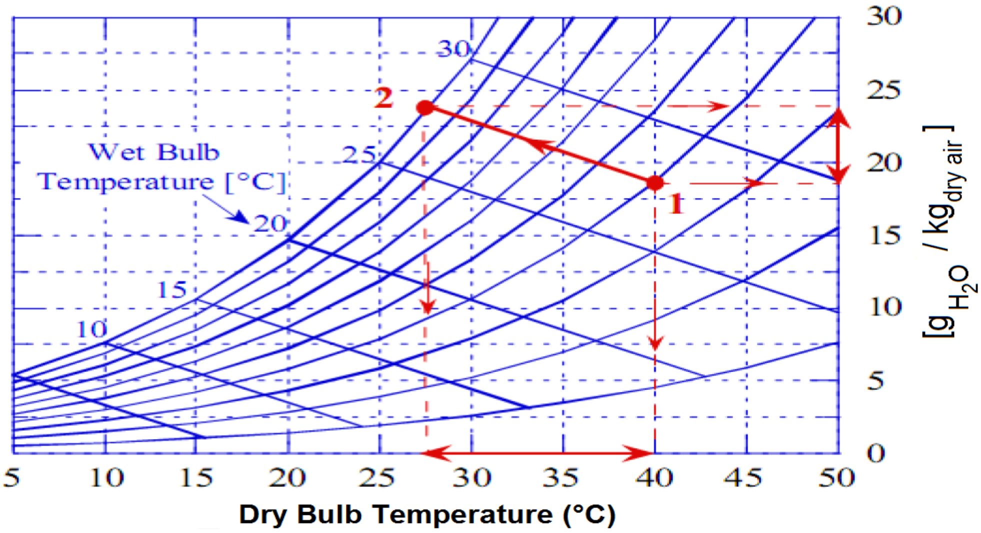

Figure (4): Air humidification process on Psychrometric chart

A water treatment is required to provide the required water quality. Table 2 indicates water specification and quality requirement to be suitable for fogging system for gas turbine applications.

Table (2): Water specification and quality requirement.

Water quality indicator	Value
Water pH	6.5—7.5
Total solids [dissolved and undissolved]	5 ppm
Total Alkali metal and other metals that promote hot corrosion	0.5 ppm
Conductivity	0.5—1 ohm/cm

The treated or demineralized water is pressurized in the range of 70-200 bar and injected through hundreds of spraying nozzles arranged inside the air inlet ducting as shown in Fig.[5].

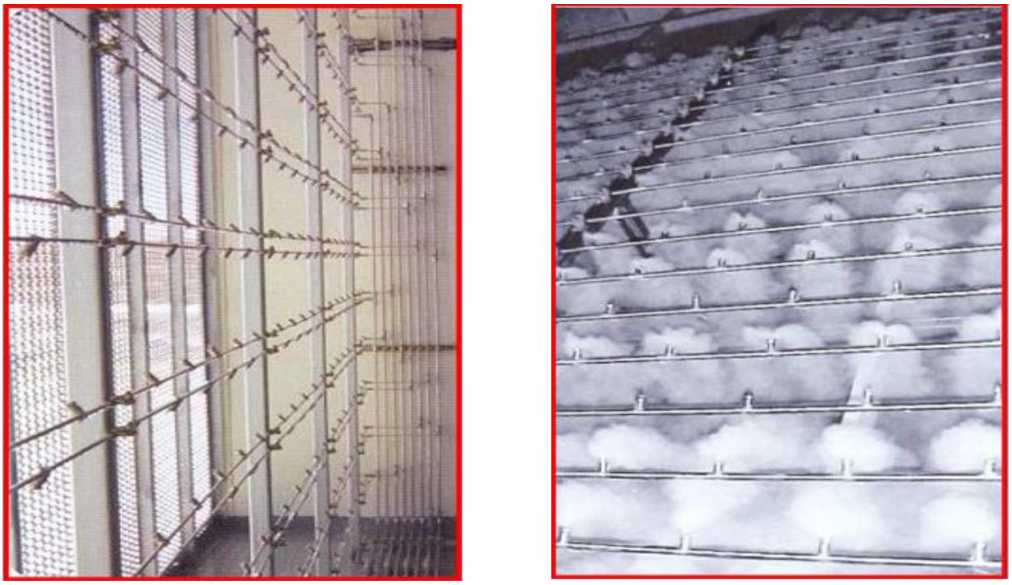

Figure (5): Air humidification process on Psychrometric chart

There are two types of water spray nozzles commonly employed in the industry. First type is the swirl jet nozzle (shown in Fig. 6) where pressurized water is forced to enter tangentially into the swirl chamber before discharging through a cylindrical hole concentric to the swirl chamber. The discharging water is in the form of an axisymmetric thin conical sheet that forms ligaments and small droplets. Second type is the impaction pin nozzle shown in Fig. 6 where pressurized water is forced through a smooth orifice and hits an impact pin, located above, with high velocity. This results in the formation of a thin sheet of water in a conical shape as the water leaves the orifice. The water sheet becomes unstable and disintegrates into small thread ligaments and subsequently into billions of small size droplets. Experimental comparison between the two types and the study showed that the impaction pin nozzle generates a significantly smaller droplets even with higher flow rates compared to swirl jet nozzles [16].

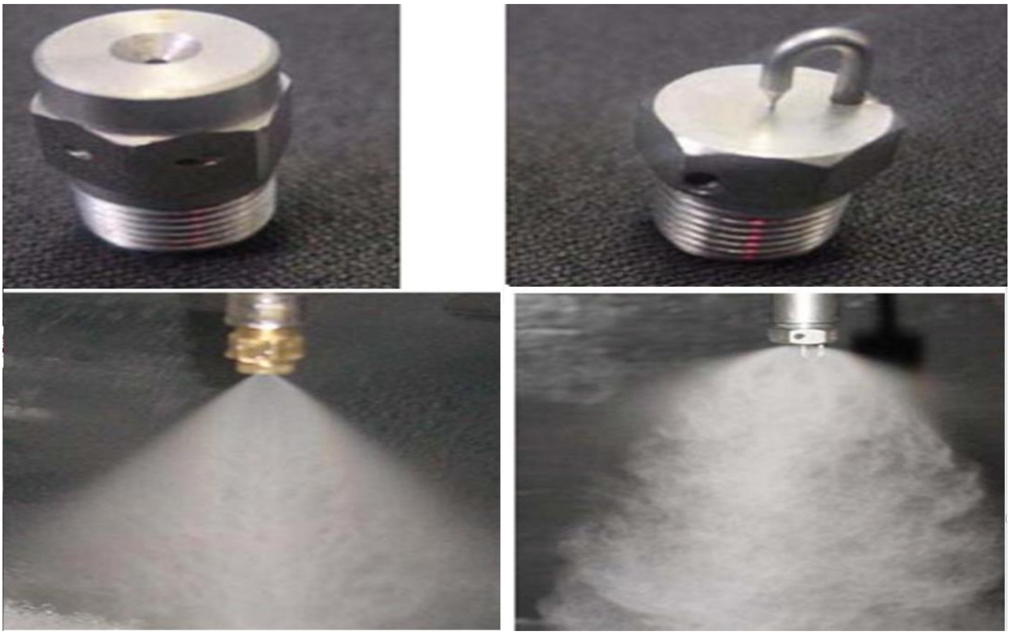

Figure (6): Swirl jet nozzle (left) and impaction pin nozzle (right)

A practical value of water spray effectiveness of 95 % was considered for the design. Water treatment and pumping depends on the required mass flow rate of water that in turn depends on cooling requirement and ambient temperature. With air flow rate of about 500 kg/s, calculation shows that system power requirement (parasitic load) at maximum ambient temperature of 41 °C is about 257 kW with water flow rate of 4.7 kg/s. Figure 7 illustrates the required water mass flow rate and parasitic load of for different ambient temperatures through one day of operation.

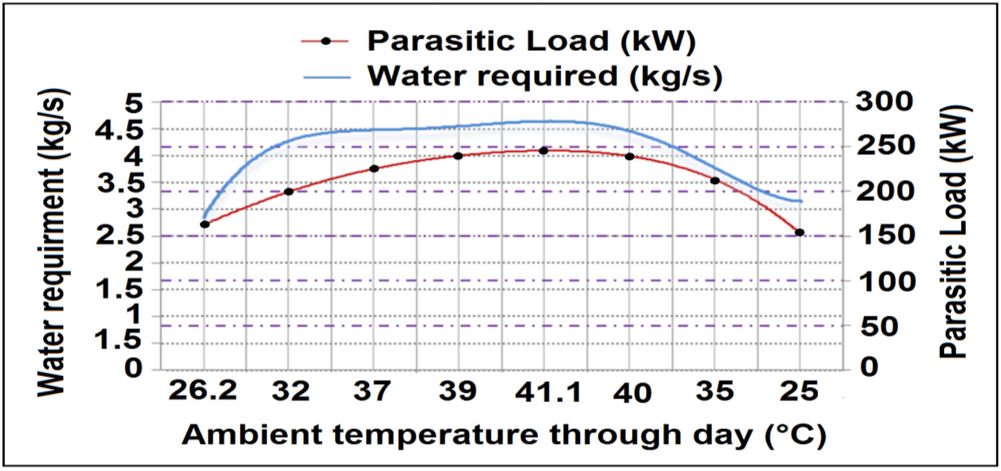

Figure (7): Fogging system load and water flow requirement through one day of operation

4. Air cooling effect on Marib power plant performance

In order to obtain an acceptable evaluation fogging system on Marib power plant performance, a mathematical model was developed. The model was verified first using actual online operation data obtained from the power plant and comparing it to the model results before adding fogging system.

Brayton cycle with air cooling (1-2-3-4) and simple cycle (1'-2'-3'-4') is illustrated in Fig. 8. Cooling air shifts air inlet point from 1' to 1 reducing entropy of air. It can be noticed that the energy required for compression (1-2) is slightly higher than simple cycle compression (1'-2') due to the additional water mass. However, the generated energy from turbine (3-4) is higher as well compared to (3'-4') and the net cycle energy (graph area 1-2-3-4-1) increases noticeably by the cooling process.

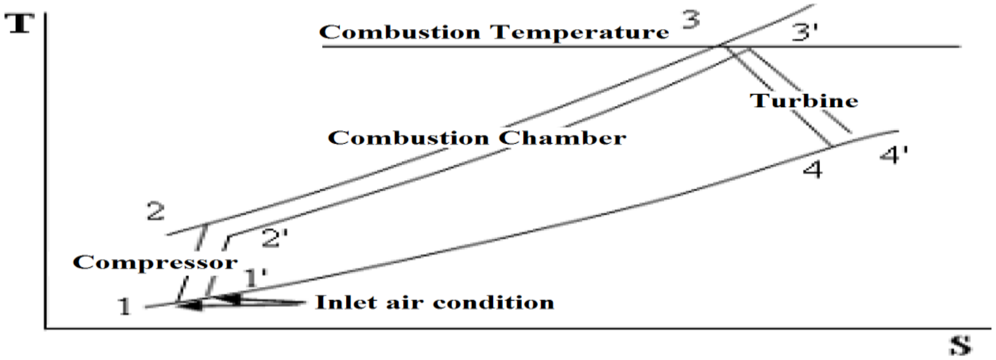

Figure (8): T-S diagram of cooled air and simple Brayton cycle

Real time recorded data from Marib power station showed a significant power drop in summer due to the increment in ambient temperature. And even through the day with desert climes, temperature fluctuates between 25 °C in early morning up to 41 °C in the afternoon time resulting in a significant net output power drop from 130 MW down to 113 MW. Adding the fogging system resulted in a significant net output power ranging from 143 MW up to 149 MW as shown in Fig. 9. Therefore, net output power gain by adding fogging air cooling system is in the range of 19 to 30 MW during the day with a negligible power consumption to run the system (150-257 kW).

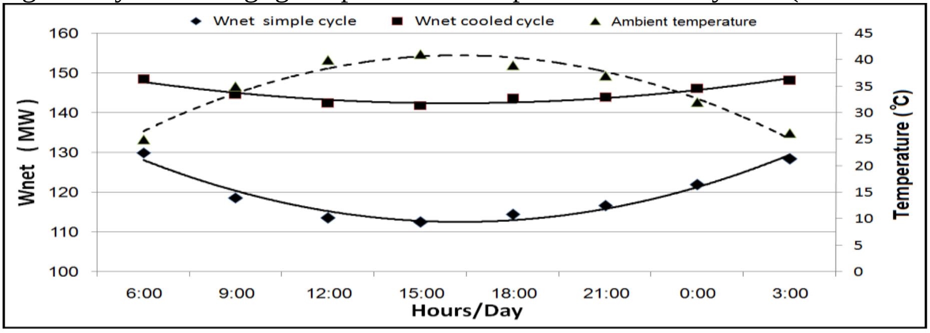

Figure (9): Net output power before and after adding the fogging air cooling system

A significant increment in thermal efficiency from 29.6 % to32.1 % (at lowest point) can be achieved by adding the fogging air cooling system as shown in Fig. 10. Similarly, natural gas fuel consumption dropped significantly after using the fogging air cooling from 0.25 to 0.23 kg/kWh (at highest point) as shown in Fig. 11. For better understanding of the amount of fuel saving per day (calculated for summer), the amount of annual fuel cost savings was found to be around 462 USD /day.

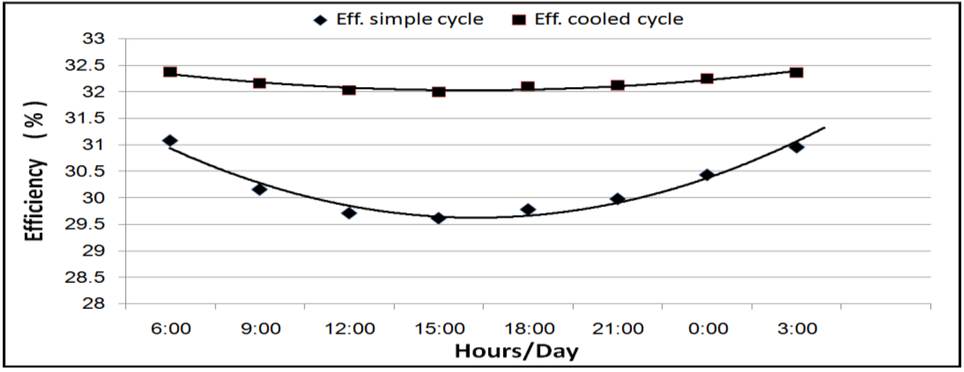

Figure (10): Power plant thermal efficiency before and after adding the fogging air cooling system

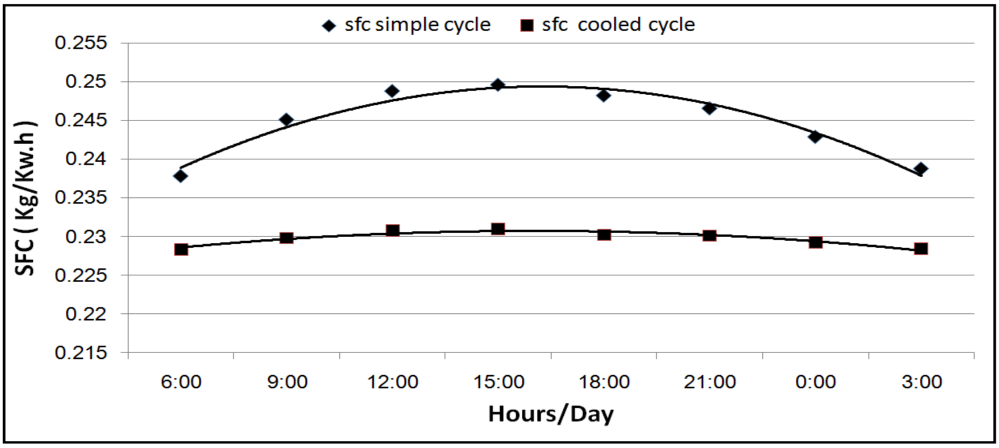

Figure (11): Specific fuel consumption before and after adding the fogging air cooling system

5. Conclusions

The significant power output de-rating due to the high altitude of the station and the elevation in ambient temperature in summer drops the power from nominal value of 163 MWe down to 113 MWe actual value. Therefore, this study investigated the means of power enhancement of the station without going through any modifications on the units on site. Air inlet cooling by using fogging system was found to be one of the most attainable and low cost approaches to enhance the performance of the gas turbine power station. A mathematical model was developed to calculate the performance parameters of Marib gas turbine, and model parameters were verified based on real time operation data of the gas turbine units in power station. The system consists of water treatment unit, water pumps and a net of water spray injectors to be installed inside air inlet ducting. Power consumption of the unit ranges from 150-257 kWe which is negligible compared to the net power gained of 19 to 30 MWe during the day. This approach can elevate the simple cycle gas turbine efficiency from 29.6 % to 32.1 %, with natural gas fuel cost savings of about 462 USD per day.

6. Acknowledgment

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