Enhancing gas turbine plant performance in hot climates through fogging technique

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ABSTRACT- Temperature of the gas turbine inlet-air has a significant effect on power output and hence its efficiency. At high ambient temperatures, there is a significant loss in air mass flow rate, and hence leads to reduce the gas turbine produced power. In the present work, the effect of lowering the compressor intake-air temperature by means of a fogging evaporative cooling on the performance of gas turbine is studied numerically. Water is atomized through compressor intake to perform evaporative cooling. The effect of air inlet temperature and relative humidity, air and water mass flow rate, water droplet injection speed and water droplet diameters are studied. Unlike previous work, the effect of cooling the spray water injected droplet is studied. The results show that air to water thermal condition and water droplet size play an impotent role in evaporative cooling processes. Cooling inlet air temperature may increase in the turbine output power by approximately 1to 8.1%. Finally, a good agreement between numerical and experimental case study is obtained.

Index Terms— gas turbine, inlet air cooling, fogging systems, gas turbine efficiency improvement.

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Nomenclature

O/p	Output Power (MW)
ȣ	Specific Heat Ratio
Mg	Mass flow rate of gas(kg)
Ti	Inlet temperature of compressor(°C)
Mi	Mass flow rate of air(kg)
Te	Inlet temperature of turbine(°C)
Mf	Mass flow rate of fuel(kg)
Hf	calorific value (c.v.)(kJ/kg)
Cp	Specific heat at constant pressure (KJ/kg.K)
Tw	Temperature of water (°C)
η_t	Efficiency of turbine
φ	Humidity (%)
η_c	Efficiency of compressor
R	Compression Ratio
η_{cc}	Efficiency of combustion chamber
η_g	Efficiency of generator
η_m	Efficiency of Mechanical
M_a	mass flow rate of air (kg/s)
M_w	mass flow rate of water (kg/s)

1 Introduction

Gas turbines have been successfully used for electricity generation, operating airplanes and for various industrial applications. Various means have been employed to improve the power product of the gas turbine and then its efficiency. One of the means is cooling of the compressor intake air where the power generated by the gas turbines fluctuates depending on environmental conditions. The increase of ambient temperature becomes a key problem especially coincide with periods of high electricity demand often occur during the middle of the day and summer season.

As ambient temperature increased by 1 K above ISO condition, the power and efficiency of gas turbine plant was decreased by 0.1% and 1.47 MW respectively [1]. Sue and Chuang [2] reported that the location of the power station played an important role on its performance when ambient temperature increases the total power output decreases. During the summer, 24% decrease in system capacity due to ambient air temperatures up to 50 °C [3]. Chakartegu et al [4] reported that when the intake temperature increased from 15 °C to 25 °C, the loses of gas turbine was approximately 7% of its power. The losses were reaching 15% of the power rating at 36 °C ambient temperature. The electric power enhancement was 1.03 kW/°C of inlet air temperature reduction [5]. Due to rise ambient temperature by 1 K the output power and efficiency of gas cycle reduced by 0.6% and 0.18%, respectively [6]. Noroozian and Bidi [7] found that a temperature drop of 3.2% in the compressor inlet air temperature lead to 1.138% increment in both thermal efficiency and net output power in the warmest month. Basha et al [8] showed that, for 70 MWe frames, as ambient inlet air temperature deceased by 10 °F, plant net output and efficiency were increased by about 5% and 2 %, respectively for all fuels. Boonnasa et al [9] found that the capacity of the combined cycle power plant was improved, at lower intake air temperature to around 15ºC and 100% RH before entering the air compressor.

The addition of air cooling system at the compressor intake was one of the effective ways to increase the gas turbine performance [10, 3]. Different techniques, including the evaporative cooling, fogging systems, indirect mechanical refrigeration system, direct mechanical refrigeration system, and absorption chiller refrigeration system were studied [1-14]. Among various cooling techniques, the fogging system has become widely used due to its relatively lower cost and also it has an effective power augmentation [11-12].

In fogging technique, air cooling was achieved by spraying water to dry air at the compressor intake causes in an increase air density, which results in elevates air mass flow rate of air entering the compressor and so the power output and efficiency for heavy duty gas turbine are enhanced. Also, relative humidity in air at the inlet compressor is about 100% and inlet air temperature is the lowest possible temperature without refrigeration systems. The fogging system has been reported by various studies. Pinilla et al [11] studied the inlet fogging process in the compressor inlet duct using computational Fluid Dynamic (CFD) method as well as performing tests in a wind tunnel. They found that the best mass and energy transfer occurred when an atomizing diameter of 20 μm was used with the lowest relative humidity as possible. Athari et al [13] investigated combined cycle power plants using exergy and exergoeconomic analyses. They reported that for both the biomass integrated fogging combined cycle and the biomass integrated fog cooling steam injection gas turbine cycle plants, fog cooling was more economic. Also they applied exergoeconomic analysis to biomass gasification in gas turbine power cycles, with and without fogging inlet cooling. They reported that inlet cooling was an effective technique for improving the gas turbine performance during hot and humid summer periods when electrical power demands peak. Using the inlet fogging system was economical in dry and hot region [14]. Ehyaei et al [14] studied the effects of inlet fog system on the performance of combined cycle power plants. They were concluded that the average output power production increases by using of inlet fogging system, and also inlet fogging system had a reasonable effect on air pollution produced in exhaust of gas turbine power plant. The performance parameters such as compressor inlet temperature, compressor work input, gas turbine power output and cycle efficiency, with existing inlet fogging and wet compression process were investigated [15]. Ehyaei et al [16] studied a comprehensive thermodynamic modeling to investigate the effect of inlet fogging system on the combined cycle power plant performance and also to determine the optimal design parameters. They reported that an increase in the average output power by using inlet fogging system. The efficiencies were increased by 17.24%, 3.6% and 3.5%, respectively, for three warm months of year. Kim et al [17] analyzed the inlet fogging process in a gas turbine system employing heat and mass transfer models. The transient details of water droplet evaporation were computed. Dawoud et al [18] compared between the different cooling systems (evaporative cooling, fogging cooling, absorption cooling using both LiBr–H_2O and aqua-ammonia, and vapour-compression) with respect to their effectiveness in power boosting of small-size gas-turbine power plants in two locations. They found that fogging cooling was accompanied with 11.4% more electrical energy in comparison with evaporative cooling in both locations. Comodi et al [19] investigated the effect of fogging technology on the improvement of the performance of a 100 kWe micro gas turbine. The results of the experimental analysis showed that the electric power augmentation ranges between 4% and 11% referred to the machine's ISO condition output depending on the initial conditions of the ambient air humidity.

The use of fogging along with steam injection to biomass gasification in gas turbine cycle and in combined cycle using energy and exergy was analyzed by [20]. Mahto and Pal [21] applied thermodynamic and thermoeconomic analysis to simple combined cycle power plant, incorporated with GT blade cooling and compressor inlet air cooling by fogging system. The results showed that compressor inlet air cooling by fogging had increased the specific power output of all configurations. Yang et al [22] developed an analytical method to evaluate the general applicability of gas turbine inlet air cooling systems in combined power plant, including inlet air cooling with absorption chiller and fogging system. This method took into account the off-design performances of Gas Turbine Combined Cycle Inlet Air Cooling (GTCCIAC) components, annual average climatic data.

The aim of the present study is to improve the output power of gas turbine plant by using fogging evaporative cooling technique. A comprisal CFD simulation program was used to simulate the spray evaporation process. A novel study of spraying cold water droplet is studied. The effect of ambient and working; condition such as ambient temperature, relative humidity, air velocity, water velocity, water temperature, and water amount, are investigated. Middle Delta Electricity Production Company (Nubaria power plant) is used as case study to verify the numerical results.

2 System description

A schematic diagram of the system consider for this study is described in Fig. 1. First raw water with high minerals enters de-mineralized section to reduce solvents, it is very important to demineralize water because of microscopic nozzles which can be sealed by minerals. De-mineralized water is injected at high pressure through atomizing nozzles. The droplets size is very important parameter because of the fact that passing time from air filter to the compressor inlet is about 1-2 s and in this period the droplet should be evaporated so droplets diameter should be less than 50 microns. Fine droplets water is evaporated and then the mixture temperature decreases. It enters compressor intake to use as working fluid.

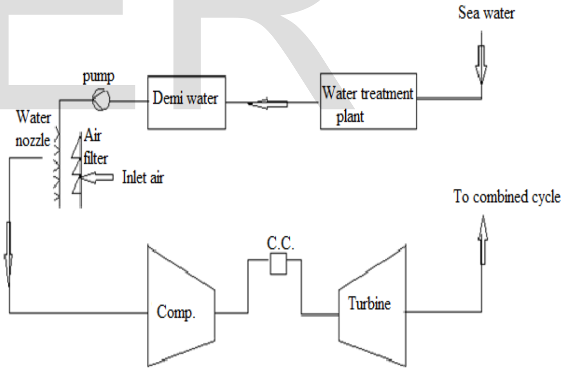

Fig. 1. Schematic diagram of inlet fogging system.

3 Numerical work

3.1 Geometry and Physical definition

As shown in Figure (2), the geometry consists of a prism of square cross section of 40 cm length and 100 cm height. The geometry was assumed as one region or domain with one inlet (hot moist air) at the top of the geometry and one outlet (to compressor intake) at the bottom. The volume mesh spacing was defined as 160 cm^3 for all the geometry. Commercial numerical software is used to simulate this problem. Euler Lagrange approach was selected in this study because it is easier to represent the droplet size, velocity and properties from its injection point to final destination. During each iteration, the mesh displacement equations are solved to the specified convergence level and the resulting displacements are applied to update the mesh coordinates. In our model we choose the RMS of residuals with target of 10^{-4} for these errors. A measure of how well the solution is converged can be obtained at the end of each time step. By the end of solution we get the output file with all variables needed.

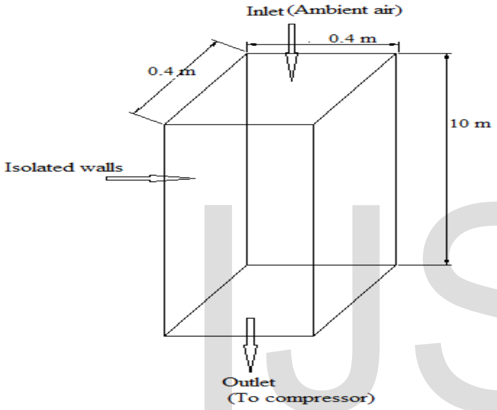

Fig. 2. Numerical work geometry

4 Calculation the Output Power of Gas Turbine Cycle

Figure (3) shows the schematic diagram of the single shaft gas turbine cycle. The compressor inlet temperature is equal to ambient temperature (Ti) in the base-case which neglects the cooling effect.

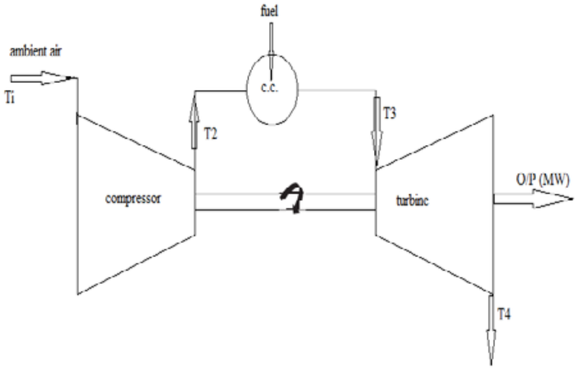

Fig.3. Schematic diagram of gas turbine cycle

$$o/p = [Mg\ cp\ \eta t\ Te\left(1-\frac{1}{R^{\left(\frac{\gamma-1}{\gamma}\right)}}\right) - Mi\ cp\ Ti\left(\frac{R^{\left(\frac{\gamma-1}{\gamma}\right)}-1}{\eta_c}\right)]\eta m \eta g \quad (1)$$

Where,

$$Te = \frac{Mf\ Hf\ \eta cc + Mi\ cp\ Ti\left(\frac{R^{\left(\frac{\gamma-1}{\gamma}\right)}-1}{\eta_c}+1\right)}{Mg\ cp} \quad (2)$$

$$Mg = Mi + Mf \quad (3)$$

$$Mi = Ma + Mw \quad (4)$$

5 Results and discussion

5.1 Validation of results obtained

For verification of the simulation code, the data from Nubaria power plant (a combined cycle with 4×250 MW Siemens gas turbine (V94.3A) and 2×250 MW GE gas turbine), an actual running gas cycle power plant in Egypt is considered for the comparison purpose. Nubaria power plant is located in a dry and relatively hot region. In this power plant the inlet fogging system is installed on unit of gas turbine which operates for hot climates. The gas turbine units (V94.3A) 250 MW, manufactured by Siemens .The turbine data are summarized in Table 1. according to ISO conditions. To assess the accuracy of the simulation, the calculated values of the output power for this power plant as well as the corresponding registered measured values for the same operating conditions are presented. The comparison shows a good agreement between the calculated and registered results.

Fig. 3 shows the comparison between the present simulated results and actual results from Nubaria power plant. The comparison is made under the same identical ambient and operating conditions. It could be noted that the average deviation between experimental and present numerical results is about 2.2% for the output power, indicating the high compatibility of the calculated and registered results. As inlet air temperature increases, the power output decreases.

TABLE 1:

Technical Specification of the Selected Gas Turbine.

Item	Adopted value
Gas turbine output, MW	250
Air inlet temperature (ISO), °C	15
Relative humidity, %	60
Ambient pressure, bar	1.009
Average air mass flow rate, kg/s	613
Fuel gas mass flow rate, kg/s	12.4
Inlet temperature to turbine, °C	1140
Natural Gas lower heating value, kJ/kg	50000
Compression ratio	14
Isentropic efficiency of compressor, %	95
Isentropic efficient of turbine, %	90
Combustion efficiency, %	95

Detailed study of the factors affecting the evaporating cooling process was made. In order to show the capabilities of this commercial program, a case study was considered. It has the following characteristics unless stated otherwise.

	theoretical			Actual
ma	Tin	Tout	MW	MW
588	37.5	30.2	235.7	230
591	31.8	31.4	238	234
595	29.5	29.2	242.5	237
613	27	26.8	255.5	249

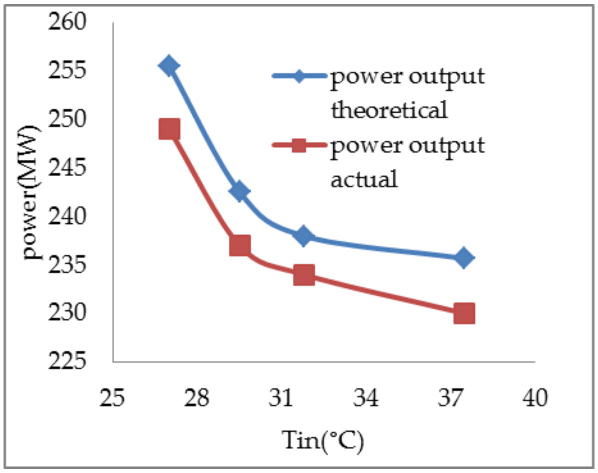

Fig.3. Comparison of power between the present theoretical results and Nubaria Power Plant (actual experimental) results.

5.2 Effect of ambient and working parameters

Detailed study of the factors affecting the evaporating cooling process was made. In order to show the capabilities of this commercial program, a case study was considered. It has the following characteristics unless stated otherwise

Fig. 4. Shows the relation between ambient air relative humidity, intake air temperature (T_{out} from the fogging system) and output power. As seen, the outlet temperature (T_{out}) increases with increasing air humidity. Also the figure shows the effect of ambient temperature on the net power output from the plant. It can be concluded that, the power output increases, as relative humidity decreases. This is because, by decreasing air relative humidity, the outlet temperature entering the compressor (T_{out}) decreases and density of air increases, hence air mass flow rate is increased, which increase the power output. It could be noted from Fig. 4.that at inlet air temperature (T_{in}) of 40°C with relative humidity of 50%, the outlet temperature entering the compressor (T_{out}) will reduce by 8.7% after fogging and the output power will increase by 0.04 % (i.e. to 241.3MW).

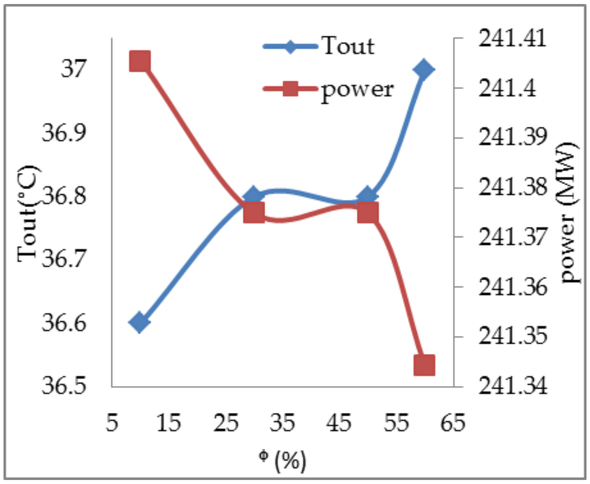

Fig.4. effect of air relative humidity on outlet temperature entering the compressor (T_{out}) and power at a inlet air temperature (T_{in}=40°C).

The relation between injected water droplet diameter size (D), on outlet temperature entering the compressor (T_{out}) and output power is shown in fig.5. As the figure illustrated, as spray water droplet diameter size decreases, the outlet temperature entering the compressor (T_{out}) decreases and hence the output power increases. This is because, as spray water droplet diameter size decreases, droplet heat and mass transfer surface area enormously increases. When the spray water droplet diameter is decreased from 80µm to 35 µm, the outlet temperature entering the compressor (T_{out}) will be decreased by 15.4 % and the output power will be increased by 0.4%.

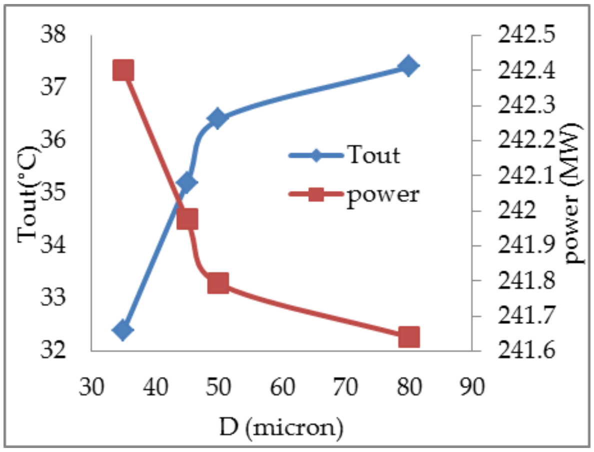

Fig.5. effect of spray water droplet size diameter on outlet temperature entering the compressor (T_{out}) and power.

Fig. 6. shows the effect of spray water mass flow rate on outlet temperature entering the compressor (T_{out}) and output power. It is evident from this figure that the outlet temperature (T_{out}) intake compressor firstly decreases and then nearly remains constant as spray water mass flow rate increases. On the other hand, as spray water mass flow rate increases, turbine output power increases. This is because as spray water mass flow rate increases weight of intake flow increases and hence output power increases.

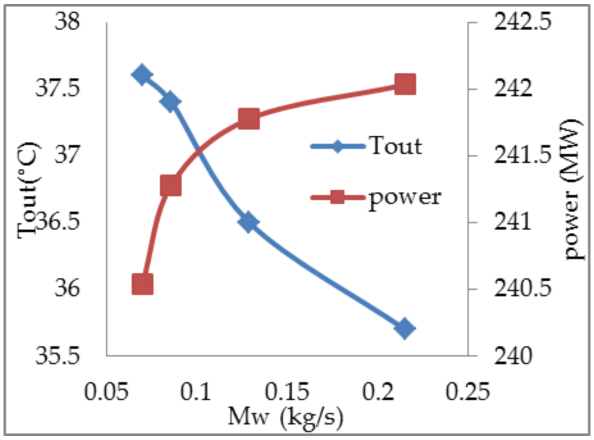

Fig.6. effect of spray water mass flow rate on outlet temperature entering the compressor (T_{out}) and power

Fig. 7. illustrates the effect of spray water injection speed on outlet temperature entering the compressor (T_{out}) and output power. It could be seen from this figure that as spray water injection speed increases, outlet temperature entering the compressor (T_{out}) firstly decreases and then increases. This is because as spray water injection speed increases, spray water mass flow rate increases, which enhances heat transfer rate, and air to water droplet contact time decreases, which contract heat transfer rate. Therefore, outlet temperature entering the compressor value depends on which one is the dominant. Also, as spray water injection speed increases, output power firstly increases and then decreases. It could be noted that the best water injection speed is 5m/s.

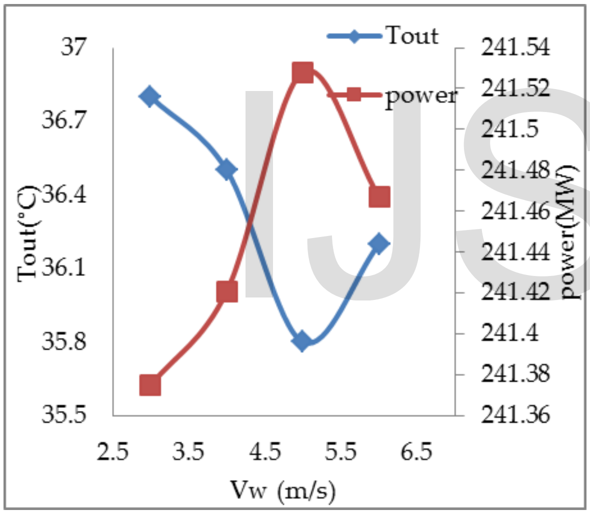

Fig.7 effect of spray water injection speed on outlet temperature entering the compressor (T_{out}) and power

Fig. 8. Shows the effect of ambient air dry bulb temperature on outlet temperature entering the compressor (T_{out}) and output power. It could be noted from this figure that as ambient air dry bulb increases, outlet temperature entering the compressor (T_{out}) increases and output power decreases. This is because as ambient air dry bulb temperature increases, its corresponding wet bulb temperature (minimum outlet temperature entering the compressor (T_{out}) can be achieved) increases. Therefore, outlet temperature will be increased and output power will be decreased. Moreover, as ambient air dry bulb temperature increases, air density decreases and hence output power decreases. When the inlet air temperature (T_{in}) increased from 30°C to 40°C, the outlet temperature entering the compressor (T_{out}) will be increased from 28.5 to 36.5°C after wet compression and the output power will be decreased from 242.6 to 241.4MW.

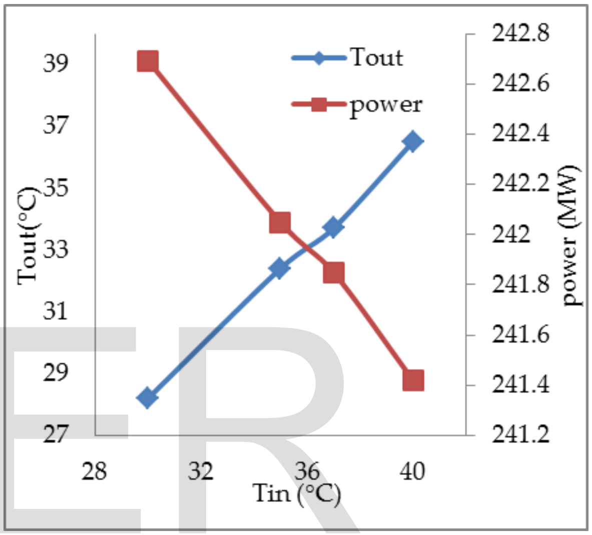

Fig.8. effect of ambient air temperature on outlet temperature entering the compressor (T_{out}) and power

Fig.9. Illustrates the effect of spray water injection temperature on outlet temperature entering the compressor (T_{out}) and output power. As shown in fig.9, by decreasing the temperature of spray water, outlet temperature entering the compressor (T_{out}) decreases and output power increases. This is because when spray water temperature is less than ambient air wet bulb temperature, sensible and evaporative cooling will be happened. Therefore, the outlet temperature entering the compressor after fogging becomes very low and hence mass flow rate of air increase augments the net power output.

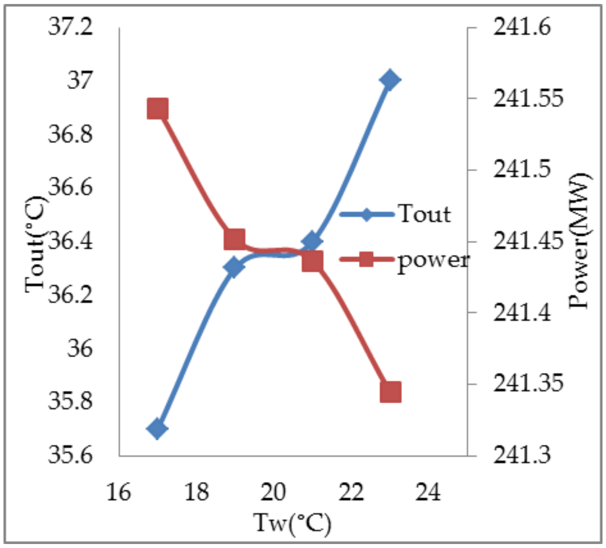

Fig.9. effect of spray water temperature on outlet temperature entering the compressor (T_{out}) and power

The figure below, Fig. 10, illustrates the difference in the output power (MW) between before and after wet compression according to Nubaria Power Plant which is the case study, the performance parameters enhancement with inlet air cooling is simulated and the results are tabulated.

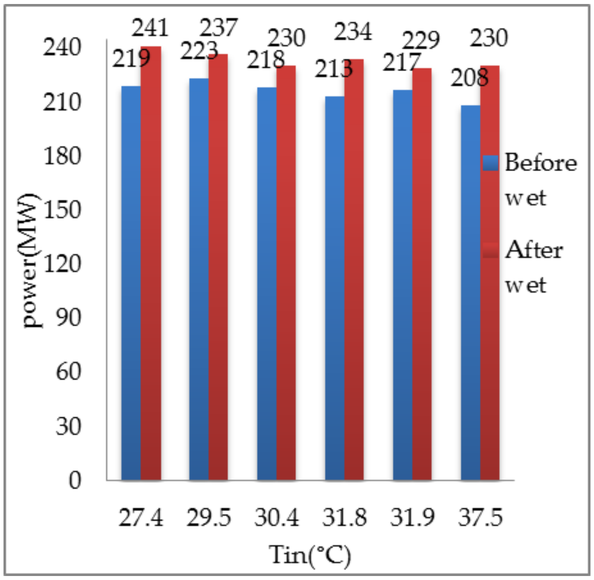

Fig.10. Difference in the output power (MW) between before and after wet compression according to Nubaria Power Plant results.

CONCLUSIONS

Gas turbine inlet air fog cooling is considered a simple and cost-effective method to increase power output and often also increase thermal efficiency. Wet compression is a popular and economic power augmentation technique, but it still needs more research in a number of different areas. All the problems ought to be fully investigated and validated by experiments.

Some recommended future work is shown below:

1. Experimental work of wet compression on the compressor only (not with turbine) is recommended to be studied first, followed by the entire GT system.
2. Spray evaporation and creation fogging system is simulated with a small deviation by using commercial program.
3. The spray evaporation technique improve the gas turbine plant performance for all working conditions
4. Fogging system is capable of reducing the ambient air temperature by 3-12°C, producing power augmentation by 1-8.1%.
5. The turbine power output is increased by increasing each of the following air mass flow rate and water mass flow rate, However, it decreased by increasing each of the following spray water droplet size, ambient air temperature, ambient air relative humidity, injected water temperature,
6. Decreasing the temperature of water spray improve the performance gas turbine power plant significantly,

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