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Performance Improvement of a 43 MW Class Gas Turbine Engine with Inlet Air Cooling

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ABSTRACT

In this study, a process of inlet air cooling was implemented in the intake of a land-based gas turbine engine for electricity generation. The motivation behind the study is to improve the performance of the gas turbine engine in hot climate conditions, which causes a significant decrease in the output power and an increase in specific fuel consumption. For inlet air cooling, a refrigeration cycle was attached to the turbo-shaft gas turbine engine, and power required by the refrigeration is extracted from the mechanical engine power output of the gas turbine. A 43 MW class gas turbine engine which is similar to the General Electric LM6000 engine was modeled in this study. Considering an average coefficient of performance of 3.0 for a refrigeration system, the inlet cooling provided (by supplying cooled inlet air at 15^{o}C) a 22.21 % net power increase and a5.2% power specific fuel consumption improvement at 55^{o}C ambient conditions.

Key words: Gas turbine engine; cycle analysis, performance, inlet cooling, refrigeration.

Nomenclature

Latin letters

LHV	*Lower heating value of fuel (MJ/kg)*
HR	*Heat rate*
m	*Mass flow rate (kg/s)*
P_{amb}	*Ambient pressure (kPa)*
PSFC	*Power specific fuel consumption*
T	*Total temperature at engine stations*
T_{amb}	*Ambient temperature*
$\dot{W}_T$	*Power of turbine*
$\dot{W}_C$	*Power of Compressor*
$\dot{W}_{net}$	*Shaft power delivered*

Greek letters

ε_{2a}	*Cooling air ratio for HPT rotor*
ε_3	*Cooling air ratio nozzle guide vanes*
η_b	*Combustor efficiency*
η_C	*Compressor isentropic efficiency*
η_F	*Booster isentropic efficiency*
η_{HPT}	*Isentropic efficiency*
η_m	*Shaft mechanical efficiency*
η_{PT}	*Power turbine isentropic efficiency*
Π_B	*Combustor total pressure ratio*
Π_C	*Compressor total pressure ratio*
Π_F	*Booster total pressure ratio*
Π_N	*Exhaust nozzle pressure ratio*

1. INTRODUCTION

The ambient conditions have a significant effect on the gas turbine output. In the new era, renewable sources of energy are considered to minimize environmental impacts [1-5].The high inlet air temperature leads to increasing the gas turbine inlet temperatures. As a result, NOx emission increases, which are limited by environmental legislation. Malewski and Holldorff [6] investigated how to decrease the inlet air temperature using a precooling process. This process was performed using a separate absorption refrigeration system in which ammonia is used as a refrigerant and water as a solvent. The demand forthe refrigeration system was covered by heat energy available in the tail end exhaust of a combined cycle. They found that the air precooling process improves the output power by 17 to 29% and efficiency by 2 to 4%. While the combustion temperature is reduced. Therefore, NOx emission decreases accordingly.

In 1995, Boggio [7] used evaporative cooling, absorption system and combined one for cooling the compressor inlet air for the LM6000 gas turbine. The air inlet conditions are based on two sites in Northern and Southern Italy. The cooling systems are used to cool the air inlet temperature such as 25^{o}C at 60% relative humidity to be 10^{o}C during the whole day in summer's hottest months. The cooling power of 3300 kW is consumed to achieve this level of temperature. In this study, the effects of both dry and wet bulb temperatures are investigated in detail. It is found that a 2-4% increment in power is achieved by evaporative cooling while the absorption system fulfills 5-10% power enhancement yearly. Moreover, the highest plant performance is achieved for the integrated absorber plus evaporative cooling. The author recommends using air cooling during the daytime only to reduce the cost of electricity significantly.

Najjar[8] introduced an absorption chiller to cool the inlet air to the gas turbine power plant. The absorption system was run using the exhaust gases. Besides, a recovery boiler was used to recover the exhaust gases before entering the generator of the absorption chiller. To evaluate the performance, efficiency, and specific fuel consumption was compared to the simple cycle. The compressor pressure ratio, turbine inlet temperature, and ambient temperature were changed in the performance evaluation. The results showed a gain of 21.5 % in power, 38 % in efficiency, and 27.7 % specific fuel consumption when using this combined system.

Air evaporative fogging system is first applied to the gas turbine inlet air in the mid-1980s, Jones and Jacobs [9]. Zurigat et al. [9] used this method to cool the inlet air for a power plant of 40 MW power in two different locations in Sultanate Oman. Zurigat el al used 274 nozzles [swirl jet and impacting pin type] at a flow rate of 7-18 kg/h/nozzle to achieve a small droplet diameter. The current study achieves that for summer months at least 13^{o}C reduction below ambient temperature and 10% increase in power output of the gas turbine. Generally, for a 1.0^{o}C drop in inlet air temperature, there is about a 0.72% increment in gas turbine power output.

Bassily[10] studied the effect of using an absorption cooling system to intercool reheat recuperated gas turbine cycle. The absorption system was run using the exhaust gases of the cycle. The cooling system was employed to cool both the inlet air to the low-pressure and high-pressure compressor. The effect of changing pressure ratio, ambient temperature, ambient relative humidity, turbine inlet temperature, and effectiveness of the recuperated heat exchanger on the performance was evaluated. The results showed an enhancement in the efficiency when using this double action of the cooling system.

An analytical study was presented by Yang et al. [11] to study the effect of introducing LiBr/water absorption chiller and fogging to cool the inlet air of the gas-steam combined power plant cycle. To evaluate the system, parameters such as efficiency ratio, profit ratio, and relative payback period were defined and analyzed. The study showed that the applicability of inlet air cooling for gas-steam combined power plants using chilling and fogging depends on the economic efficiency of the gas turbine combined cycle power plant.

Thermal energy storage systems are one of the important air-cooling systems. There are two major categories of sensible and latent heat types. In the sensible type, the energy can be stored in water and sand/stone. While in the second type, the energy storage media change its phase from solid to liquid in receiving energy, and from liquid to solid in the energy rejection process. The latent type stores energy more than the sensible type. Therefore, in Sanaye et al.[12] 's study, latent type is used to cover a thermos-economic analysis to get the optimum design parameters using genetics algorithm optimization technique. The current study is performed for a gas turbine with net output power of 25-100 MW. The system under investigation contains a gas turbine beside the cooling system that includes an air cooler, an ice storage system in which chilled water (25% Ethylene Glycol and 75% water) passes through the air cooler with a vapor compression refrigeration system. The gas turbine output power increases by 3.9-25.7% and the efficiency increases by 2.1 - 5.2%. A payback period for the used thermal storage system is computed and found to be 4.0-7.7 years. Also, it is found that the payback period decreases with increasing the gas turbine power.

Rahim [13] compared the performance of combined cycle gas turbine power plants with different cooling systems. Evaporative cooling, fogging, chiller cooling, and absorption cooling were used and the performance was evaluated with parametric study for ambient conditions, turbine inlet temperature, pressure ratio, etc. The net power output and efficiency of the combined cycle using each system were evaluated. Also, carbon dioxide emissions are also discussed. It was found that the absorption cooling system is the most effective.

Santos and Andrade [14] have a theoretical thermodynamics analysis of a gas turbine using evaporative cooling, absorption, and Mechanical Chiller system. The heat rate, power output, and thermal efficiency are the main key for this study. Also, a comparison between these parameters with the corresponding one without air cooling is drawn at different intake temperatures and relative humidity of 18% and 60%. It is found that the absorption chiller method gives a better cooling effect compared with evaporative cooling when the ambient intake temperature is high, up to 20^{o}C. At 36 ^{o}C and relative humidity of 18%, a 9.6% power increment is obtained when the evaporative cooling is used while 13. 56% and 15.97% increments for the mechanical and absorption systems, respectively.

Givi and Li [15] examine the effect of inlet cooling air on gas turbine performance. Moreover, the coefficient of performance (COP) is considered a function of ambient temperature. In fact, the main objective of this study is to obtain the optimal temperature at which the inlet cooling should be operated to fulfill the highest efficiency. It is found that the power needed for a cooling system depends on the second-order of temperature reduction that may lead to lower performance as the temperature reduction significantly increases. The maximum efficiency is achieved when the compressor inlet temperature decreases to 10^{o}C. While the net power output improved by 0.6%/^{o}C.

A techno-economical study was done by Barigozzi et al. [16] for the effect of using the cooling system on the inlet air of a gas turbine in a combined gas turbine. The cooling system consists of cold-water thermal storage charged nighttime by mechanical chillers. The cold water was used in the hottest day hours to cool the inlet air to the compressor. Three climate conditions were studied representing three cities: Phoenix, New Orleans, Abu

Dhabi. The study showed that the size of cooling storage is the main parameter for economical revenue.

In a recent paper, Kamal et al.[17], the performance of a gas turbine generator using an electric chiller to cool the inlet air was evaluated. The ambient condition of Malaysia was used however the inlet temperature was cooled to 12 °C. An improvement in the performance of the gas turbine was achieved. An increase of 32.11% in the net power and a reduction of 3.74% in the net heat rate was predicted.

Gas turbine performance due to ambient conditions is evaluated not only for land-based gas turbines but also for the gas turbine aircraft engines such as turboprop, turbo-shaft, turbo-fan engines in literature [18]-[24].

2. MATERIALS AND METHODS

Figure 1 shows a flow diagram for a standard gas turbine power plant with a mechanical inlet air cooling system. As shown in the diagram, the inlet air to the compressor is cooled using a mechanical cooling system. The turbine generates power to run both the air compressor of the power plant and the compressor of the refrigeration cycle of the chiller. A simple refrigeration cycle is considered with a 3.0 coefficient of performance. Considering Kuwait's climate, different ambient temperatures (15°C-55°C) are used to evaluate the gas turbine performance. The working fluid in both compressor and turbine are air and flue gases, respectively.

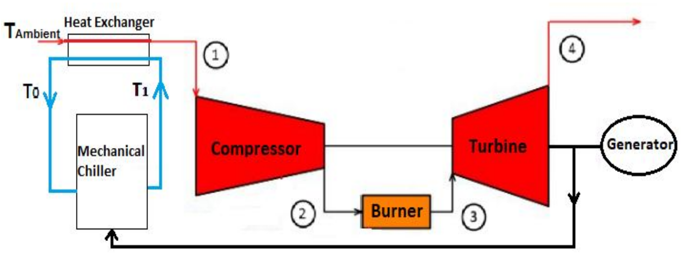

Figure 1: Schematic of flow diagram of the gas turbine system.

The net power output, $\dot{W}_{net}$ and power-specific fuel consumption, PSFC, are calculated using the mathematical analysis for each component as indicated below to evaluate the gas turbine performance.

Mechanical chiller: The cooling load, $\dot{Q}_{cool}$, and the requiredwork for the chiller compressor,$\dot{W}_{cool}$, can be evaluated as follow:

$\dot{Q}_{cool} = \dot{m}_a \cdot (h_1 - h_0)$,(1)

$\dot{W}_{cool} = \frac{\dot{Q}_{cool}}{COP}$, (2)

where, $\dot{m}_a$, h, COP are the air mass flow rate [kg/s], the enthalpy[kJ/kg], and the coefficient of performance, respectively.

Air compressor: the power required to drive the compressor,$\dot{W}_C$, is calculated from:

$\dot{W}_C = \dot{m}_a \cdot (h_2 - h_1)$.(3)

Burner: the amount of heat, $\dot{Q}_{in}$, and the required fuel mass flow rate, $\dot{m}_f$, are calculated by:

$\dot{Q}_{in} = \dot{m}_a \cdot (h_3 - h_2)$, (4)

$\dot{m}_f = \frac{\dot{Q}_{in}/_{LHV}}{\eta_b}$, (5)

where, *LHV* is the lower heating value [kJ/kg].

Turbine: the output power,$\dot{W}_T$, and the total mass inlet to the turbine are calculated as follow,

$\dot{W}_T = \dot{m}_T \cdot (h_4 - h_3)$, (6)

$\dot{m}_T = \dot{m}_a + \dot{m}_f$. (7)

Overall gas turbine: the net power output, $\dot{W}_{net}$, and the power specific fuel consumption, *PSFC*, heat rate, *HR*, and thermal efficiency, η_{th}, are calculated by

$\dot{W}_{net} = \dot{W}_T - \dot{W}_C - \dot{W}_{cool}$(8)

$PSFC = \frac{3600 \cdot \dot{m}_{fuel}}{\dot{W}_{net}}$(9)

$HR = PSFC \cdot LHV$(10)

$\eta_{th} = \frac{3600}{PSFC \cdot LHV}$(11)

2.1 Gas Turbine Engine Performance Model

To estimate emissions of a gas turbine engine, a detailed cycle analysis is needed. The cycle analysis is the total of thermodynamic calculations performed for every component of the engine e.g. compressor, combustor, turbine, nozzle, etc. The cycle analysis results include the total pressure and temperature values at every engine station, engine performance values such as shaft power output, specific fuel consumption, fuel flow rate, etc. Then, exhaust emissions of the engine can be calculated from those values.

In this study, cycle analysis of a gas turbine was done for a 43 MW class similar to the General Electric LM6000 gas turbine engine [25]. A set of input values were assumed and used in the cycle analysis calculations which are given in Table 1. Comparison of results with manufacturer`s data isgiven in Table 2 which are in good correlation despite a small deviation[26].

Table 1: Assumed design input parameters for baseline engine.

Engine parameter	Definition	Assumed Value
T_3	total temperature at turbine entry (K)	1500
ΠB	burner/combustor total pressure ratio	0.95
ΠC	compressor total pressure ratio	12.2
ΠF	booster total pressure ratio	2.4
ΠN	exhaust nozzle pressure ratio	1.1
η_b	Burner efficiency	0.9995
η_C	compressor isentropic efficiency	0.90
η_F	booster isentropic efficiency	0.90
η_{HPT}	high pressure turbine isentropic efficiency	0.88
ηm	shaft mechanical efficiency	0.999
η_{PT}	power turbine isentropic efficiency	0.91
ε_{2a}	cooling air ratio for high pressure turbine rotor	0.03
ε_3	cooling air ratio nozzle guide vanes	0.03
T_{amb}	ambient temperature (K)	288.15
P_{amb}	ambient pressure (kPa)	101.325
M	inlet corrected air mass flow rate (kg/s)	119
LHV	Fuel heating value (natural gas) (MJ/kg)	44.194

Table 2: Comparison of main performance parameters for baseline engine.

Parameter	Literature Data*	Calculated Value for Baseline Engine	Deviation (%)
Shaft power (MW)	43,284	43,370	0.19%
Heat rate (kJ/kWh)	8,581	8,591	0.12%

*Source: [25]

2.2 Performance Calculations in Hot Climate

This study uses the local data of dry bulb temperature, wet bulb temperature, and relative humidity from Kuwait as it has several power plants such as Shuwaikh, Shuaiba North, Doha East, Doha West, Az-Zour South, Sabiya, and Az-Zour North stations. Gas turbine stations share 41.4% [8151 MW- generated by gas turbines out of 19673 MW- total] of the total power generated in Kuwait. Therefore, the performance improvement of these stations will have significant economically and environmental contribution.

The net power output, $\dot{W}_{net}$, and Power specific fuel consumption, PSFC, are selected as the key parameters used to evaluate the gas turbine performance in the current study. Table 1 presents the net power output, and the power specific fuel consumption, PSFC, for gas turbine engines with and without implementing an inlet air cooling system. The comparison was presented for various ambient air temperatures. The temperature range was selected on the climate of Kuwait from 15 ^oC to 55 ^oC. The temperature of 15 ^oC is used as a reference and baseline temperature for comparison purposes. To show the effect of changing ambient temperature, the percentage change in output power is calculated as follows:

$$\frac{\dot{W}_{net@T_{inlet}} - \dot{W}_{net@T=15^oC}}{\dot{W}_{net@T=15^oC}} \times 100\% \quad (12)$$

The required fuel consumption for each kW. Hour is calculated for the ambient inlet temperature, cooled ambient temperature as well as baseline temperature. The percentage change in PSFC output power is calculated as follow:

$$\frac{PSFC_{@T_{inlet}} - PSFC_{@T=15^oC}}{PSFC_{@T=15^oC}} \times 100\% \quad (13)$$

3. RESULTS AND DISCUSSION

Figure 2, shows the effect of changing inlet air temperature on the change of net power output from hot ambient with and without using inlet air cooling.It is clear from the figure that for the uncooled scenario, increasing the ambient temperature leads to a significant decrease in output power compared to the baseline temperature. For example, 21.3% reduction occurred at T=55 ^oC. On the other hand, the reduction is 3.8% for the same ambient temperature is achieved in the cooling scenario. By comparing all percentage reductions for both scenarios, it is found that the cooling process decreases the power reduction by about 6 times.

A similar effect for the ambient temperature on the change in PSFC is noticed as indicated in Figure 3. The Figure 3 shows the same two scenarios of Figure 2. The higher the inlet air temperature the more PSFC is obtained. Thus, the cooling process becomes more convenient. For example, as shown in Figure 3 at 55 ^oC for uncooled scenario 9.31% more fuel consumption is needed than that of baseline one. On contrary, extra 3.9% PSFC is needed for the same ambient temperature, 55^{o}C, when it is cooled to 15^{o}C. Comparing the percentage of PSFC reduction for both scenarios, the cooling process will save about 50% of fuel consumption/kW-hour.

Overall results are given in Appendix A, Table A-1 for effect of inlet air cooling on the engine performance within the range of 15^{o}C -55^{o}C.

4. CONCLUSION

A compression refrigeration cycle has been introduced to cool the compressor inlet air gas for the gas-turbine cycle to 15 ^oC [baseline temperature]. The compressor of the refrigeration cycle is run by the gas turbine. A parametric study of the effect of ambient temperature on the output power and specific fuel consumption leads to the following conclusions:

- Applying compression refrigeration cycle could increase the net output power for the cycle by 22.21% when the ambient temperature reaches 55°C.
- According to the improvement of net power, the specific fuel consumption dropped by 5.2% at 55°C ambient temperature.

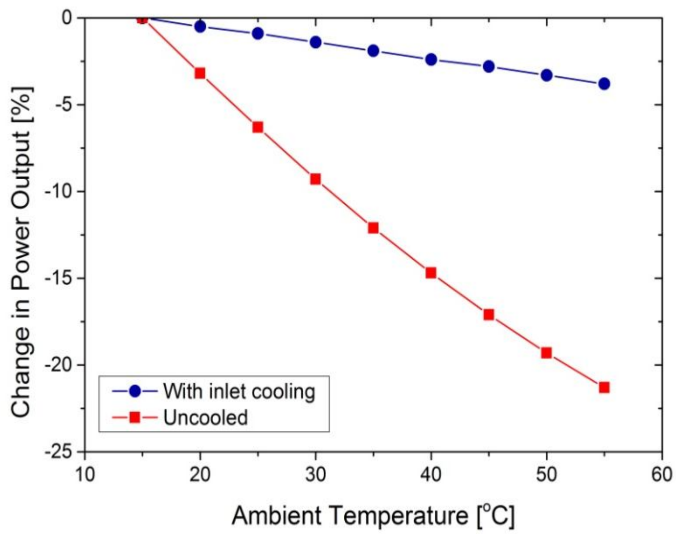

Figure 2: Effect of compressor inlet temperature on power output (%).

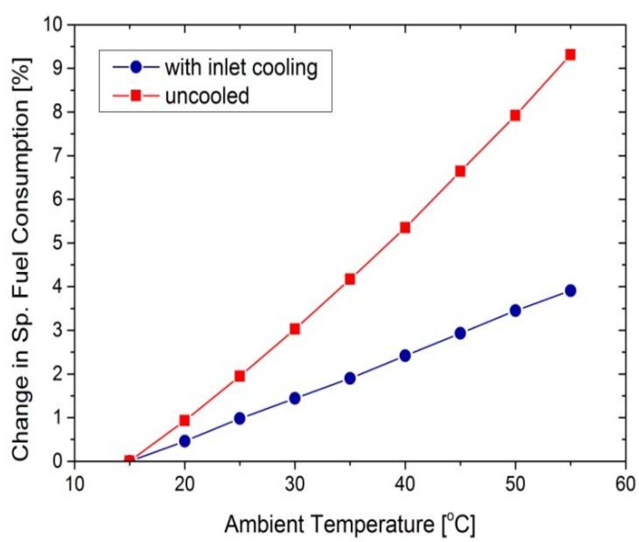

Figure 3: Effect of ambient temperature on PSFC (%).

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APPENDIX-A

Table A-1: Effect of Inlet Air Cooling on the engine performance

Ambient Temp [^{o}C]	***Inlet Temp [^{o}C]***	***Config***	***Power [kW]***	***Power Change from 15^{o}C baseline***	***Power Change from hot ambient***	***PSFC [kg/(kW*h)]***	***PSFC Change from 15^{o}C baseline***	***PSFC Change from hot ambient***
55	55	uncooled	34147	-21.3%		0.2125	9.31%	
	15	cooled to 15	41731	-3.8%	22.21%	0.2020	3.91%	-5.20%
50	50	uncooled	34993	-19.3%		0.2098	7.92%	
	15	cooled to 15	41929	-3.3%	19.82%	0.2011	3.45%	-4.33%
45	45	uncooled	35950	-17.1%		0.2073	6.64%	
	15	cooled to 15	42141	-2.8%	17.22%	0.2001	2.93%	-3.60%
40	40	uncooled	37004	-14.7%		0.2048	5.35%	
	15	cooled to 15	42342	-2.4%	14.43%	0.1991	2.42%	-2.86%
35	35	uncooled	38143	-12.1%		0.2025	4.17%	
	15	cooled to 15	42552	-1.9%	11.56%	0.1981	1.90%	-2.22%
30	30	uncooled	39358	-9.3%		0.2003	3.03%	
	15	cooled to 15	42753	-1.4%	8.63%	0.1972	1.44%	-1.57%
25	25	uncooled	40638	-6.3%		0.1982	1.95%	
	15	cooled to 15	42961	-0.9%	5.71%	0.1963	0.98%	-0.97%
20	20	uncooled	41976	-3.2%		0.1962	0.93%	
	15	cooled to 15	43165	-0.5%	2.83%	0.1953	0.46%	-0.46%
15	**15**	**baseline**	**43370**	**0.0%**		**0.1944**	**0.00%**	