Economic Analysis of Compressor Inlet Air Precooling Techniques of a Gas Turbine Operational in Nigerian Energy Utility Sector

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

Original Research Article

ABSTRACT

Economic analysis of gas turbine compressor inlet air precooling is based on the economical evaluation (maintenance, operations and personnel costs) of the various precooling systems used to improve the performance of gas turbine operational in Nigeria energy utility sector. The precooling techniques studied are evaporative, vapour compression and vapour absorption precooling techniques. This study objectively compared the three precooling techniques taking into consideration the prevailing climatic conditions of Nigeria. The overall yearly cost for evaporative, vapour compression and vapour absorption precooling techniques are evaluated to be USD25501.31/KWh, USD69867.19/KWh and USD1184548.01/KWh respectively and the payback time is three years. The system profitability for evaporative, vapour compression and vapour absorption precooling systems are USD1785376.83/KWh, USD7198182.79/KWh and USD11103747.4/KWh respectively and the payback time is three and a half year. The Net Revenue of the systems is USD8782909.21/KWh, USD15888192.52/KWh and USD84947043.84/KWh respectively. In conclusion, it is recommended that evaporative precooling system should be used in dry and humid weather conditions (Northern region of Nigeria) but it must be ensured that water is in abundance and refrigeration precooling should be employed in the moderate climatic conditions (Southern Region of Nigeria).

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NOMENCLATURES

C_{ch}^{c} is the cost of installation of the chiller (USD/kWh)

C_{cc}^{c} is the cooling coil cost (USD/kWh)

C_{el}^{c} is the electricity rate cost (USD/kWh)

C_{total} is the total annual cost (USD/kWh)

T_{e} is the electrical power (kW)

a^{c} is the capital recovery factor

i is the interest rate (%)
∩ is the specific period (years)

$\dot{W}_{pf}$ is the power consumed by both pump and fan (KW)

$\dot{W}_{p}$ is the power consumed by pump (kW)

$\dot{W}_{f}$ is the power consumed by fan (KW)

m_{w} is the mass flow rate of water (kg/s)

Δp is the pressure drop (N/m^2)

η_{pump} is the mechanical efficiency of pump (%)

v_{f} is the flow rate of water (m/s)

$\dot{W}_{mc}$ is the electric power required to drive the compressor (kW)

$\dot{W}_{Ge}$ is the power required to drive the generator (kW)

E is the annual exported energy by the power plant with a precooling system (kWh)
NR is the net revenue (USD)

$\dot{W}_{net}$ is the net power output (kW)

$\varepsilon_{withouth\ cooling}$ is the power plant's yearly electricity generation without a precooling technique (USD/kWh)

$\varepsilon_{with\ cooling}$ is the power plant's yearly electricity generation with a precooling technique (USD/kWh).

1. INTRODUCTION

Gas turbine plants are used for electricity production in many countries. According to Ali et al. [1], the net power output of a gas turbine is reduced when the temperature gets to 40°C. This is because as the temperature increases, the air density reduces hence the compressor specific work increases. To overcome the problem of reduction in the power output of a gas turbine when the temperature is high, inlet air precooling is usually modeled for the compressor with the purpose of reducing the ambient air temperature before it enters the system, hence reducing the work done by the compressor. Compressor inlet air precooling techniques are very pivotal in enhancing the performance of the gas turbine. Compressor inlet air precooling is of two types, namely direct mechanical precooling technique (evaporative compressor inlet air precooling) and indirect mechanical precooling technique (vapor compression or vapor

absorption compressor inlet air precooling. According to Jassim et al. [2], the overall annual gas turbine output power gained and cost by using chiller cooling system are 117027MWh and 7,624USD respectively; the total annual cost and net cash flow are 1, 524, 779.7USD and 4, 503, 548.5USD, respectively and the payback time is 0.66 years. Chalker et al. [3] have studied the economic potential of using evaporative precooling for gas turbines in U.S.A, while [4] examined the use of ice storage methods for the air cooling of the gas turbines in the Kingdom of Saudi Arabia. Chalker et al. [3] presented analytical method for evaluating a cooling technology of a combined cycle gas turbine that included parameters such as the interest rate, payback period and the efficiency ratio for off-design conditions of both the gas turbine and the cooling systems. The objective of this study is to analyze the economics of evaporative, vapour compression and vapour absorption precooling techniques using thermodynamic principles with Nigerian climatic conditions as a case study.

2. MATERIALS AND METHODS

Operating data for the gas turbine (GT) units were collected from the daily turbine control log sheet for a period of the years. The analysis of the plant was divided into different control units and mass/energy conservation laws were applied to each component/unit. The performance of the plant was determined for the reference plant (without precooling technique) and for the precooled system (with evaporative precooling

techniques, mechanical chiller precooling system and chilled water refrigeration precooling techniques). Furthermore, the economics of the respective precooling techniques was considered.

The developed algorithm of this study is applied to an open cycle HITACHI MS – 7001B plant located at the Nigeria Agip Oil Company (NAOC), Port Harcourt-Nigeria, with its main design specifications shown in Table 1.

2.1 Description of the Precooling Systems

Evaporative inlet air precooling is mostly utilized in hot climate. It uses the latent heat of vaporization to cool ambient temperature. Cortes [5] found that the method can increase the power output to about 14% and the annual operation and maintenance costs are about 3 – 5% of the installation cost. Nabati et al. [6] concluded that parasitic power consumption is less than 0.5% of the increased production, and evaporative inlet air precooling reduces the emission of NO_x by 0.8 – 1.5% per °C of cooling. According to Meher-Homji [7], evaporative precooling of turbine inlet air involves the spraying of demineralized water droplets of about 5 – 20 microns in diameter into the air inlet ducts. The sensible heat content of air is utilized to evaporate the fog droplets. In the process the air is cooled to the wet bulb temperature and 100% relative humidity is produced as illustrated in Fig. 1.
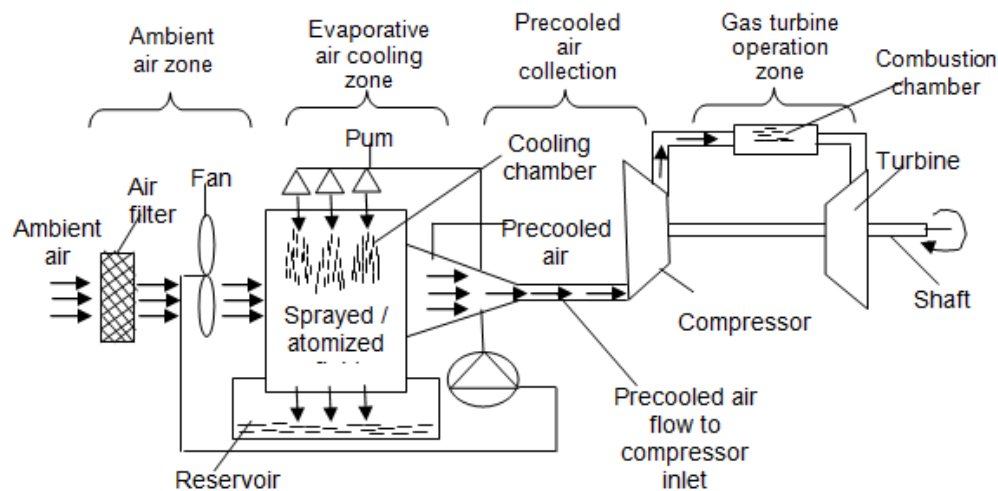

Fig. 1. Schematic diagram of a gas turbine cycle with an evaporative cooler

Table 1. Range of parameters for HITACHI MS – 7001B plant analysis

Parameters	Range
Ambient air	
Ambient air temperature, T_o	34°C
Ambient air relative humidity, RH_0	78%
Gas turbine, model HITACH – MS – 7001B	
Pressure ratio, P_2/P_1	10
Net power, 1S0	52.4 MW
Site power	37 MW
Turbine inlet temperature, T_3	1273K
Air mass flow rate, m_a	141.16 kg/s
Fuel net calorific value, NCV	46000 kJ/kg
Turbine isentropic efficiency, η_t	88%
Air compressor isentropic efficiency, η_c	82%
Combustion efficiency, η_{comb}	85%
Air – fuel ratio	80:1
Generator	
Electrical efficiency	95%
Mechanical efficiency	90%
Pump efficiency	65%
Water Chiller	
Refrigerant	R_{22}
Evaporating temperature, T_e	$T_{chws} - TD_e$ ^oC
Super heat	10K
Condensing temperature, T_c	$T_0 + TD_c$ K
Condenser design temperature different, TD_c	10 K
Evaporator design temperature difference, TD_e	6 K
Sub-cooling	3 K
Chilled water supply temperature, T_{chws}	5°C
Chiller evaporator effectiveness, $\xi_{eff,er}$	85%
Chiller compressor energy use efficiency, $\dot{\eta}_{eu}$	85%
Maintenance cost of chiller, $\propto_{ch}$	USD149 kW^{-1}
Cooling Coil	
Cooling coil effectiveness, $\xi_{eff,cc}$	85%
Contact factor, CF	50%
Economics Analysis	
Interest rate, i	10%
Period of repayment (payback period), n	3 years
The maintenance cost, $\propto_m$	10% of C_{cn}^c
Electricity rate, C_{el}	USD12 kWh^{-1} USD12– USD31 kWh^{-1} 7240 hr.yr^{-1}

2.2 Vapour Compression Refrigeration Precooling System

Fig. 2 describes the gas turbine plant fitted with the vapour compression refrigeration inlet air pre-cooling. Another option to provide gas turbine in-take air cooling is the vapour compression refrigeration pre-cooling techniques. In this technique, the refrigerant evaporates and condensates at suitable pressure for practical equipment design. The refrigerant used for the vapour compression refrigeration analysis in this research is ammonia (NH_3), R_{22}.
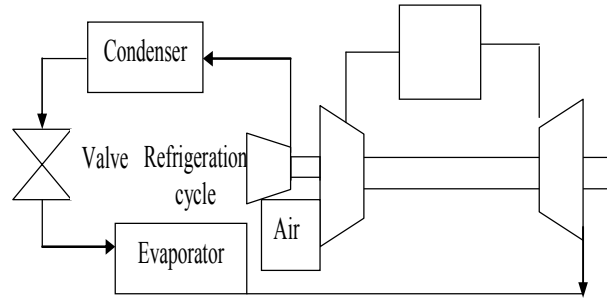
Fig. 2. Schematic diagram of a gas turbine plant integrated with vapour compression system
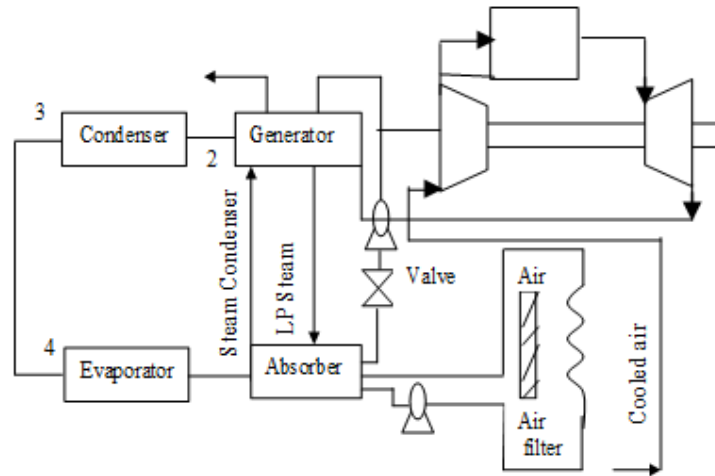

Fig. 3. Schematic diagram of a gas turbine plant integrated with a vapour absorption refrigeration system

2.3 Vapour Absorption Refrigeration Precooling System

Absorption refrigeration precooling system utilizes the heat of the exhaust gases from the turbine to produce chilled water in a lithium-bromide absorption chiller. The chilled water cools the ambient air temperature by passing through a heat exchanger.

2.4 Economic Analysis

Precooling the intake air of the gas turbine plant enhances the power output and consequently raises its annual revenue. However, installation cost and operation cost of the precooling system add to the total annual expenditure which partially offsets the revenue.

The operation cost depends on the operation period (t_{op}), the cost of installation of the chiller,

c_{ch}^c, the cooling coil cost c_{cc}^c and the electricity rate cost c_{el}^c.

If different precooling methods consume electrical power T_e, and the cost of electricity rate is c_{el}^c (N/kWh), then the overall yearly cost can be expressed as [8]:

$$c_{total} = a^c \left[c_{el}^c + c_{cc}^c \right] + \int_o^{top} c_{el} T_e \; dt \quad (1)$$

Where:

T_e is the electrical power used by the precooling systems. The capital recovery factor, a^c, is calculated as [8].

$$a^c = \frac{i(I + i)^n}{(I + i)^{n-1}} \quad (2)$$

Where:

i is the interest rate (%) and n is the specific period (years). It is pertinent to point out that interest rate, I is one of the key economic factors of any sovereign nation. It affects the cost of borrowing an equipment or asset as well as return on investments. It is a veritable variable of the total return on various investment schemes. Its significance is that certain rates of interest give vision into future economic and financial market conditions.

2.4.1 Economic analysis for evaporative pre-cooling system

For evaporative precooling techniques, C_{ch}^c and C_{cc}^c are negligible, and T_e is taken as the electrical power consumed by the pump and fan; thus equation (1) becomes:

$$C_{total} = a^c + \int_o^{top} c_a \dot{W}_{pf}\, dt \tag{3}$$

Where:

$\dot{W}_{pf}$ is the power consumed by both pump and fan and it is given as:

$$\dot{W}_{pf} = \dot{W}_p + \dot{W}_f \tag{4}$$

$\dot{W}_p$ and $\dot{W}_f$ represent the pump and fan power consumption respectively.

According to Shanbghazani et al. [9], pump power consumption is given by:

$$\dot{W}_p = \dot{m}_w V_f \left. \Delta p \middle/ \eta_{pump} \right. \tag{5}$$

While the fan power consumption is calculated as 10% of the pump power consumption:

$$\dot{W}_f = 0.1 \dot{W}_p \tag{6}$$

Where:

$\dot{m}_w$ is the mass flow-rate of water (Kg/s), Δp is the pressure change in the flow of water (N/m²), η_{pump} is the mechanical efficiency of the pump, (%) and V_f is flow rate of water through the cooling media.

2.4.2 Economic analysis for vapour compression precooling technique

For vapour compression pre-cooling method, the power consumed by the compressor ($\dot{W}_{mc}$) replaces T_e in equation (1). Therefore, the total cost is given as:

$$C_{total} = a^c \left[c_{ch}^c + c_{cc}^c \right] + \int_o^{top} c_{el} \dot{W}_{mc}\, dt \tag{7}$$

Where: $\dot{W}_{mc}$ is the electrical power required to drive the compressor.

2.4.3 Economic analysis of vapour absorption precooling technique

Here, a generator and an absorber replaced the compressor in the vapour compression refrigeration technique. Hence, the power consumed is that required to drive the generator.

The overall cost needed to operate the vapour absorption precooling system is given as:

$$C_{total} = a^c \left[c_{ch}^c + c_{cc}^c \right] + \int_o^{top} c_{el} \dot{W}_{Ge}\, dt \tag{8}$$

Where: $\dot{W}_{Ge}$ is the power required to drive the generator (KW).

The chiller's purchase cost (C_{ch}^c) and cost of the cooling coil (C_{cc}^c) is obtained from vendors data or mechanical equipment cost index. For this study, C_{cc}^c = USD1832601.71 approximately, C_{ch}^c = USD371, 651.13.

2.4.4 System profitability

To determine the economic feasibility of a gas turbine plant with intake air precooling technique, the installation and operational cost of the precooling system and the additional annual income from power savings due to the use of the pre-cooling method is determined.

The annual exported energy by the power plant with a precooling system is given by [8] as:

$$E \text{ (kWh)} = \int_{o}^{top} W_{net}\, dt \tag{9}$$

If the annual electricity generation without a precooling system is $\varepsilon_{without\ cooling}$ and that of the precooling system is $\varepsilon_{with\ cooling}$, then revenue net increase due to the precooling system is

$$\text{Net Revenue} = (\varepsilon_{with\ cooling} - \varepsilon_{without\ cooling}) c_{els} \tag{10}$$

The profitability of the power plant with a precooling system is the increase in revenue resulting from increase in power generation and it is given by:

$$\text{Profitability} = (\varepsilon_{with\ cooling} - \varepsilon_{without\ cooling}) C_{els} - C_{total} \tag{11}$$

The profitability can be either positive or negative depending on whether there is economic incentive for using precooling system, or there is no economic incentive despite increased power generation by the plant. The performance of the gas turbine fitted with evaporative pre-cooling system, vapour compression precooling technique and vapour absorption pre-cooling system and their respective economical feasibilities are investigated.

3. RESULTS AND DISCUSSION

3.1 System Profitability and Revenue for the Various Precooling Techniques: Economic Analysis

Figs. 4 and 5 show that vapour absorption precooling technique records more elevated system profitability and net revenue than the vapour compression and evaporative precooling technique respectively; though vapour compression precooling technique has a higher result than the evaporative precooling technique. This is because in vapour absorption refrigeration inlet air precooling system, the parasitic power consumption is very low compared to that of vapour compression refrigeration system.
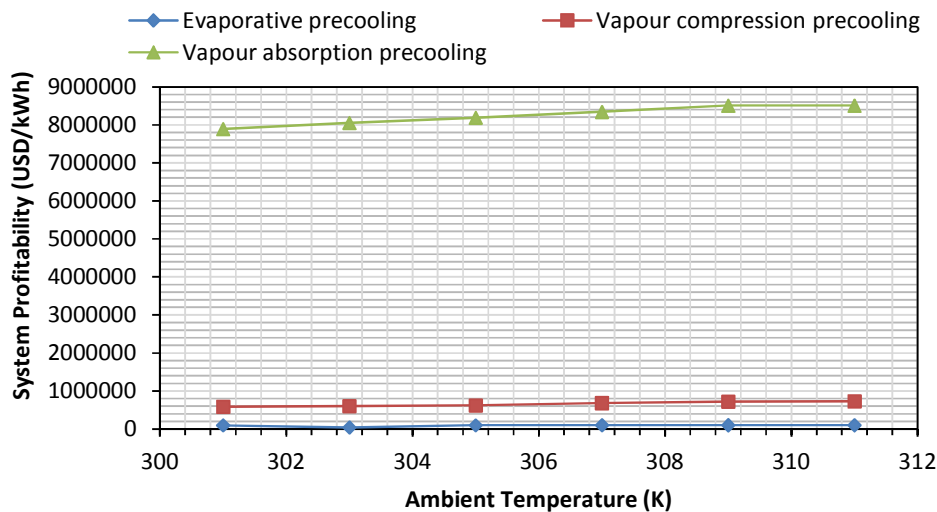

Fig. 4. Variation of the system profitability for the various precooling techniques at different inlet air temperatures
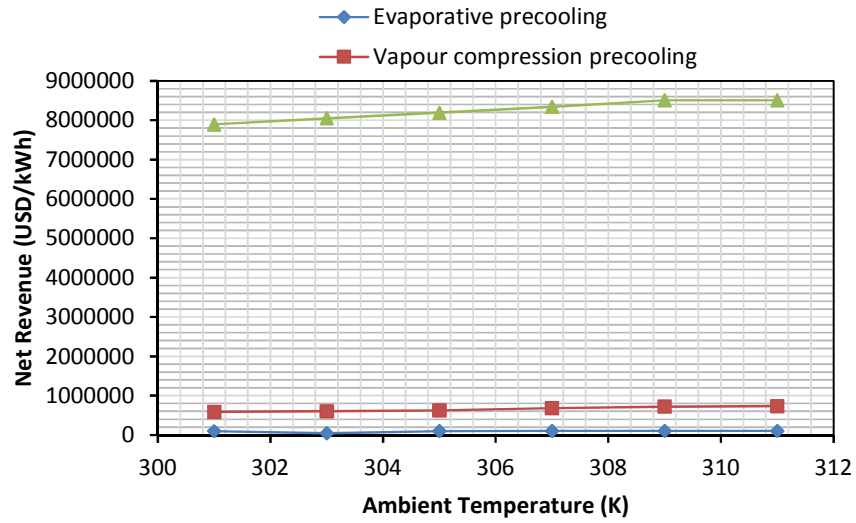
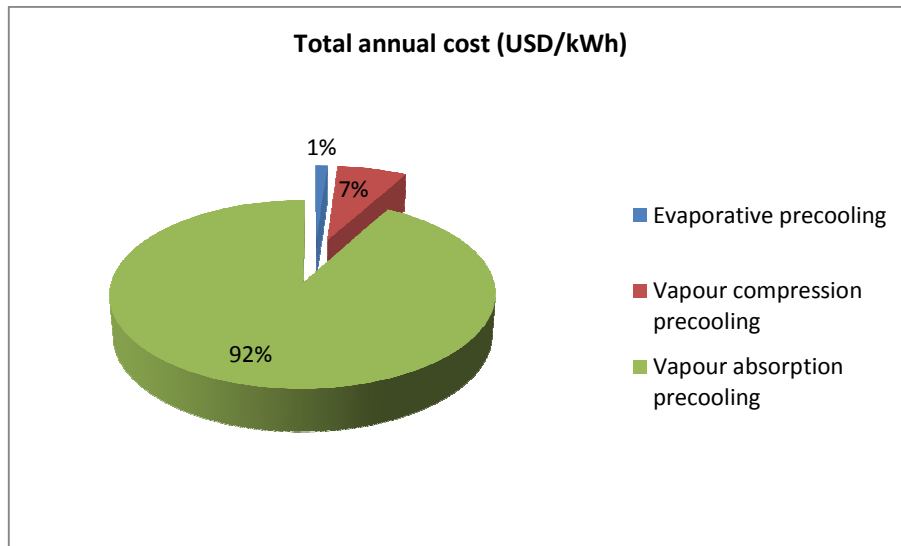**Fig. 5. Variation of net revenue for the different precooling techniques at different ambient air temperatures**

Fig. 6. Pie chart showing the total annual cost for the various precooling techniques

Table 2. Additional cost values for economic analysis

Additional cost	Cost (USD/kWh)
Cost of installation of the chiller C_{ch}^{c}	371,651
Cooling coil cost C_{ch}^{c}	1,832,601
Electricity rate Cost C_{ch}^{c}	302

3.2 Total Annual Cost Analysis

The total annual cost (C_{total}) for evaporative precooling technique is USD25501.31/kWh; that of the vapour compression and vapour absorption precooling techniques are USD69867.12/kWh and USD1184548.01/kWh, respectively. From Fig. 6, 92% of the total annual cost was accrued by the vapour absorption precooling technique, whereas the evaporative precooling operation consumed only 1% of the annual cost. This generally indicates the cost effectiveness of the precooling methods of the gas turbine system. However, additional accrued costs for running the plant were presented in Table 2.

4. CONCLUSION

This study is based on the economic analysis of evaporative, vapour compression and vapour absorption precooling systems integrated to a HITACHI – MS – 7001B single shaft open cycle gas turbine operational in Nigeria energy utility cycle. The plant is located in Obrikom town, Omoku, Onelga L.G.A, Rivers State South – South Nigeria. The results of the analysis show that the:

- Total annual cost (C_{total}) of the evaporative, vapour compression and vapour absorption precooling systems are USD25, 501.3/kWh, USD69, 867.19/kWh, and USD1, 184, 548.01/kWh respectively and the payback time is three years.
- System profitability for evaporative, vapour compression and vapour absorption precooling systems are USD1786376.83/kWh, USD7198182/kWh, and USD11103747.4/kWh respectively and the payback time is three and a half year.
- Net Revenue of the systems is USD8782909.21/KWh, USD15888192.52/kWh and USD84947043.84/kWh respectively.
- This research justifies that vapour absorption precooling technique is more economically viable than evaporative and vapour compression inlet air precooling techniques. However, in areas where there is abundant supply of water, evaporative precooling techniques are best recommended for gas turbine inlet air precooling technique.
- As ambient temperature of gas turbine site increased, the gas turbine power output

decreased thus its economic profitability reduces. To handle this bottleneck, compressor inlet air precooling techniques are always employed so as to reduce the compressor inlet air temperature increasing turbine power output and system profitability, hence the significance of the study.

- The choice of the compressor inlet air precooling technique to be used is a function of the prevailing climatic and economic condition of the energy utility sector. In areas where water is in abundance, evaporative precooling technique is required but in areas where less paralytic load consumption is required, vapour absorption precooling technique is used. Both areas are recommended for future economic analysis of the turbine plant.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Ali. Fundamentals of gas turbine precooling techniques. American J. Thermal Engineering. 2001;5(1):26-39.
2. Jassim R, Zaki G, Habeebullah B, Alhazmy M. Thermo-economic analysis of gas turbines power plants with cooled air intake. International Journal of Energy and Power Engineering. 2015;4(4):205-215.
3. Chalker M, Meher CB, – Hemji, Mee TR. Inlet fogging of gas turbine engines – Part A: Fog droplet thermodynamics, heat transfer and practical considerations. In: Proceedings of ASME Turbo Expo 2002, Amsterdam, Netherlands; 2002.
4. Hasnain F. Gas turbine precooling techniques: A review. Effect of temperature on energy profitability of gas turbine. American J. Thermal Eng. 2002;5(1):33-48.
5. Cortes S. Effect of critical temperature on gas turbine inlet air precooling techniques. J. Thermal Engineering. 2003;5(2):45-59.
6. Nabati H, Soltani M, Hosseini R, Ameri M. Technical and economic assessment of the inlet air cooling system application for power augmentation in the hot seasons for Ray power plant Fiat gas turbine units. Proceeding of 18th PSC Conference. Tehran – Iran. 2002;203–213.

7. Meher-Homji D. Thermodynamic principles of gas turbine energy profitability. Journal of Thermal Engineering. 2000;59(1):34-49.

8. Ameri M, Shahbazian HR, Nabizadeh M. Comparison of evaporative inlet air cooling systems to enhance the gas turbine generated power. Int. J. Energy Res. 2007;31:483-503.

9. Shanbghazani F, Yaky U. Danshi. Technical review on the effect of temperature on energy generation of gas turbine. American J. Thermal Engr. 2008;3(2):45-59.

APPENDIX

Table I. System profitability for different ambient air temperatures for the different precooling systems

Ambient temperature (K)	System profitability (USD/kwh)		
	Evaporative precooling	Vapour compression	Vapour absorption
301	154559163	915472904	1205708358
303	169343523	921559904	1219251358
305	202266704	922359707	1229810358
307	224753163	934625904	1233660358
309	244139763	944176904	1246836358
311	274573163	954731904	1247452558

Table II. Net revenue for different ambient air temperatures for the different precooling systems

Ambient temperature (K)	Net revenue (N/KWH)		
	Evaporative precooling	Vapour compression	Vapour absorption
301	15914940	104124200	1418927000
303	15981657	106789543	1447245672
305	16243889	110325676	1472417458
307	16589700	121245678	1499870234
309	16821895	12790876	1529879025
311	16925467	129980234	1557863290