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Performance analysis of gas turbine power plants pre-cooling techniques in the tropics

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Abstract
Several gas turbines are operational in many tropical countries and require evaporative pre-cooling techniques for smooth and durable operation. The issues of limited power gain due to wet-bulb temperature, high maintenance cost due to scaling and water treatment and high consumption of large amounts of purified water are common challenges associated with evaporative pre-cooling techniques of these systems. The need to address these challenges within the environment of operation of a gas turbine motivated this study which is aimed at the analysis of the economics and thermodynamics parameters of a gas turbine towards pre-cooling techniques of the installed turbine. The prevailing heterogeneous climatic conditions in most tropical countries are taken into effect. The study is centered on the economic analysis of different inlet air pre-cooling techniques utilized in the performance enhancement of gas turbines operation in the tropics. An open cycle HITACHI – MS – 7001B Gas turbine plant was utilized for this analysis. Its operating data were collected from the daily turbine control log sheet for a period of ten years. The plant was divided into different control units namely compressor, turbine and pre-cooling units. Energy and mass conservation laws were applied to each of the units to ascertain the economic feasibility of the pre-cooling techniques studied. The performance of the plant was therefore determined for the reference plant (without pre-cooling technique) and for the pre-cooled system (with evaporative, vapour compression and vapor absorption pre-cooling systems). Furthermore, the economics of the respective pre-cooling techniques was considered and compared with that of the reference plant (without pre-cooling). Results indicated that the Total Annual Cost (TAC) for Evaporative, Vapour Compression and Vapour Absorption compressor inlet air pre-cooling are approximately $28,689/KWh, $78,601/KWh and $1,332,617/KWh respectively and that the system profitability is $994,684/KWh, $650,776/KWh and $8,868,294/KWh respectively. The study concludes that Evaporative pre-cooling techniques should be utilized in areas of abundance of water, while Vapour Compression and Vapour Absorption pre-cooling techniques can be utilized regions of low availability of water.

Keywords: Pre-cooling, economics, gas turbine, total annual cost

1.0 Introduction

The performance of a gas turbine plant mainly depends on the inlet air temperature. To overcome the problem of low performance of a gas turbine in hot periods of the year, several pre-cooling techniques are studied with respect to the prevailing economic and climate conditions [1]. The economics (operations and maintenance cost) of these pre-cooling techniques still pose serious challenges in the operation of the gas turbine [2,3]. The cost effectiveness of the gas turbine inlet air pre-cooling techniques will obviously depend on the reference operating conditions for a given gas turbine plant. Inlet air temperature is a critical factor in turbine performance analysis [4]. For warmer climates to show greater incremental power production, it will incur greater pre-cooling loads and cooling system cost. On the other hand water shortages may preclude evaporative pre-cooling technique in drier climates. The evaporative pre-cooling technique has the following benefits: very low unit capital cost, simple and reliable designs/operations, low limitation on the time or duration of inlet air cooling operations, lower parasitic power consumption, low operational cost and quick delivery. In spite of all these benefits, limited power gain due to wet-bulb temperature and high consumption of large amounts of purified water, high maintenance cost due to scaling and water treatment, limited capacity improvement are all problems associated with evaporative pre-cooling techniques.

Furthermore, high capital cost, high operations and maintenance cost, high heat rejection than other reference systems are problems associated with the absorption pre-cooling system. Higher parasitic load than the evaporative pre-cooling technique, additional chilled water cooling circuit, longer delivery time, very high maintenance cost, formation of ice at the compressor inlet are all

drawbacks related to the vapour compression pre-cooling system. The above-mentioned problems associated with the various pre-cooling techniques are considered in this study with particular interest to their economics and thermodynamic parameters as well as the prevailing climatic conditions. Recent studies include comparison of the different inlet air cooling methods [5,6] and applications to selected countries.
The objectives of this study, therefore, considers the economics of the different pre-cooling techniques utilized in the enhancement of Gas Turbine Power output operational in a typical tropical country. A case study of Nigeria is presented. Most countries in tropical areas do not have homogenous climate and weather conditions. Nigeria, for example, has two major climatic zones in the northern and southern parts of the country. This means that the climatic condition in the northern region of Nigeria is different from that of the Southern region. It is similarly so for many tropical countries where heterogeneous climates is common. Based on this, the pre-cooling technique employed in the various regions must differ. This study is therefore necessary as it compares the various pre-cooling techniques and recommends the exact technique that will be suitable for use for a tropical region based on the prevailing climate and economic factors.

2.0 Materials and methods

An open cycle HITACHI – MS – 7001B Gas turbine plant was utilized for this study. Its operating data were collected from the daily turbine control log sheet for a period of ten years. The plant was divided into different control units namely compressor, turbine and pre-cooling units.

Energy and mass conservation laws were applied to each of the units to ascertain the economic feasibility of the pre-cooling techniques studied. The performance of the plant was therefore determined for the reference plant (without pre-cooling technique) and for the pre-cooled system (with evaporative, vapour compression and vapor absorption pre-cooling systems).

Furthermore, the economics of the respective pre-cooling techniques was considered and compared with that of the reference plant (without pre-cooling). Table 1 shows the list of the main design specifications of the Gas turbine plant studied.

Table 1: Range of Parameters for the Present Analysis

PARAMETERS	RANGE
AMBIENT AIR	
Ambient Air Temperature	27 – 50^0 C
Ambient Air Relative Humidity	18 – 84%
GAS TURBINE MODEL HITACHI – MS – 7001B	
Pressure Ratio (P_2/P_1)	10
Net Power (I.S.O)	52.4MW
Site Power	37MW
Turbine Inlet Temperature	1274K
Air Mass Flow rate	141.16kg/s
Fuel Calorific Value	46000kJ/kg
Turbine Isentropic Efficiency	82%
Air – Fuel ratio	80:1
Electrical Efficiency	95%
Mechanical Efficiency	90%
Pump Efficiency	65%

2.1 Description of the Systems

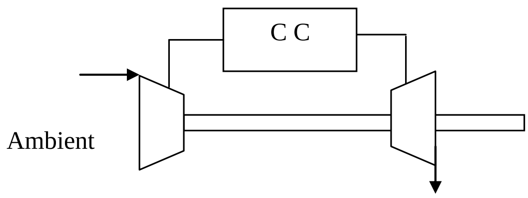

Figure 1: Schematic Diagram of the Standard Gas Turbine Cycle

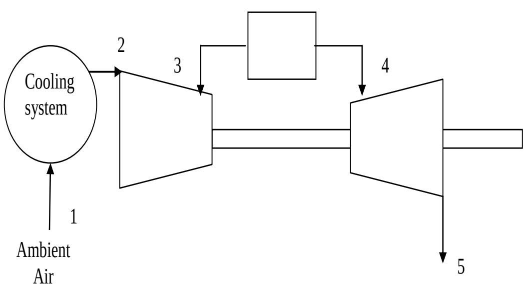

Figure 2: Schematic Diagram of a Gas turbine cycle with pre-cooling techniques

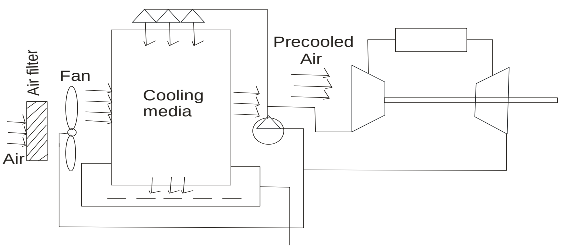

Figure 3: schematic diagram of an evaporative pre-cooling system integrated to a gas turbine plant

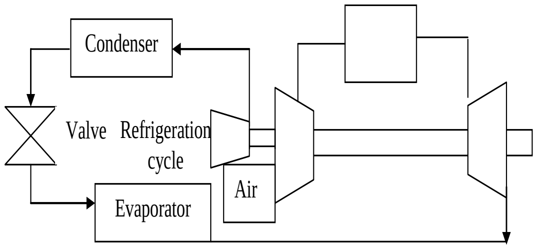

Figure 4: Schematic diagram of a gas turbine plant integrated with vapour compression system

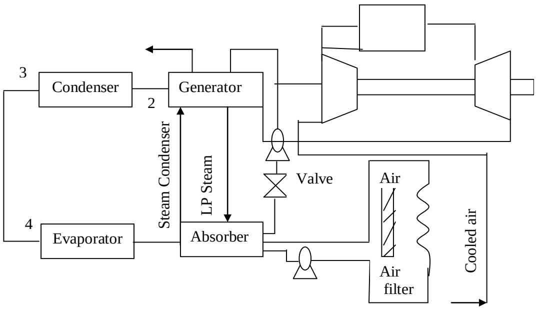

Figure 5: Schematic diagram of a gas turbine plant integrated with a vapour absorption refrigeration system

Figure 1 shows the schematic diagram of a single shaft gas turbine (HITACHI –MS – 7001B) cycle, the type considered in this work. Ambient air is drawn into the compressor, and the air is been compressed by the compressor and passed to the combustion chamber. Energy is supplied in the combustion by spraying fuel into the compressed air stream, and the resulting hot gas expands through the turbine to the atmosphere. The combustion of the fuel in the combustion chamber produces a mechanical work which drives the turbine shaft.

Figure 2 shows a schematic diagram of the gas turbine coupled with a pre-cooling system. It is composed of a standard gas turbine plant and an inlet air pre-cooler.
In this study, the following pre-cooling techniques are proposed for analysis:

i. Evaporative pre-cooling,
ii. Vapour compression pre-cooling and,
iii. Vapour absorption pre-cooling.

The evaporative pre-cooling technique utilizes the latent heat of evaporation to cool ambient temperature from the dry-bulb to the wet-bulb temperature. The evaporative pre-cooling equipment is placed after the air filter so as to prevent dust from entering the compressor and the pre-cooling equipment as shown in Figure 3. Figure 4 shows an integration of vapour compression system to the gas turbine plant while Fig. 5 is an integration of the plant to a vapour absorption refrigeration system.

The inlet air temperature after pre-cooling is calculated by [7]:

$$T_1 = T_{b2} - (T_{b2} - T_{w2})\varepsilon \qquad (1)$$

Where:

T_{b2} is the dry-bulb temperature (K)

T_{w2} is the wet-bulb temperature (K),

ε is the evaporative pre-cooling effectiveness (%)

2.2 Economic Analysis of the Precooling Techniques

The increase in the power output due to intake air pre-cooling will add to the revenue of the Gas Turbine plant. However, this will be partially offset by the increase of the annual payments associated with the cost of installation, personnel and utility expenditures for the operation of the respective pre-cooling systems.
The annual operation cost is a function of the operation period, t_{op}, cost of installation of the chiller, C^{c}_{ch}, cost of cooling coil, C^{c}_{cc} and the electricity rate cost, C^{c}_{el}.
If the various pre-cooling techniques consume electrical power, T_e, and the electricity rate is C^{c}_{el} ($/KWh) then the total annual cost can be expressed as [8]:

$$C_{total} = a^{c}\left[C^{c}_{el} + C^{c}_{cc}\right] + \int_{o}^{top} c_{el} T_e \, dt \qquad (2)$$

Where:
T_e represents the electrical power consumed by the vapour pre-cooling systems (i.e. evaporative, vapour compression and vapour absorption pre-cooling techniques).

The capital recovery factor, a^{c}, is calculated as [8]:

$$a^{c} = \frac{i(I+i)^n}{(I+i)^{n-1}} \qquad (3)$$

Where:
n is the specific period (years), and i is the interest rate (%).

(a) Economic Analysis for Evaporative Precooling System

The performance of the gas turbine plant using evaporative pre-cooling technique is usually dependent on ambient temperature and humidity. This analysis is focused on ambient temperature.

For evaporative pre-cooling techniques, C_{ch}^{c} and C_{cc}^{c} are negligible, and T_e is taken as the electrical power consumed by the fan and pump; thus equation (2) is reduced to:

$$C_{total} = a^{c} + \int_{o}^{top} c_a \dot{W}_{pf}\, dt \qquad (4)$$

Where:

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

$$\dot{W}_{pf} = \dot{W}_{p} + \dot{W}_{f} \qquad (5)$$

$\dot{W}_{p}$ and $\dot{W}_{f}$ is power consumed by pump and power consumed by fan respectively.

Electrical power consumed by pump is given as [7]:

$$\dot{W}_{p} = \dot{m}_{w} V_{f} \,\Delta p / \eta_{pump} \qquad (6)$$

And that consumed by the fan is given as 10% of the power required to drive the pump

$$\dot{W}_{f} = 0.1 \dot{W}_{p} \qquad (7)$$

Where:

$\dot{m}_{w}$ is the mass flow rate of water (kg/s), Δp is the pressure change in the flow of water (N/m^2), η_{pump} is the mechanical efficiency of the pump, (%) and V_f is the velocity of water flowing into the evaporative pre-cooling header media.

(b) Economic Analysis for Vapour Compression Precooling Technique

For vapour compression pre-cooling technique, the electrical power consumed by the compressor ($\dot{W}_{mc}$) replaces T_e in equation (7) thus the total cost is given as:

$$C_{total} = a^{c}\left[C_{ch}^{c} + C_{cc}^{c}\right] + \int_{o}^{top} c_{el} \dot{W}_{mc}\, dt \qquad (8)$$

Where:

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

(c) Economic Analysis for Vapour Absorption Precooling Technique

For vapour absorption pre-cooling techniques, the compressor in vapour compression refrigeration system is being replaced with a generator and an absorber. Hence, the electrical power usually consumed in vapour absorption pre-cooling system is that required to drive the generator.

The total cost required to run the vapour absorption pre-cooling system is given as:

$$C_{total} = a^{c}\left[C_{ch}^{c} + C_{cc}^{c}\right] + \int_{o}^{top} c_{el} \dot{W}_{Ge}\, dt \qquad (9)$$

Where:

$\dot{W}_{Ge}$ is the power required to drive the generator.

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 the following values are from the maintenance log book of the utilized turbine as:

C_{cc}^{c} = $ 2,061,676.93 approximately

C_{ch}^{c} = $ 418,107.53 approximately.

2.3 Evaluation Criteria of Gas Turbine Precooling System

In order to evaluate the feasibility of a pre-cooling system coupled to a Gas turbine plant, it is important to examine the performance of the plant with and without any pre-cooling techniques.

In this work, the study is done by considering the performance of the Gas turbine for the various pre-cooling methods chosen as well as the economic analysis of the resulting system. In order to study the performance of a gas turbine fitted with a pre-cooling method the power gain ratio (PGR) and the thermal efficiency change (TEC) [8, 9] is given as:

$$PGR = \frac{\dot{W}_{net\ with\ cooling} - \dot{W}_{net\ without cooling}}{\dot{W}_{net\ without cooling}} \times 100 \qquad (10)$$

$$TEC = \frac{\eta_{th\ with\ cooling} - \eta_{th\ without cooling}}{\eta_{th\ without cooling}} \times 100 \qquad (11)$$

2.4 System Profitability

In order to investigate the economic feasibility of retrofitting a gas turbine plant with air intake pre-cooling system, the total cost of the pre-cooling system and the increase in annual income cash flow from selling the additional electricity generated is determined.

The annual exported energy by the power plant fitted with a pre-cooling system is [8]:

$$E\ (kWh) = \int_{o}^{top} W_{net}\,dt \qquad (12)$$

3.0 Results and Discussion

Figures 6 and 7 highlight some significant results from this investigation.

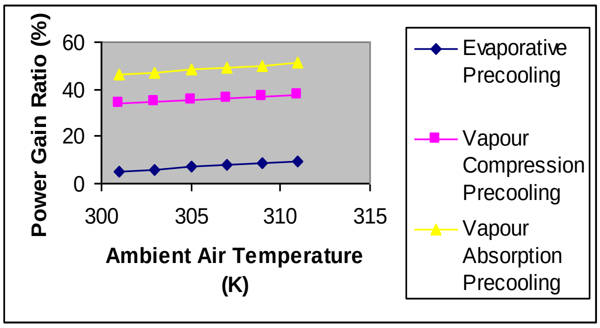

Figure 6: Variation of Power Gain Ratio (%) for the various pre-cooling techniques

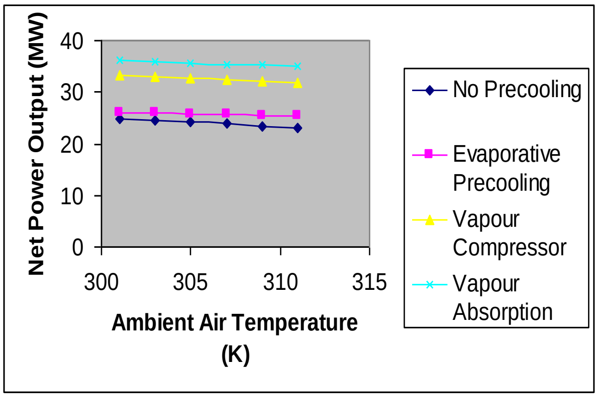

Figure 7: Comparison of Net Power Output for various precooling techniques at different ambient air temperatures

Figs 6 and 7 show the variation of Net Power Output and Power Gain Ratio for the various precooling techniques studied. This shows that vapour absorption precooling techniques records the highest Power Output and Power Gain Ratio compared to other precooling techniques respectively. Increase in inlet air temperature shows a relatively low performance in the dry season as compared to the rainy season. Based on this reduction in power generation during the hot season, various pre-cooling techniques are employed to cool the inlet air entering the compressor. While pre-cooling the compressor inlet air, it is very important that the air is pre-cooled in such a way that it will not form ice on the compressor blades (i.e. below 10^{0}C)

Evaporative pre-cooling techniques reduces the ambient temperature by approximately 2% and also the power required to drive the compressor is reduced as compared to the reference case (without any pre-cooling techniques). The net power output of the gas turbine plant has also increased by about 3% which shows a compensation of the effect of ambient air temperature to power generated in the hot season. The ambient air temperature is pre-cooled by approximately 2%, the power required to drive the compressor is reduced to about 1.23% hence the gas turbine will generate more power and perform better as compared to the reference case

Pre-cooled air using vapour compression pre-cooling method increased the net power output by about 28% compared to the reference case (without any pre-cooling techniques). When the air is pre-cooled, the compressor consumes less work as compared to the reference case.

3.1 Cost analysis

Using the above equations for economic analysis, the results in Table 2 were obtained. The table contains result for system profitability and net revenue for different ambient temperatures depicting typical seasons in a tropical country.

Table 2: System Profitability and Net Revenue for different precooling techniques

Amb temp. (k)	System profitability ($ / KWh)			NET REVENUE (N$/KWh)		
	Evap. precooling	Vapour comp.	Vapour absorption	Evap. precooling	Vapour comp.	Vapour absorption
301	965,994.8	5,721,705.7	7,535,677.2	99,468.4	650,776.3	8,868,293.8
303	1,058,397	5,759,749.4	7,620,320.99	99,885.4	667,434.6	9,045,285.5

305	1,264,166.9	5,764,748.2	7,686,314.7	101,524.3	689,535.5	9,202,609.1
307	1,404,707.3	5,841,411.9	7,710,377.2	103,685.6	757,785.5	9,374,188.96
309	1,525,873.5	5,901,105.7	7,792,727.2	105,136.8	799,436.7	9,561,743.9
311	1,716,082.2	5,967,074.4	7,796,578.5	105,784.2	812,376.5	9,736,645.6

The total annual cost, C_{total}, for evaporative pre-cooling techniques is $28,688.98/KWh; those of vapour compression and vapour absorption Pre-cooling techniques are $78,600.60/KWh and $1,332,616.51/KWh respectively. From eq. (12), system profitability for evaporative precooling is $994,684/KWh; for vapour compression it is $650,776/KWh while for vapour absorption precooling it is $8,866,294/KWh.

4.0 Conclusion and Recommendation

The performance of gas turbine plants in a typical tropical country has been studied taking into account the various inlet air pre-cooling techniques from thermodynamics and economics perspective. This study showed that the system works more efficiently during the dry and hot climatic conditions session. The results obtained at different ambient temperatures yearly show that, the use of evaporative inlet air pre-cooling system as a measure for system enhancement was found to increase the power output of the gas turbine by over 7%. Vapour compression pre-cooling system increased the system power output by about 10%. More so, vapour absorption pre-cooling system increased the turbine power output by 13%. The total yearly gas turbine output power gained due to cooling by evaporative, vapour compression and vapour absorption inlet air precooling are 5.24%, 33.8% and 46% respectively. Therefore evaporative precooling is best suited for areas with abundance of water; while vapour compression and vapour absorption precooling techniques can be utilized safely in areas of low availability of water.

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The 1st International Conference on Energy, Environment and Economics (ICEEE 2016) was held at Heriot-Watt University, Edinburgh, EH14 4AS, UK, 16-18 August 2016. ICEEE2016 focused on energy, environment and economics of energy systems and their applications. More than fifty eight delegates from 31 countries with diverse expertise ranging from energy economics, solar thermal, water engineering, automotive, energy, economics and policy, sustainable development, bio fuels, Nano technologies, climate change, life cycle analysis etc. made conference true to its name and completely international. During conference total 51 oral presentations and six posters were shared between delegates. The presentations showed the depth and breadth of research across different research areas ranging from diverse background. ICEEE2016 aimed:

- To identify and share experiences, challenges and technical expertise on how to tackle growing energy use and greenhouse gas emissions and how to promote sustainability and economical, cost effective energy efficiency measures.

In total 11 technical sessions and two invited talks both from academia and industry provided insight into the recent development on the proposed theme of the conference. Preparation, organisation and delivery of the conference started from July 2015 and further co-ordinated by vibrant team of Conference Centre, Heriot Watt University. Conference organisers would like to acknowledge support from the sponsors particularly World Scientific Publication ltd and its team members for the delivery of the conference. Organisers are also thankful to all reviewers who contributed during peer review process and their contributions are well appreciated. At the end and during vote of thanks following awards have been announced and we would like to congratulate all well deserving delegates.

- Best Paper –Academia: Amela Ajanovic, EEG, TU Vienna, Austria
- Best Paper – Student : Christian Jenne,University of Duisburg-Essen, Germany
- Best Poster – Student: Yoann Guinard, University of New South Wales, Sydney, Australia
- Best Poster – Academia: E. Salleh, Universiti Kebangsaan Malaysia, Malaysia
- Active Participation Award - Yoann Guinard, University of New South Wales, Sydney, Australia

At the end we would like to extend our gratitude to all of you for your participation and hopefully welcome you again during ICEEE2017.

Editors:

Dr. Singh is Senior Scientist at Indian Agricultural Research Institute, New Delhi, India. Her area of expertise are bio energy and bio fuels, environmental engineering, carbon accounting and renewable energy integration for rural development.

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