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.

Article Information

DOI: 10.9734/JERR/2020/v15i417152

Editor(s):
(1) Dr. Pierre-Olivier Logerais, Université Paris-Est Créteil, France.
(2) Dr. Raad Yahya Qassim, The Federal University of Rio de Janeiro, Brazil.

Reviewer(s):
(1) Anand P. Darji, S. V. National Institute of Technology, India.
(2) Pankaj Mishra, India.

Complete Peer review History: http://www.sdiarticle4.com/review-history/57665

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 years. 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).
Keywords: Absorption; precooling; pump; refrigeration.

NOMENCLATURE

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

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

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

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

$T_e$ is the electrical power (kW)

$\alpha$ is the capital recovery factor

$i$ is the interest rate (%)

$n$ is the specific period (years)

$W_{pf}$ is the power consumed by both pump and fan (KW)

$W_p$ is the power consumed by pump (kW)

$W_f$ is the power consumed by fan (KW)

$m_w$ is the mass flow rate of water (kg/s)

$\Delta p$ is the pressure drop (N/m$^2$)

$\eta_{pump}$ is the mechanical efficiency of pump (%)

$v_f$ is the flow rate of water (m/s)

$W_{me}$ is the electric power required to drive the compressor (kW)

$W_{ge}$ 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)

$W_{net}$ is the net power output (kW)

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

$E_{with\ cooling}$ 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
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 NOx 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.

![Schematic diagram of a gas turbine cycle with an evaporative cooler](image-url)
Table 1. Range of parameters for HITACHI MS – 7001B plant analysis

| Parameters                                           | Range          |
|------------------------------------------------------|----------------|
| **Ambient air**                                      |                |
| Ambient air temperature, $T_0$                       | 34°C           |
| Ambient air relative humidity, RH$_0$                | 78%            |
| **Gas turbine, model HITACHI – 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, $\eta_t$              | 88%            |
| Air compressor isentropic efficiency, $\eta_c$       | 82%            |
| Combustion efficiency, $\eta_{comb}$                 | 85%            |
| Air – fuel ratio                                     | 80:1           |
| **Generator**                                        |                |
| Electrical efficiency                                | 95%            |
| Mechanical efficiency                                | 90%            |
| Pump efficiency                                      | 65%            |
| **Water Chiller**                                    |                |
| Refrigerant                                          | R$_{22}$       |
| Evaporating temperature, $T_e$                       | $T_{chws} - TD_e$ °C |
| 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, $\xi_{eff-ch}$     | 85%            |
| Chiller compressor energy use efficiency, $\eta_{eu}$ | 85%            |
| Maintenance cost of chiller, $\infty_{ch}$          | USD149 kW$^{-1}$|
| **Cooling Coil**                                     |                |
| Cooling coil effectiveness, $\xi_{eff-co}$           | 85%            |
| Contact factor, CF                                   | 50%            |
| **Economics Analysis**                               |                |
| Interest rate, $i$                                   | 10%            |
| Period of repayment (payback period), $n$             | 3 years        |
| The maintenance cost, $\infty_{m}$                  | 10% of $C_{eu}$ |
| 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$_{22}$. 
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, \(C_{a}^{c}\), the cooling coil cost \(C_{c}^{v}\), and the electricity rate cost \(C_{el}^{e}\). If different precooling methods consume electrical power \(T_{e}\), and the cost of electricity rate is \(C_{el}^{e} \text{ (N/kWh)}\), then the overall yearly cost can be expressed as [8]:

\[
C_{total} = a^e \left[ C_{a}^{c} + C_{c}^{v} + \int_{0}^{t_{op}} c_{el} T_{e} \, dt \right]
\]

(1)

Where:

\(T_{e}\) is the electrical power used by the precooling systems. The capital recovery factor, \(a^c\), is calculated as [8],

\[
a^c = \frac{i(1+i)^n}{(1+i)^{n-1}}
\]

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

\[
C_{total} = C + \int_{0}^{\top} c_a W_{pf} \, dt
\]

Where:

\(W_{pf}\) is the power consumed by both pump and fan and it is given as:

\[
W_{pf} = W_p + W_f
\]

\(W_p\) and \(W_f\) represent the pump and fan power consumption respectively.

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

\[
W_p = \frac{m_w V_f \Delta p}{\eta_{pump}}
\]

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

\[
W_f = 0.1 W_p
\]

### 2.4.2 Economic analysis for vapour compression precooling technique

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

\[
C_{total} = C + \int_{0}^{\top} c_a W_{mc} \, dt
\]

Where: \(W_{mc}\) 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:

\[
C_{total} = C + \int_{0}^{\top} c_a W_{ge} \, dt
\]

Where: \(W_{ge}\) is the power required to drive the generator (KW).

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

\[ E (\text{kWh}) = \int_{0}^{\text{top}} W_{\text{net}} dt \]  

(9)

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

\[ \text{Net Revenue} = (E_{\text{with cooling}} - E_{\text{without cooling}}) C_{\text{els}} \]  

(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:

\[ \text{Profitability} = (E_{\text{with cooling}} - E_{\text{without cooling}}) C_{\text{els}} - C_{\text{total}} \]  

(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](image-url)
Fig. 5. Variation of net revenue for the different precooling techniques at different ambient air temperatures

![Graph showing net revenue variation](image)

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

![Pie chart showing cost distribution](image)

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 ($C_{\text{total}}$) 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 ($C_{\text{total}}$) 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 USD178,637.63/kWh, USD719,818.2/kWh, and USD1,110,374.74/kWh respectively and the payback time is three and a half year.
- Net Revenue of the systems is USD8,782,909.21/kWh, USD15,881,92.52/kWh and USD84,947,043.84/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.

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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        |

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Peer-review history:
The peer review history for this paper can be accessed here:
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