Enhancing Gas Turbine Output Through Inlet Air Cooling

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ABSTRACT

Combustion gas turbines are constant-volume engines for which shaft horsepower is proportional to the combustion air mass flow. Their output and efficiency are known to decrease as the ambient temperature increases. The present paper investigates the technical and economical feasibility of using turbine inlet air cooling and its effect on the performance of gas turbines in Khartoum area. The study entertained three options namely: refrigerative, fogging and wetted media evaporative cooling. Although refrigerate cooling is proved to provide the lowest inlet air temperature but was found very costly.

Based on the study results of this investigation wetted media evaporative cooling is found to be the most economically feasible option and is therefore recommended to be utilized to improve gas turbine performance in Khartoum area.

Keywords: gas turbines, wetted media, inlet air cooling

1. INTRODUCTION

The Gas Turbine (GT) cycle consists of four processes: compression, combustion, expansion and exhaust. Characteristics of this cycle differ from the Otto and diesel cycles in that the compression, combustion, expansion and exhaust processes for the gas turbine are continuous, rather than intermittent as with the reciprocating engines. The advantages of gas turbines include the following:

1. Gas turbine units have the advantage that the number of machines on line can be increased or decreased in a very short time.

2. The Gas turbine is the most readily available power plant to meet the variation of load profile.

3. The installation costs for gas turbines per Megawatt are relatively low and the turbines can be operational in a very short time.

4. Gas turbines require less highly specialized operation and maintenance staff.

Gas turbine applications in Sudan date back to 1967. Many difficulties were encountered during their application in Sudan. The main problem was that the units output was always less than the ISO rating due to high ambient temperature throughout the year.

2. EFFECT OF DUST ON THE GAS TURBINE PERFORMANCE

Khartoum is classified as a dusty area (dust load is >0.1 ppm by weight) [1]. One extra advantage of the selected cooling system is that it is expected to contribute in the removal or reduction of dust particles in the inlet air. The effect on GT performance of the dust contaminant depends on its amount, size, mechanical properties and its chemical composition. This effect can be explained as follows:

1- Erosion of compressor and turbine components from the sand and mineral dust.

2- Fouling, since submicron of dust is too small to be trapped by conventional filtration systems, it can enter the compressor and deposit on the blades.

3- Corrosion of compressor blades causes pitting of the blade surface.

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4- Cooling passage plugging, since the cooling air flow is extracted from the compressor. Contaminant in the inlet air may also be present in the cooling air. If these contaminant cause a build up in the cooling passage heat transfer is degraded and temperature may increase to levels which give rise to cracking.

5- The presence of sodium, potassium, vanadium and lead in the inlet air after combining with sulfur and/or oxygen during the combustion process deposit on the surfaces of the hot gas path cause protective oxides film on the hot gas path part to be disrupted so that the parts oxides several times faster than in the presence of gases free of them [2].

3. Gas Turbine Performance Improvements
Traditionally many modifications were carried out to improve GT performance; the following are the most used methods:

3.1 Regeneration
The regenerator is simply a surface-type heat exchanger used to preheat the compressed air by exhaust gases and result in increasing the efficiency accompanied with a decrease in the pressure ratio.

3.2 Compressor Intercooling
Air is first compressed to some intermediate pressure, and then passed through an intercooler, before passing through another stage of the compressor, where its pressure is further raised to the final pressure. The overall result is a lowering of the net work input required for a given pressure ratio.

3.3 Turbine Reheat
Reheat can be performed in two separate turbine stages, (HP and LP). This can be done by placing a second combustion chamber between the two turbine stages in order to heat the gases leaving the HP turbine. The use of reheat increases the turbine work output without changing the compressor work or the maximum limiting turbine inlet temperature.

4. GAS TURBINE INLET COOLING
Recently more power out of a gas turbine is achieved by simply increasing the mass flow rate of air into the compressor. Turbine inlet air cooling (TIAC) systems are commonly used to cool the inlet air, this process increases the air density which increases the total mass flow rate and therefore enhances power production and net efficiency. The installation of gas turbine and combined cycle power plants has particularly increased in North America during recent years, 35% to over 50% of the delivered stationary gas turbines are already equipped with an evaporative cooler [3].

MS5001 unit with an ISO rating of 25.5 MW and site rating of 21.750 MW at an ambient condition of 31°C and 1.013 bar was selected for wetted media evaporative inlet cooling test. When the system is operated at the same ambient temperature, using evaporative cooling the maximum load achieved during the test was 24.6 MW, which represents an increase of 2.4 MW [4].

A TIAC system with ice storage for Nebraska Company GT unit with an ISO rating of 59.8 MW, cools the inlet air from an ambient air temperature of 38°C to 4°C and produces a net power increase of approximately 12 MW (about 21%) [5].

The GE-7EA GT normally produces about 140 ppm of NOx. An evaporative cooling system is used in one unit of this type fitted with steam injection system, that injects steam directly into the primary zone of the combustors. Both these systems were found to reduce NOx emissions. A Fogging system was installed downstream of the evaporative cooling system (Fog intercooling). Emissions tests performed with the inlet fogging system in operation showed a further reduction in specific NOx of about 18% [6].

5. THE STUDY SITE
5.1 The Weather
Khartoum (384 m altitude) the capital of Sudan is considered in general to lie in a hot and dry region. The average wet bulb temperature depression of 12.2, indicates low humidity ratio through out the year. Khartoum is consuming around 80% of the energy generated in the National Grid (NG). In 2003...
the NG total installed capacity was 1,016 MW and the available was 689 MW. The Maximum peak at 2003 summer was 570 MW and the maximum winter peak was 480 MW. The daily peak hours are between 7 pm to 10 pm. During the period from April to June all generating units of NG were on full load operation [7].

5.2 Site power output and heat rate correction factors

Gas turbine output depends on the air density. Air density is affected by the altitude, temperature and humidity [8]. The following equations are used to compute the actual GT output and heat rate at any location.

\[
\text{GT output (site)} = \text{output (ISO)} \times \text{altitude Correction factor (C.F)} \times \text{temperature C.F} \times \text{humidity C.F} \\
\text{GT heat rate (site)} = \text{heat rate (ISO)} \times \text{temperature C.F} \times \text{humidity C.F} 
\]

(1)

Altitude C.F = air density at site altitude / air density at sea level

Temperature C.F = air density at Ti / air density at 15°C

where Ti = compressor inlet temperature

Humidity C.F = air density at site R.H. / air density at 60% R.H.

The above correction factors when compared (see Table 1) show that, in Khartoum, the temperature correction factor is the most effective factor in the turbine performance.

6. THE COOLING SYSTEM

In this study three cooling systems were investigated from the technical and economical points of view, when used individually to cool inlet air at entry to gas turbines in Khartoum area. The three cooling systems are depicted below.

6.1 Evaporative cooling system

Evaporative cooling is an effective and commonly used system in drier climates, for cooling gas turbine inlet air, since large amount of cooling is accomplished with expenditure of relatively small amount of electric power which is needed to drive small pumps. The system is shown in Figure 1 below. The performance calculation is shown in Table 1 according to Equation (1).

6.2 Fogging system

Inlet fogging is simply described as spraying atomized water into the inlet air stream of the GT. When the fog droplets evaporate they cool the inlet air and make it denser. Evaporation in fogging system will continue up to saturation line, and in some cases may exceed the saturation point causing over saturation. Water droplets of less than 40 microns in diameter make up the fog, when droplet sizes become larger than this, they are called a mist. Fogs tend to remain longer times in air than mists [9]. The system is shown schematically in Figure 2. The performance calculation is shown in Table (1) according to Equation (1).

![Figure 1: Schematic drawing of Wetted media Evaporative cooling.](image-url)
6.3 Refrigerative inlet air cooling system

Refrigerative inlet cooling systems are used to cool the inlet air through the heat exchanger coils installed in gas turbine inlet filter house, by using direct refrigerant in the cooling coils or by secondary cooling fluid (usually water). Refrigerative systems are much more effective and reliable; hence it can cool the air to less than 10°C regardless of the ambient wet-bulb temperature. While it is significantly more expensive on a first-cost basis than evaporative cooling and inlet fogging, but the systems can be installed at half the cost of installing new turbine. The system is shown schematically in Figure 3 below and the performance calculation is shown in Table (1) according to Equation (1).

7. TECHNICAL FEASIBILITY OF COOLING SYSTEMS

The selection of any cooling system depends on the site conditions. General electric gas turbine PG7111EA with ISO rating of 83.5 MW and heat rate of 10,500 kJ/kWh, was chosen to be the experimental unit in this study because an enormous amount of data is available about it. The data which satisfy the base load equation (max output) was selected for the temperatures range from 7°C to 43°C. A curve was drawn as shown in Figure 4. It is depicted that a decrease of 1 °C of inlet air temperature will increase output by 0.623 %. This value is approximately equal to the manufacture's value of 0.616 % [10].
7.1 Inlet Cooling Degree Hour (ICDH)

This term of degree-hour is used in inlet cooling to define the total amount of cooling that can be expected in a particular climate zone. Useful ICDH for Khartoum city of 103,349 and 88,902 represent 96.4% and 97.6% for fogging and wetted media respectively for 8760 hour per year. ICDH for refrigative cooling with inlet cooling temperature of 10°C was found to be 180,275.

7.2 Power Capacity Enhancement

In order to study the effect of TIAC on GT performance, calculations will be done for gas turbine with and without TIAC at the maximum dry bulb temperature recorded (45.6°C).

Corrected Output at Khartoum without TIAC = 83.5 x 0.81 x 0.9575 x 0.9999 = 64.75 MW

Corrected heat rate at Khartoum without TIAC = 11,025x 1.05x1.0001 = 11,577 kJ/kWh

The Net Power Capacity enhancement with TIAC cooling options shown in Figure 5 shows 16.98, 11.88, 10.15 MW which represent percentage enhancement of 26.2%, 18.3%, 15.8% for refrigative, fogging and wetted media respectively.

7.3 Total output power enhancement, MWh

Figure 6 depicts the monthly MWh that can be produced throughout the year for TIAC options while Figure 7 shows the effect of cooling options on the total net gas turbine energy production. The calculation is based on an hourly weather data of Khartoum city.
The refrigerative cooling can cool the inlet air to 10°C whenever the ambient temperature is greater than 13°C. Equation (3) is used to calculate total energy enhancement [11]:

\[
\text{Total gain in megawatt hour} = \text{ICDH} \times \text{MW increase per one degree of inlet cooling} = \text{ICDH} \times (0.62\%) \quad (3)
\]

Using Equation (3), calculations show total gain of 77,348 MWh, 51,255 MWh and 44,028 MWh for refrigerative, fogging and wetted media evaporative cooling respectively.

7.4 Total heat rate reduction, kJ/kWh

Using Equation (2) calculations shows that, refrigerative cooling achieved the highest reduction of 667kJ/kWh compared to 454kJ/kWh and 425kJ/kWh for fogging and wetted media evaporative cooling respectively. Heat rate improvement was found to be 5.8, 3.9 and 3.7 for refrigerative, fogging and wetted media respectively.

8.0 Economical feasibility

In order to select a suitable system for Khartoum city, a cost benefit analysis is required to determine the economic feasibility of any inlet cooling option. Refrigerative cooling depicted the maximum benefit of TIAC options. The energy generated when using this option equals 1.51 and 1.75 times the energy that can be generated from fogging and wetted media evaporative cooling respectively. The installation cost of refrigerative cooling is nearly half that of installing a new unit, and is 4 and 5 times more expensive than the cost of fogging and wetted media evaporative cooling respectively. The pay back period is found to be 2.2, 0.6 and 0.4 years for refrigerative, fogging and wetted media respectively.

In the calculations of the revenues, energy production price was taken as $0.107/kWh. The selling price was taken to be $0.136/kWh, which represents the commercial selling price of Sudanese National Electricity Corporation (NEC) [7]. The summary of all calculations performed to evaluate the different options technically and economically is shown in Table (1).

<table>
<thead>
<tr>
<th>Cooling option</th>
<th>Evaporative cooling</th>
<th>Refrigerative system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>wetted media</td>
<td>Fogging</td>
</tr>
<tr>
<td>Inlet temperature (°C )</td>
<td>24.7</td>
<td>21</td>
</tr>
<tr>
<td>Evaporative cooling effectiveness (%)</td>
<td>85</td>
<td>100</td>
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<tr>
<td>Altitude correction factor</td>
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<tr>
<td>Temperature correction factor</td>
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<tr>
<td>Humidity correction factor</td>
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<tr>
<td>Turbine output, (MW)</td>
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<td>76.63</td>
</tr>
<tr>
<td>Heat rate improvement (%)</td>
<td>3.7</td>
<td>3.9</td>
</tr>
<tr>
<td>% Gain in power</td>
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<td>18.3</td>
</tr>
<tr>
<td>Cost / cost of new unit</td>
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<td>0.125</td>
</tr>
</tbody>
</table>
9. DISCUSSION

Evaporative cooling (fogging and wetted media) appears to be the best economical solution according to the weather condition of Khartoum city. Wetted media is recommended because it is less risky when used with mist eliminator, approved by all GT manufacturers. Nile water can be used directly for most of the year as raw water without treatment. The Fogging system is not recommended due to the following reasons:

1. Risk of over spray is high.
2. Demineralized water is required and its long use can deteriorate inlet ducts.
3. Droplets coalesced on downstream components may grow into larger droplets, and cause compressor blades erosion. Proper design and careful drainage is needed in this case.
4. Corrosive and erosive effects can cause roughness of the blades, which result in compressor fouling and hence reduce the benefits of the system on the output.

10. CONCLUSION

The technical and economical feasibility of different means available for cooling inlet air to the compressor of Gas Turbine Power Plants in the Khartoum area is investigated. The two main cooling systems, evaporative cooling and refrigerated inlet air-cooling, were considered in this study. Based on the study results, the following conclusions can be made:

1. Turbine inlet cooling enhanced the GT output by 26.2%, 18.3% and 15.8% for refrigerative, fogging and wetted media evaporative cooling respectively and showed an improvement in the efficiency by reducing the heat rate (5.8%, 3.9% and 3.7% for refrigerative, fogging and wetted media evaporative cooling respectively).
2. Refrigerated inlet air-cooling is found to be the most feasible technical option, since it can reduce the inlet air temperature below the wet bulb temperature (cooling to 10°C). The energy generated from refrigerative cooling equals 1.51 and 1.75 times the energy that can be generated from fogging and wetted media evaporative cooling respectively. But it is 4 and 5 times more expensive than the cost of fogging and wetted media evaporative cooling respectively.
3. The wetted media inlet air-cooling is found to be the most feasible economical option. Operation of wetted media is simple, safe and economical. Unlike operation of other systems, it requires less maintenance cost and less experience.
4. The wetted media inlet air-cooling system can eliminate major problems such as compressor fouling and cooling passage plugging of turbine blades that result in reduced power output. Wetted media act as second stage cleaning filter in this regard.
5. Evaporative cooling increases the water vapour content of the combustion air and hence, causes significant decrease in NOx emissions.

REFERENCES

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