Turbine Inlet Air Cooling for Industrial and Aero-derivative Gas Turbine in Malaysia Climate

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Abstract. The performance of a gas turbine is dependent on the ambient temperature. A higher temperature results in a reduction of the gas turbine’s power output and an increase in heat rate. The warm and humid climate in Malaysia with its high ambient air temperature has an adverse effect on the performance of gas turbine generators. In this paper, the expected effect of turbine inlet air cooling technology on the annual performance of an aero-derivative gas turbine (GE LM6000PD) is compared against that of an industrial gas turbine (GE Fr6B.03) using GT Pro software. This study investigated the annual net energy output and the annual net electrical efficiency of a plant with and without turbine inlet air cooling technology. The results show that the aero-derivative gas turbine responds more favorably to turbine inlet air cooling technology, thereby yielding higher annual net energy output and higher net electrical efficiency when compared to the industrial gas turbine.

1. Introduction
The gas turbine (GT) which was originally used as a jet engine technology and was later transformed into power generation in the early 1990s [1]. The performance of the GT (power output, heat rate, exhaust gas flow and exhaust gas temperature) is greatly dependent on the inlet air temperature to the GT [2]. In a tropical country such as Malaysia the GT its own drawback as its performance is rated at ISO condition with inlet air temperature of 15ºC, while the ambient temperature varies between 25ºC to 37ºC [3]. Power producers de-rate their GT power plants to reflect the higher ambient temperature. It is possible to recover these performance losses by utilizing the air inlet cooling by chilled water. Turbine inlet air cooling (TIAC) technology is designed to chill the inlet air to 15ºC and lower temperatures, thereby enhancing the power output and efficiency of the GT.

The GT has been used in Malaysia to generate electricity and the demand for electricity was estimated to increase annually at 4% for the year 2010 to 2014. It is predicted to achieve more than 150000 GWh by 2030 [4].

In the past, studies of the GT inlet air cooling had been undertaken by many authors. All this research has proven that there is an increase in the GT power output when inlet air cooling technology is implemented [5-8]. The majority of industries using inlet air cooling technology are in those part of
the world where the climate is tropical and the Middle East as there is a tremendous de-rating factor due to high relative humidity (RH) [9-12].

Dbral et al. [13] in their research stated that ambient air conditions including dry bulb and humidity were important parameters affecting the performance of the GT when it was operated as an open cycle. The researchers reported that the lower air temperatures resulted in a high density of air which led to a high mass flow. As a result, there was a higher output from the turbine since output is proportional to the mass flow of the air inlet.

Jonsson and Yan [14] reported that the implementation of the TIAC technology has increased in recent years due to the increase in the demand for power at a lower cost. The researches made a comparison between two cooling methods (evaporative cooling and mechanical chiller) for the GT’s inlet air cooling which was installed at the Khangiran Refinery in Iran. The researches indicated that the inlet air temperature using a mechanical chiller was much lower than that the evaporative cooling method. The increase in thermal efficiency was as low as 7% to 13.2%.

De Sa and Al Zubaidi [10] did a study of the SIEMENS Gas Turbine (SGT) 94.2 and SGT 94.3 which were installed at the DEWA Power Station located at AL Aweer in Dubai, UAE. It was reported that at a higher temperature, thermal efficiency and output were lower. For every Kelvin rise of ambient temperature, the resulted showed a 0.1% loss in thermal efficiency. By varying its ambient temperature accordingly to the ISO, both GT’s showed an increase of 44 MW of useful power generated.

Hence, the impact of the increased ambient temperature can be dramatic, due to decreased air density and higher fluid temperatures. The compressor absorbs more power when inlet air is hot, leaving a small percentage of total power available for the output [13]. The equations also show that the compressor’s specific work is reduced when there is a decrease of the air inlet temperature. Consequently, the GT’s efficiency increases.

Mohanty et al. [15] reported that by reducing the ambient temperature to 15ºC, the power output of its GT (typical 100MW) showed increases in the range of 8 to 13%. The cooling technique that was applied used an absorption chiller.

In China, Cheng Yang et al. [5] conducted a study using a chiller with Lithium Bromide/water (LiBr-H2O) and also by fogging method to cool down the inlet air temperature. The results showed a superiority in power efficiency when the ambient temperature was in the range of 15ºC to 20ºC.

Meanwhile in Iran, a research conducted by Farzaneh and Deymi [16] at the Kangiran Gas refinery recorded an increase of 7% to 13.5% of thermal efficiency when there was a drop in the temperature from 46ºC to 3ºC. This study implemented the evaporative cooling and mechanical chiller methods to cool down the GT’s inlet air.

![Figure 1. System performance [17]](image)
Figure 1 verifies that the correction factor of the turbine output is dependent on the compressor’s inlet air temperature as stated by Sakhaei et al. [17]. This proves that a decrement of 20°F in the inlet air temperature can increase the GT power to approximately 7%. This finding is supported by Komuro et al. [18] as shown in Figure 2 below. The figure shows that by decreasing the inlet air ambient temperature to 15°C, the power output of the GT is 100% efficient. The red array in Figure 2 shows the power which can be recovered as the ambient is at the ISO setting (15°C).

![Figure 2](image-url)

**Figure 2.** Power output recovery mechanism by the inlet air cooling system [18].

In the current study, the annual performance of different GT (industrial and aero-derivative) systems are evaluated in order to determine the higher power augmentation when TIAC technology is applied.

### 2. Methodology

The local data of dry bulb, wet bulb and RH for year 2015 from Sitiawan, Perak, Malaysia have been used for this study. The local data were evaluated using the binning method to determine the net power output and overall net electrical efficiency of a plant with and without using TIAC technology.

The data gathered from the meteorology department in the year of 2015 is specified to hourly ambient temperature. Data of wet bulb (WB) temperature, dry bulb (DB) temperature and the relative humidity (RH) were used. Based on these data, a scatter graph of RH versus DB was plotted.

The GT Pro software is used to simulate the annual performance of two gas turbine models which are GE LM6000PD (aero-derivative GT) and GEFr6B.03 (industrial GT) operating with and without Turbine Inlet Air Cooling, in Malaysian climate. For the purpose of annual performance analysis, Sitiawan’s weather data is analysed and divided into 27 discrete time periods covering a total of 8756 operating hours. Each time bin indicate the associated operating hours, mean dry bulb and wet bulb temperatures.

### 3. Result and Discussion

The results from the GT Pro software were tabulated for a total of 8,756 operating hours for the year 2015. Table 1 shows the simulation results for aero derivative GT model LM6000PD. The increase in performance is substantially higher for all performance parameters compared to the industrial model of GT.
Table 1. Simulation Results for GTG Model LM6000PD.

| Simulation Result                          | With TIAC | Without TIAC | % Gain from TIAC |
|-------------------------------------------|-----------|--------------|------------------|
| Annual Operating Hours                    | hr        | 8,756        | 8,756            |
| Annual Plant Gross Energy Output          | kWh       | 388,289,450  | 311,912,549      | 24.49            |
| Annual Plant Nett Energy Output           | kWh       | 368,740,564  | 303,543,725      | 21.48            |
| Annual Plant Fuel LHV Energy Input        | kWh       | 935,284,256  | 788,545,060      | 18.61            |
| Annual Plant Gross Heat Rate              | kJ/kWh    | 8,671.43     | 9,101.15         |
| Annual Plant Nett Heat Rate               | kJ/kWh    | 9,131.14     | 9,352.07         |
| Annual Plant Gross Electrical Efficiency  | %         | 41.52        | 39.56            | 4.96             |
| Annual Plant Nett Electrical Efficiency   | %         | 39.43        | 38.49            | 2.42             |

Table 2 shows the simulation results for the industrial GT model GEfr6B.03 operates in an open cycle mode. The results show that there is huge gain in performance with TIAC except for overall plant net electrical efficiency.

Table 2. Simulation Results for GTG Model GEfr6B.03.

| Simulation Result                          | With TIAC | Without TIAC | % Gain from TIAC |
|-------------------------------------------|-----------|--------------|------------------|
| Annual Operating Hours                    | hr        | 8,756        | 8,756            |
| Annual Plant Gross Energy Output          | kWh       | 389,390,997  | 352,598,974      | 10.43            |
| Annual Plant Nett Energy Output           | kWh       | 372,551,672  | 347,342,827      | 7.26             |
| Annual Plant Fuel LHV Energy Input        | kWh       | 1,163,415,86 | 1,081,930,437    | 7.53             |
| Annual Plant Gross Heat Rate              | kJ/kWh    | 10,756.02    | 11,046.40        |
| Annual Plant Nett Heat Rate               | kJ/kWh    | 11,242.19    | 11,213.56        |
| Annual Plant Gross Electrical Efficiency  | %         | 33.47        | 32.59            | 2.70             |
| Annual Plant Nett Electrical Efficiency   | %         | 32.02        | 32.10            | -0.25            |

Figure 3 shows the annual plant net energy output for both GT models with and without using the TIAC. The introduction of the TIAC has improved the net power output by 7.26 % for the industrial model and 21.48 % for the aero- derivative model respectively.

![Annual Plant Nett Power Output](image)

**Figure 3.** Annual Plant Nett Energy Output

As shown in Figure 4, with TIAC the annual plant net heat rate for the GE LM6000PD is expected to decrease by 2.36% while for the GEfr6B.03, it is expected to increase by 0.25%. Heat rate is the
amount of fuel energy it heat input required to generate a kilowatt hour and deliver it to the
transmission line [19].

![Annual Plant Nett Heat Rate](image1)

**Figure 4.** Annual Plant Nett Heat Rate

Figure 5 illustrates the annual plant net electrical efficiency for both GT models. The
implementation of the TIAC technology has improved the net electrical efficiency by 2.42% for the
aero-derivative GT. However the overall plant net plant electrical efficiency is marginally reduced by
0.25%.

![Annual Plant Nett Electrical Efficiency](image2)

**Figure 5.** Annual Plant Nett Electrical Efficiency

From the result obtained, it can be concluded that both GT models are responsive to the difference
of turbine inlet air temperatures. The GE LM600PD, being an aero-derivative machine, is highly
responsive to the inlet air temperature. By contrast, the GEFr6B.03, being an industrial gas turbine, is
moderately responsive to the inlet air temperature.

With the inlet air cooled to 12°C, the annual net power output and net electrical efficiency can be
improved when the parasitic load of the chiller system for turbine inlet air cooling is taken into account

4. Conclusion

The aero-derivative heritage of the GE LM600PD enables the machine to respond more favourably to
TIAC power augmentation technology, thereby yielding higher annual net energy output and higher
annual plant nett electrical efficiency when compared to the industrial GEFr6B.03. Hence it may be
worthwhile for plants with aero-derivative GT installations to consider implementing TIAC technology
to reap the potential benefits of increased power output and improved net electrical efficiency. Plants
with industrial GTs can expect increased power output with TIAC albeit with potentially lower net
electrical efficiency.
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