Performance Characteristics of GE Frame 8 Gas Turbine Power Plant at Different Climatic Zones in Nigeria

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Abstract- Climatic conditions such as the ambient temperature and relative humidity has been reported to affect the performance of gas turbines. Nigeria has three major climatic zones: the tropical rain forest, savanna zone, and swampy zone. The different climatic conditions at these zones will affect the performance of power plant. In this work, the performance characteristics of a 125 MW General Electric (GE) frame 8 gas turbine plant were studied at these zones. Sokoto, Lagos and Delta states were used as the representative states for the savanna zone, Tropical rain forest, and swampy zone, respectively. Thermodynamic analysis of various components of the gas turbine was carried out using Engineering Equation Solver (EES) software. The model developed was validated using operating data of 2016 for a currently installed power plant located in Ondo state, Nigeria. The predicted and actual power generated were observed to follow the same trend. The maximum deviation between the predicted power generated using the model developed and actual power generated is less than 4%. Results further showed that when relative humidity was considered, the power generated from the modelled gas turbine was higher than the power generated when the relative humidity was neglected. By neglecting the effect of humidity, the power output from a GE frame 8 gas turbine can be under-predicted by about 2.3%. This represents an average daily under prediction of about 65 MWh. The power generated by GE frame 8 gas turbine in the month of January was highest in Sokoto state, while the power generated in the months of April, July and October were highest in power plant located in Delta state. The power plant located in Delta state will generate 6,157 MWh and 1,244 MWh more power annually than power plants located in Sokoto and Lagos state, respectively.

Keywords- Frame 8 gas turbine, Engineering Equation solver software, Performance characteristics, Nigeria, climatic zones

1 INTRODUCTION

Gas turbines are widely being used for generating electricity, operating airplanes and for various industrial applications such as refineries and petrochemical plants (Oyedepo and Kilanko, 2014). The efficiency and net power output are performance criteria of gas turbines. Research has shown that climatic conditions such as ambient temperature and relative humidity affect the performance of gas turbines (Barigozzi et al., 2015; Mohapatra and Sanjay, 2015; Santos et al., 2016). In tropical countries, ambient temperature varies between 5°C and 45°C while relative humidity varies between 24% and 81% (Shukla and Singh, 2014). This implies that the performance of gas turbine will depend on geographical location and seasonal changes.

Nigeria is located in the tropical region with four climatic conditions: Arid zone, Savanna zone, Tropical rain forest, and swampy zone. Nigeria has not been able to generate adequate electricity for its teeming populace (Adhekpuokli, 2018). The power shortage has greatly affected the industrialization drive of the government as well as the commercial activity of its citizens. In order to improve the availability of electric power supply, Nigerian government has embarked on aggressive installation of gas turbine in different part of the country that covers different climatic zones. The performance of these gas turbines depends on the prevailing climatic conditions of the project sites. Research has shown that the average efficiency of gas turbine plants in the Nigerian energy utility sector over the past three decades was in the range 27-30% (Oyedepo and Kilanko, 2014). The low efficiencies of the gas turbine plants are tied to many factors which include: operation mode, poor maintenance procedures, age of plant, discrepancies in operating data (Kumar et al., 2017). It has also been well documented that the relative humidity and the ambient temperature affect the performance characteristics of gas turbines (González-Díaz and Alcatraz-Calderon 2017; Kumar et al., 2017). For instance, a study carried out by Liu et al. (2017) showed that the efficiency of gas turbine increases with increasing ambient temperature up till 288 K. They reported that a further increase in the ambient temperature led to a decreased gas turbine efficiency due to the fuel gases losses. González-Díaz and Alcatraz-Calderon (2017) reported that the power generated decreases from 676.3 MW at 15 °C to 530 MW at 45 °C due to seasonal changes in ambient temperature. This implies that the fuel cost per unit power increases at the expense of a decreased efficiency from 50.95% to 43.46%.

Kumar et. al., (2018) also reported that for every 1°C increase in ambient temperature of air, specific work output decreases by 0.5-0.9%. The decreased power output can be attributed to lower density of air at higher temperatures. The decreased ambient temperature and increased relative humidity increased power output of a gas turbine plant in Iran by about 14.6% and 13.3% respectively (Kumar et al., 2017). Ebrahimi (2017) reported that performance of a power plant is more sensitive to ambient temperature than relative humidity and altitude. For political stability, Nigeria government is embarking on installation of gas turbine in different geopolitical zones. These zones are characterized with different climatic conditions that include variations in the ambient temperature and relative humidity. Therefore, there is need to understand performance characteristics of gas turbine under these climatic conditions.

In this work performance characteristics of frame 8 gas turbine plant was studied under Lagos, Sokoto and Delta States climatic conditions (i.e. tropical rain forest, savanna zone and swampy) in Nigeria. The climatic conditions considered are ambient temperature and relative humidity only. The frame 8 gas turbine manufactured by

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General Electric (GE) is the most widely installed gas turbine power plant in Nigeria.

2 Methodology

2.1 Description of the Power Plant

The gas turbine power plant considered in this work is General Electric (GE) frame 8 power plants currently installed in one of the power generation sites in Nigeria. The power rating of a unit in the power plant is 125 MWe. The plant is an open cycle gas turbine with the following major components: compressor, combustion chamber, turbine and the generator (alternator). A simple schematic description of the plant is shown in Fig. 1. The gas-turbine plant operates on the principle of the Brayton cycle, where the compressed air from the compressor is mixed with fuel, and burned under constant pressure conditions in the combustion chamber. The combustion product is allowed to expand through a turbine to perform work. The turbine shaft is used to drive the alternator for electricity generation. Operation data were collected from the selected power plant site. These data were used to validate the model presented in section 2.3. The validated model of the power plant was used to evaluate the gas turbine at different climatic zones under consideration.

\[ W_T = (\sum_c m_c C_{pc}) (T_2 - T_1) \]  
\[ m_T = m_a + m_v \]  

The mass of vapour and dry air were calculated from specific humidity relation, given by:

\[ \omega = \left( \frac{0.622 \times P_v}{P - P_v} \right) = \left( \frac{m_v}{m_a} \right) \]  

Table 1. Data from GE frame 8 Gas Turbine Power Plant

| S/N | TIME | INLET AIR AMB. TEMP. \( T_1 \) \(^\circ\)C | CPD \( P_2 \) (bar) | CTD(P) \( T_2 \) \(^\circ\)C | POWER OUTPUT \( W_2 \) (MW) |
|-----|------|---------------------------------|----------------|-----------------|-----------------|
| 1   | 0:00 | 26                             | 10.6           | 357             | 113.0           |
| 2   | 1:00 | 25                             | 10.8           | 357             | 114.5           |
| 3   | 2:00 | 24                             | 10.8           | 357             | 115.1           |
| 4   | 3:00 | 24                             | 10.8           | 357             | 115.2           |
| 5   | 4:00 | 24                             | 10.8           | 357             | 115.0           |
| 6   | 5:00 | 24                             | 10.8           | 357             | 115.3           |
| 7   | 6:00 | 24                             | 10.9           | 357             | 116.2           |
| 8   | 7:00 | 24                             | 10.9           | 358             | 115.8           |
| 9   | 8:00 | 24                             | 10.9           | 358             | 115.8           |
| 10  | 9:00 | 25                             | 10.8           | 359             | 115.0           |
| 11  | 10:00| 27                             | 10.7           | 360             | 112.7           |
| 12  | 11:00| 29                             | 10.6           | 363             | 111.1           |
| 13  | 12:00| 31                             | 10.5           | 364             | 109.5           |
| 14  | 13:00| 31                             | 10.5           | 365             | 109.5           |
| 15  | 14:00| 32                             | 10.4           | 365             | 108.5           |
| 16  | 15:00| 34                             | 10.3           | 366             | 106.5           |
| 17  | 16:00| 33                             | 10.3           | 365             | 106.2           |
| 18  | 17:00| 33                             | 10.4           | 366             | 107.0           |
| 19  | 18:00| 33                             | 10.3           | 365             | 106.5           |
| 20  | 19:00| 31                             | 10.3           | 360             | 108.3           |
| 21  | 20:00| 29                             | 10.4           | 358             | 110.0           |
| 22  | 21:00| 29                             | 10.5           | 359             | 110.8           |
| 23  | 22:00| 27                             | 10.6           | 358             | 111.6           |
| 24  | 23:00| 27                             | 10.6           | 358             | 111.5           |

Source: Power plant log book, Ondo state

2.2 GE Frame 8 Gas Turbine Operation Data

The operating data for the power plant were collected from the control log sheet for 2016. The hourly data were obtained for the period of January to December. The sample operating parameters for the GE Frame 8 gas turbine unit used for this study were presented in Table 1. The data were obtained for a typical day in April for power plant located in Ondo state.

2.3 Thermodynamic Model

The thermodynamic equations of various components of the simple open cycle gas turbine shown in Fig. 1 are as follows (Sanusi and Mokheimer, 2019).

Compressor

The air temperature at the air compressor was modelled by (Sanusi and Mokheimer, 2019):

\[ T_2 = T_1 \left( 1 + \frac{1}{\eta_c} \left( \frac{T_c}{T_1} - 1 \right) \right) \]  

Where the specific heat capacity ratio at constant pressure at compressor mean temperature was computed from:

\[ Y_c = \frac{m_{c1}(\text{air} \ T=T_{mc}) + m_{c2}(\text{vapour} \ T=T_{mc})}{m_{c1}(\text{air} \ T=T_{mc}) + m_{c2(\text{vapour} \ T=T_{mc})} \ (2)} \]  

\[ T_{mc} = \frac{T_2 + T_1}{2} \]  

The exit temperature of the gas turbine was modelled by (Sanusi and Mokheimer, 2019):

\[ T_3 = T_2 \left( 1 - \eta_c \left( 1 - \frac{Y_c}{\psi} \right) \right) \]  

The gas specific heat ratio of the turbine working fluid (\( Y_t \)) was computed at turbine mean temperature as:

\[ Y_t = \frac{\sum m_{c1}(\text{air} \ T=T_{mc})}{\sum m_{c1}(\text{air} \ T=T_{mc})} \]  

\[ T_{mt} = \frac{T_3 + T_4}{2} \]  

The turbine work was calculated from:

\[ W_t = \left( \sum m_c C_{pc} \right) (T_3 - T_4) \]  

Combustion chamber

For simplicity, methane was used as the representative gas of natural gas (Sanusi and Mokheimer, 2017). The burning of the fuel in the combustion chamber was modelled as:

\[ \text{CH}_4 + \frac{2}{9} (\text{O}_2 + 3.762N_2) \rightarrow \text{CO}_2 + 2(\text{H}_2\text{O}) + \frac{7.524}{9} \text{N}_2 + 2 \left( \frac{5}{3} - 1 \right) \text{O}_2 \]  

\[ h_3 = h_2 + m_{CH_4} \cdot \text{LHV}_{CH_4} \cdot \eta_c \]  

Gas turbine

The exit temperature of the gas turbine was modelled by (Sanusi and Mokheimer, 2019):

\[ T_4 = T_3 \left( 1 - \eta_t \left( 1 - \frac{Y_t}{\psi} \right) \right) \]  

The gas specific heat ratio of the turbine working fluid (\( Y_t \)) was computed at turbine mean temperature as:

\[ Y_t = \frac{\sum m_{c1}(\text{air} \ T=T_{mc})}{\sum m_{c1}(\text{air} \ T=T_{mc})} \]  

\[ T_{mt} = \frac{T_3 + T_4}{2} \]  

The turbine work was calculated from:

\[ W_t = \left( \sum m_c C_{pc} \right) (T_3 - T_4) \]  

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The turbine net work done was computed from:
\[ W_{\text{net}} = W_t - W_c \] (13)

Power generation was obtained from:
\[ P_{\text{gen}} = W_{\text{net}} \eta_{\text{c}} \eta_{\text{e}} \] (14)

The power plant efficiency was computed from:
\[ \eta_p = \frac{P_{\text{gen}}}{mc_{\text{in}} \times \text{LHV}} \] (15)

3 Model Validation

In order to validate the set of equations presented in this work for GE frame 8 gas turbine, on site operation data shown in Table 1 were used. The set of equations presented in section 2.3 were solved using Engineering Equation Solver (EES) software. The flow chart presented in Figure 2 shows the routine followed in the simulation process. The thermodynamic and transport properties of the working fluid in-built in the software (EES, 2013) were used for the simulation process. The simulation was carried out based on the following assumptions: All processes were under steady state conditions, methane was used as the representative gas for the natural gas and all the gases were ideal gases. The compressor discharge temperature and power output obtained from the control log sheet were used for the model validation.

Fig. 3 shows the simulated power generated from GE frame 8 gas turbine and the actual power generated. It can be seen that the EES code generally over predicted the power generation. The predicted power generation however, followed the same trend as those of the actual power generation. The trend was characterized by higher power generation during the early hours of the day. This period has low ambient temperature. Previous studies has shown that a lower ambient temperature leads to lower compressor work (Rahman et. al., 2011), that enhances the power plant output. Besides, air density is higher at lower ambient temperature, leading to increased mass flow rate to the compressor and amount of power generated at the turbine. In Table 2, the performance of the plant for the range of ambient temperature at plant location was compared. The maximum deviation between the predicted power generated using the EES code and actual power generated is less than 4% (see Table 2). This implies the EES model developed in this work for GE frame 8 power plant gave a good prediction of the actual power generation on site.

**Table 2. Comparison of actual and simulated power output of GE frame 8 gas turbine**

| Compressor inlet temperature (K) | Compressor discharge temperature (K) | Power output (MW) | Compressor discharge temperature (K) | Power output (MW) |
|---------------------------------|--------------------------------------|-------------------|--------------------------------------|-------------------|
| 295                             | 631                                  | 115.8             | 601.2 (4.7 %)                       | 117.558 (1.5 %)   |
| 306                             | 657                                  | 109.5             | 620.2 (2.6 %)                       | 113.011 (3.2 %)   |

4 Results and Discussion

Relative humidity is used to express the amount of water vapor needed to saturate air at the same temperature. It simply denotes the presence of water vapour in air. If the relative humidity is considered in gas turbine modelling, it means that certain percentage of the compressor air intake is modelled as water vapour with the balance modelled as dry air. On the other hand, the compressor air intake is modelled as 100 % dry air if, the relative humidity is neglected. Figure 4 shows the effect of humidity on modelled frame 8 gas turbine in Lagos, Nigeria. It can generally be observed that when relative humidity was considered, the power generated from the
modelled gas turbine was higher than that generated from the gas turbine when the relative humidity was neglected. This can be attributed to the fact that the presence of water vapour in moist air reduces the air temperature rise in the compressor. This reduces the compressor work, thereby increasing the gas turbine net power output. This implies that by neglecting the effect of humidity, the power output from a GE frame 8 gas turbine can be under-predicted by about 2.3%. This represents an average daily under prediction of about 65 MWh. This is significant in power nominal term. Therefore, this work was carried out taking into consideration, the relative humidity in the simulation.

The seasonal power generated from frame 8 gas turbine in Lagos is shown in Figure 5. The power generated in the early and later part of the day were generally higher than those generated during the afternoon. This is due to the fact that air temperatures were generally lower during the early and later part of the day. During these periods, the air density is higher leading to high compressor charge rate. Thus, higher power generation at the turbine unit. The low air temperature also enhances the cooling of the compressor which lowers the compressor power consumption. In Lagos, March-May are categorized as hot spring with highest ambient temperature compared to the other months of the year. Therefore, the power generated during the month of April was observed to be the lowest when compared to other months presented in Figure 5. Further analysis shows that the average power generated by the plant in the month of July was the highest and more than those generated in January, April and October by 320, 531 and 296 MWh, respectively. It is important to state that the months of June, July and August are referred to as warm summer month that are characterized with heavy rainfall and higher relative humidity.

Figures 6 and 7 show the power generated and efficiency of GE frame 8 gas turbine in Lagos, Sokoto and Delta States. These states are used as representative state in Tropical rain forest, Savanna zone, and swampy zone that majorly characterize Nigeria climatic conditions. The power generated by GE frame 8 gas turbine in Sokoto state is the highest in January and lowest in other months presented in Figure 6. This is due to the fact that in January, Sokoto has cold weather and harmattan wind that is blowing Sahara dust. The dust dims the sunlight, thereby lowering temperatures significantly. Thus, the ambient temperature obtainable in January is lowest in Sokoto when compared to other states considered in this work. Also, Sokoto is one of the hottest cities in Nigeria with the highest recorded temperature of 45°C (Nwankwo & Shehu, 2015).

The ambient temperature obtainable in the month of April, July and October in Sokoto is higher than those obtainable in Lagos and Delta states. Apart from the month of January, the highest power is generated by GE frame 8 gas turbine located in Delta state. This is because Delta state has a lower ambient temperature and higher relative humidity than Sokoto and Lagos states in most days of April, July and October. As stated earlier, lower ambient temperature and higher relative humidity leads to a higher air density and a lower compressor work that in turn gives a higher gas turbine net power generated and efficiency (Pathirathna, 2013; Sidum et.al.,2015).
Figure 6 shows simulated monthly average power output from GE frame 8 power plant in Lagos, Sokoto and Delta state for the months of January, April, July and October. It can be seen that the power output of gas turbine plant located in Sokoto is the highest in January while the plant located in delta generate the highest power in the month of April, July and October. Further analysis shows that GE frame 8 power plant located in Delta will generate 6,157 MWh more power than GE frame 8 power plant located in Sokoto annually. Also, GE frame 8 power plant located in Delta will generate 1,244 MWh more power than GE frame 8 power plant located in Lagos over the same period.

Fig. 6: Power output of GE frame 8 gas turbine power plant in Lagos, Sokoto and Delta states for January, April, July and October.

Fig. 7: Thermal efficiency of GE frame 8 power plant in Lagos, Sokoto and Delta states for January, April, July and October.

Fig. 8: Monthly average power output from GE frame 8 gas turbine power plant in Lagos, Sokoto and Delta.
5 CONCLUSION

Performance characteristics of a General Electric (GE) frame 8 gas turbine plant was studied under different climatic conditions (Savanna zone, Tropical rain forest, and swampy zone) in Nigeria. Sokoto, Lagos and Delta States were used as the representative state for the Savanna zone, Tropical rain forest, and swampy zone, respectively. Results showed that there is month-to-month variation in the power generated at all locations studied. For example, the power generated from the turbine plant in Lagos on month-to-month basis shows that power generated in July is the highest and more than those generated in January, April and October by 320, 531 and 296 MWh, respectively.

A comparison of the power generated at various locations studied revealed that the power generated by GE frame 8 gas turbine in Sokoto state is the highest in the month of January due to the lowest ambient temperature obtainable in Sokoto. The power generated in Sokoto is however the lowest when compared to other states for other months considered. The highest power is generated by GE frame 8 gas turbine located in Delta state. This is because Delta state has a lower air temperature and a higher relative humidity than Sokoto and Lagos states in most days of April, July and October. Further analysis shows that the power plant located in Delta will generate more 6,157 MWh and 1,244 MWh annually than power plants located in Sokoto and Lagos, respectively.

NOMENCLATURE

- CO₂: carbon dioxide
- CH₄: methane
- c_p: specific heat at constant pressure (kJ/kgK)
- c_v: specific heat at constant volume (kJ/kgK)
- H₂O: water
- h: specific enthalpy (kJ/kg)
- LHV: lower heating value = 45742kJ/kg
- m: mass flow rate (kg/s)
- N₂: nitrogen
- O₂: oxygen
- P: pressure (kPa)
- r: pressure ratio
- RH: relative humidity (%)
- SH: specific humidity (%)
- T: temperature (K)
- w_c: compressor work output (kW)
- w_t: turbine work output (kW)
- w_net: network output (kW)
- η_c: compressor efficiency (%) = 0.85
- η_e: electrical efficiency (%) = 0.985
- η_t: turbine efficiency (%) = 0.87
- η_th: thermal efficiency (%)
- η_cch: combustion chamber (%)
- γ: gas specific heat ratio
- φ: equivalent ratio

SUBSCRIPT

- c: compressor
- cc: combustion chamber
- cf: compressor working fluid
- t: turbine
- ct: turbine working fluid

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