The Effect of Ambient Conditions of Tropical Savanna Climate on the Performance of a Uniform Speed, Single Shaft Gas Turbine

Edeowede Abel Abhulimen
National Power Training Institute of Nigeria, NAPTIN
RTC-Afam, Port Harcourt, Nigeria
able.abel01@gmail.com

***Abstract*— A collection of climatic data with the primary parameters being the monthly ambient temperature and relative humidity was carried out on Tropical savanna climate with the Köppen climate classification System. This research investigates the combined effects of these climatic parameters on the performance of a uniform speed single shaft Gas Turbine, sited in Tropical Savanna Climatic zone. A single shaft gas turbine simulator (known as GPAL) from Gas Path Analysis ltd was employed whereas Benin City, Nigeria, was chosen from the Climatic zone, and its climatic data of monthly ambient temperature and relative humidity obtained from Koppen. With parameters like speed and reference power as well as inlet and exhaust losses kept constant, the ambient conditions were continually varied according to their climatic values. Each time, the performance of the gas turbine was simulated and parameters such as; Efficiency, Turbine power/Net power output, Turbine inlet Temperature/Exhaust Gas Temperature and Specific fuel consumption were monitored. The environmental impact of the gas turbine under these conditions was equally assessed in terms of; Carbon (IV) Oxide (CO_2) emission in Tonnes/day and in Kg/MWhr, Oxides of Nitrogen (NO_X) emission and Carbon Monoxide (CO) emission. The results of the study indicate that it is most efficient and productive to operate the gas turbine in Benin City in the month of June whereas it is worse off, in the month of December. The CO emission was found to be relatively low and uniform throughout the year whereas the specific fuel consumption was found to be highest in the months of March and April**.

Keywords*— *Gas Turbine; Performance; Ambient Conditions; Climate

I. INTRODUCTION

The gas turbine or combustion turbine is a type of continuous combustion, internal combustion engine which operates in a thermodynamic cycle known as the “Brayton cycle”, with air as its working fluid. Fresh atmospheric air flows through the compressor which brings it to higher pressure where energy is added by spraying fuel and igniting it so as to generate a high-temperature flow. This high-temperature high-pressure gas then enters a turbine, where it expands down to the exhaust, producing a shaft work output in the process [1]. The compressor draws in air, compresses it and feeds it at high pressure into the combustion chamber, increasing the intensity of the burning flame in a positive feedback mechanism. As the gas turbine speeds up, it causes the compressor to speed up, forcing more air through the combustion chamber which in turn increases the burn rate of the fuel and sending more high-pressure hot gases into the gas turbine thereby increasing its speed [2]. The gas turbine is widely used in industrial applications that require power. This power is employed in driving equipment such as pumps and process compressors or for electricity generation [3].

Ambient condition (from the word *ambience*), refers to the general environmental condition in an area which would certainly include temperature and could also be humidity, air pressure, air movement and presence of dust [4]. It refers to a set of parameters used by designers and a condition often considered when systems are commissioned and tested. A key factor that affects the performance of the gas turbine is the condition of inlet air, typically its temperature, humidity and pressure (since the density of air depends on its temperature and pressure) as well as water vapour content [5]. Ambient temperature is the temperature of any object or environment where equipment is situated and it relates to the immediate surroundings, sometimes referred to as the ordinary temperature or the baseline temperature. In the gas turbine, ambient temperature represents the compressor inlet temperature. If this temperature drops, the air density will increase and hence heaver air will be compressed by the compressor which will increase mass flow rate thereby increasing the compressor work requirements. As heavy compressed air enters the turbine section, it creates extra expansion & more work from turbine will be produced [6] – [8]. The humidity of air is the amount of water vapour needed to saturate the air and is referred to as relative humidity. It is related to specific humidity in that, an increase in relative humidity brings about increase in specific humidity. However, the increase in specific humidity and the change in the mass of vapour in air are small at low ambient temperature whereas at high ambient temperature, relative humidity will have a noticeable effect on the thermodynamic properties of air and products of combustion. At any given ambient temperature and pressure, an increase in relative humidity increases the specific humidity thus resulting in an increase in the gas constant, R, and specific heat at constant pressure, Cp for air while decreasing its isentropic index, γ and hence influencing engine performance [9].

A Tropical savanna climate is a tropical climate sub-type that corresponds to the Köppen climate classification categories Aw (for a dry "winter") and As (for a dry "summer") [10] . It is an area whose dry months have between 60mm and 100mm of precipitation. Relatively, a tropical savanna climate tends to either see less overall rainfall than a tropical monsoon climate or have more pronounced dry season(s) with distinct wet and dry seasons of about the same duration. Most of the region's annual rainfall is experienced during the wet season with very little precipitation. On one extreme, the region receives just enough precipitation during the short-wet season to preclude it from a semi-arid climate classification. This drier variation of the tropical savanna climate is typically found adjacent to regions with hot semi-arid climates. Tropical savanna climates are most commonly found in Africa, Asia, and South America. It is also prevalent in sections of Central America, northern Australia, the Pacific Islands, in sections of North America, and some islands in the Caribbean [11] – [13].

II. METHODOLOGY

The methodology of this research involves the collection of climatic data on tropical monsoon climate, represented by Benin City, Nigeria. The primary parameters considered were the monthly ambient temperature and relative humidity. The data were obtained from the Köppen climate classification systems [14]. The monthly ambient temperature and relative humidity for Benin City is as shown in Table I below. With the parameters from **Error! Reference source not found.** being fed into the Gas Path Analysis software (GPAL) as input, the performance of the gas turbine was analyzed in terms of efficiency, turbine power as well as net power output. The turbine inlet temperature, the exhaust Gas temperature and the Specific fuel consumption were equally modeled whereas the Emissions of Carbon IV Oxide (CO_2) in Tonnes/day and in Kg/MWhr, Oxides of Nitrogen (NO_X) and Carbon Monoxide (CO) were as well simulated.

III. RESULTS AND DISCUSSION

A. Efficiency

Fig. 1 Effects of ambient temperature and humidity in Benin City, on Thermal Efficiency shows the monthly variation in gas turbine efficiency as a result of variations in the ambient temperature and relative humidity in Benin City, Nigeria. It was found that the gas turbine fared best in terms of efficiency, in the month of June being 31.8% efficient. A better efficiency was also recorded in the months of August and September whereas it is least efficient to operate a single shaft uniform speed gas turbine in the months of January and December in Benin City, although there is no prominently disadvantageous month in terms of efficiency.

B. Power

The power output from the turbine as well as the net power output is presented in Fig. 2, Effects of ambient temperature and humidity in Benin City, on Power Output. The difference between the turbine work output and the net work output suggests the work done on the compressor. For a uniform monthly load setting of 45MW based on the conditions under investigation; the unit was only able to deliver an average of 35MW, being lowest for several months in Benin City. The month of June has a predominantly high-power output of 39MW. The decline in output in the worst months could be attributed to the effect of combined ambient temperature and relative humidity.

C. Specific Fuel Consumption

The specific fuel consumption (SFC) is an alternative means of determining the heat input per unit of work done. In line with the conditions being investigated, the result of the specific fuel consumption is displayed in **Error! Reference source not found.**. This was found to be predominantly high in April whereas it was best in the month of March and better in January and February as well as November, in Benin City. This relatively favourable SFC could be attributed to a higher value of the compressor discharge temperature (T_2) in these months, resulting in a reduced demand for fuel.

Table 1. Relative Humidity in Benin City [15]

	January	February	March	April	May	June	July	August	September	October	November	December
Min. Temperature (°C)	23.3	24.8	25.4	24.8	24.3	23.3	23.2	22.7	23.2	23.3	23.8	23.8
Max. Temperature (°C)	31.7	31.7	31.8	31.7	30.7	29.5	28.3	27.8	28.3	29.4	31.1	31.1
Avg. Temperature (°C)	**27.5**	**28.2**	**28.6**	**28.2**	**27.5**	**26.4**	**25.7**	**25.2**	**25.7**	**26.3**	**27.4**	**27.4**
Relative Humidity (%)	**72**	**70**	**71**	**71**	**75**	**81**	**81**	**78**	**78**	**78**	**74**	**70**

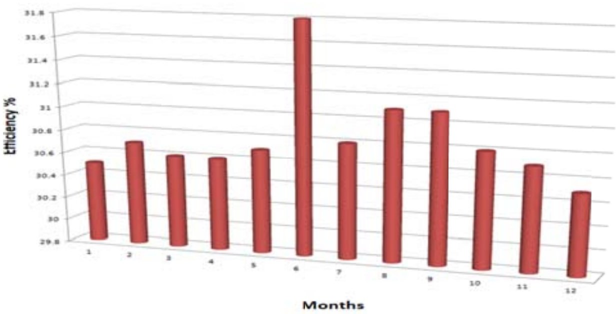

Fig. 1 Effects of ambient temperature and humidity in Benin City, on Thermal Efficiency

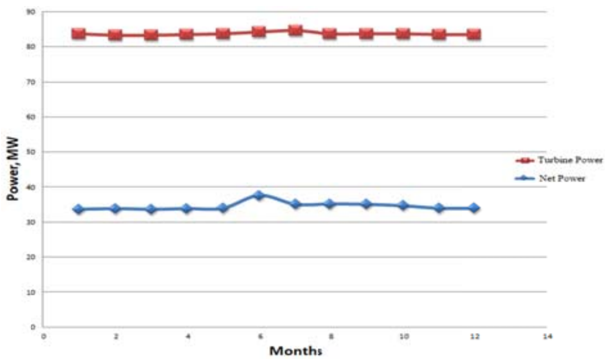

Fig. 2, Effects of ambient temperature and humidity in Benin City, on Power Output.

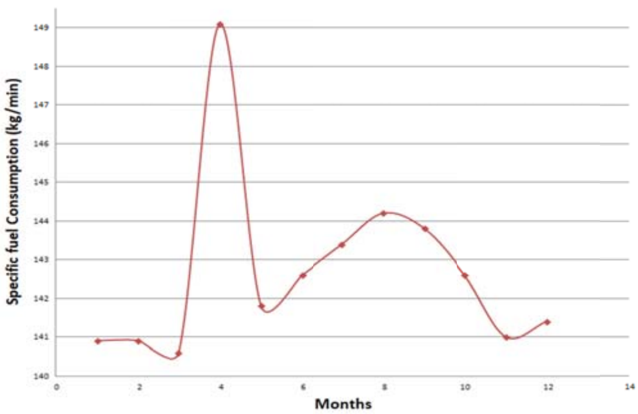

Fig. 3, Effects of ambient temperature and humidity in Benin City, on SFC

D. Temperature

Fig 4. Effects of ambient temperature and humidity in Benin, on TIT and EGTshows the turbine inlet temperature (TIT) and the exhaust gas temperature (EGT). Based on the conditions under investigation, the turbine inlet temperature was found to be lowest in the month of July and almost uniform at about1400k in other months in Benin City. The exhaust gas temperature was found to be fairly uniform at about 815K across the year. The uniformity in EGT could be attributed to EGT control system of the gas turbine which tends to keep the exhaust gas temperature constant and in turn vary other operating parameters of the gas turbine, pro rata.

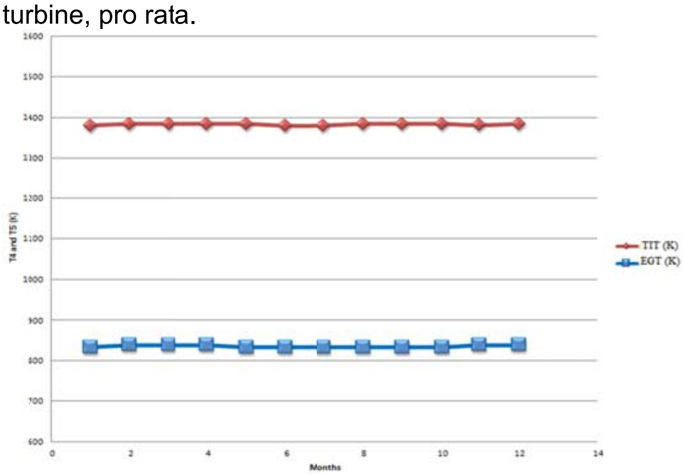

Fig 4. Effects of ambient temperature and humidity in Benin, on TIT and EGT

E. Emissions

The combustion system that uses hydrocarbon fuel produces carbon IV oxide (CO_2) and water vapour (H_2O) as the products of carbon and hydrogen oxidation. CO_2 and H_2O may be considered as non-toxic but they are greenhouse gases and have been associated with global warming. All combustion systems including those in the gas turbine, produce pollutants like oxides of nitrogen (NOx) and carbon monoxide (CO) as well. In this research, the environmental impact of the variation in ambient temperature and relative humidity on the gas turbine was investigated. From the results, efficiency was found to have an inverse bearing on CO_2 emissions as the increase in thermal efficiency results in a decrease in the CO_2 emission in Tonnes/day as shown in Fig. 5; Effects of ambient temperature and humidity in Benin City, on CO2 emission in Tonnes/day 5. The city was found to receive the lowest of such emission from the gas turbine in the months of June, August and September. The trend in CO_2 emission in kg/MWhr, was found to be highest in the months of April and August – Fig 6; Effects of ambient temperature and humidity in Benin City, on CO2 emission in Kg/MWh, whereas it was relatively low in the months of March, May and September respectively. This is not unconnected with the specific fuel consumption, as CO_2 emission increases with increase in the specific fuel consumption. The trend in NOx emissions is in line with the TIT. At higher turbine inlet temperatures, being in the months of June, July and August in Benin City; NOx emission was found to increase as shown in Fig 7; Effects of ambient temperature and humidity in Benin City, on NOX emission. The formation of CO is generally due to poor combustion efficiencies. When an engine operates at a lower load than the design value, it is possible to increase the combustion temperature helping to maintain CO emissions, which tend to increase due to lower combustion pressure. The research was conducted at 45MW for a gas turbine rated 50MW and the CO emission was therefore found to be fairly low and uniform at about 8.8PPMV @15% dry O_2, as shown in Fig. 8; Effects of ambient temperature/humidity in Benin City, on CO emission -PPMV @15% dry O2.

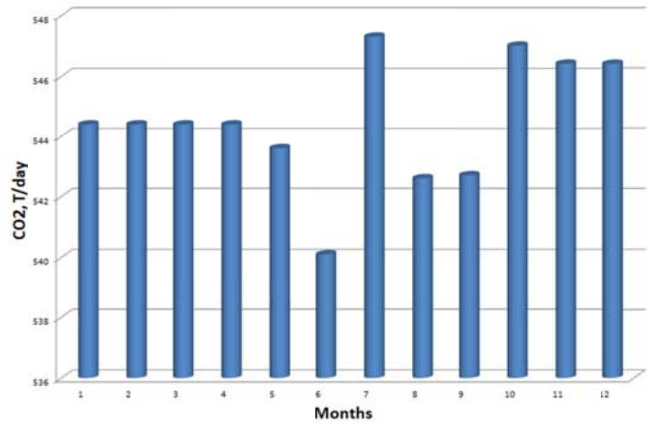

Fig. 5; Effects of ambient temperature and humidity in Benin City, on CO_2 emission in Tonnes/day

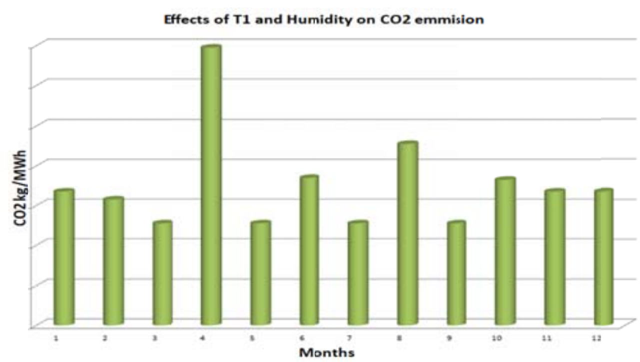

Fig 6; Effects of ambient temperature and humidity in Benin City, on CO_2 emission in Kg/MWh

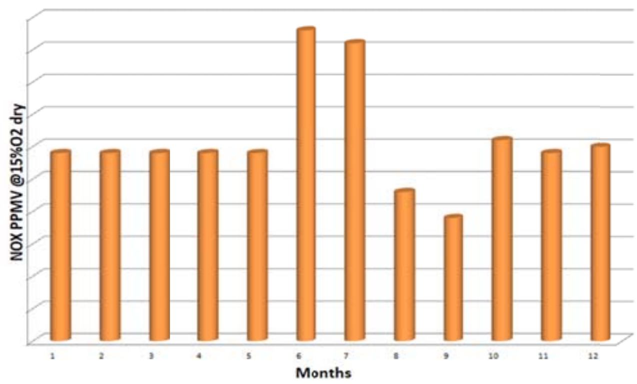

Fig 7; Effects of ambient temperature and humidity in Benin City, on NO_X emission

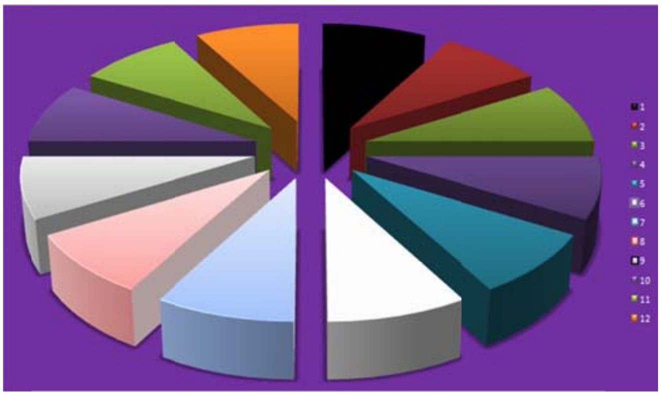

Fig. 8; Effects of ambient temperature/humidity in Benin City, on CO emission -PPMV @15% dry O_2

F. Impact on Revenue, Life Cycle Cost and Profitability

The use of Gas Path Analysis simulator made a holistic view of engine performance and operability, a possibility which may not be achieved with numerical exercise. This is a key area in gas turbine performance monitoring. The gas turbine deteriorates in performance as it operates, leading to reduced capacity and thermal efficiency. This loss of capacity results in production decline which in turn affects revenue whereas the loss in thermal efficiency increases fuel consumption leading to higher fuel costs. Both factors reduce profits. The off-design performance of the gas turbine was investigated with reference to the impact of the conditions below, on revenue, cost and profitability.

1) Impact on Revenue

The impact of the variation in ambient temperature and relative humidity on the gas turbine revenue was investigated. From the results; an increase in power output was worthwhile in terms of increased production and in turn, revenue. Thus, the month of June stood out in Benin City as depicted by Fig. 9: Monthly Revenue from a Gas Turbine in Benin. The overall performance of the gas turbine in terms of revenue is not unconnected with section B above.

2) Fuel Cost.

Fuel cost, together with some engine faults in gas turbines (such as compressor VIGV/VSV schedule problems) which result in incessant trips, increase life cycle costs. These problems affect revenue and profits thereby increasing life cycle costs. The increase in compressor pressure ratio and the turbine inlet temperature (TIT) as well as the maximum to minimum cycle temperature ratio, T_3/T_1, in the gas turbine often lead to increase in thermal efficiency. This increase in thermal efficiency lowers the operating cost, leading to a reduction in fuel cost. Increased heat rate, is another factor that increases the operating cost (fuel cost) of the gas turbine and this increase in fuel cost is one of the factors that determine when it is economical to wash the compressor. Fig. 10: Monthly Fuel Cost of a Gas Turbine in Benin shows the performance of the gas turbine in Benin City, in terms of fuel cost under the conditions being investigated. The months of May and July were found to be most expensive whereas the month of June fared best in terms of fuel cost in operating a uniform speed single shaft gas turbine in Benin City.

3) Profitability

In any of the gas turbine applications, its performance is the end product that strongly influences the profitability of the business employing it. Since the Industrial gas turbine has to operate for prolonged periods at conditions not corresponding to its design conditions, maximizing profit in its operation is paramount. The operating cost of the gas turbine as well as the overall life cycle cost was juxtaposed with revenue in this research to achieve the profit margin. Variations in atmospheric conditions, resulting in a loss in power output and unfavourable exhaust gas temperature limit were found to yield less revenue and thus less profit. Conversely, any operational or environmental condition that produces a significant increase in power output optimizes production capacity, resulting in increased revenue and profit. The variation of profit across the months in the year, for a uniform speed single shaft gas turbine in Tropical Savanna climatic zones in Nigeria, is presented in Fig. 11: Monthly Profit from a Gas Turbine in Benin. Prominently, the month of June was found to be most profitable whereas the months of November and December were not quite profitable in the life of a uniform speed single shaft gas turbine in Benin City.

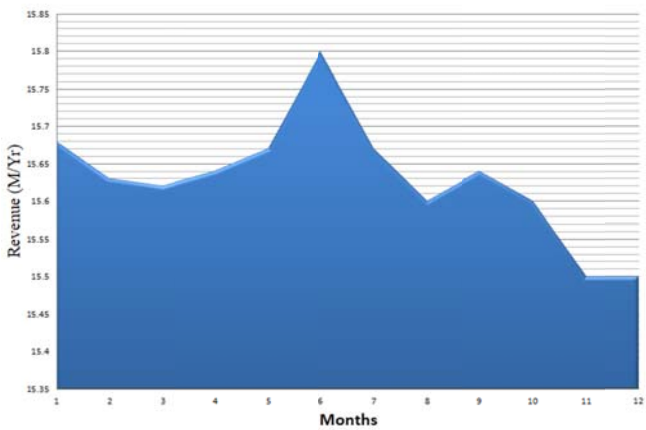

Fig. 9: Monthly Revenue from a Gas Turbine in Benin City

Fig. 10: Monthly Fuel Cost of a Gas Turbine in Benin City

Fig. 11: Monthly Profit from a Gas Turbine in Benin City

4) Turbine Creep Life

An increase in turbine inlet temperature (TIT) increases the gas turbine creep life usage, leading to a reduction in turbine creep life. As the power output increases, the turbine creep life was also found to be decreasing. This is not unconnected with the increased stresses due to the increase in torque in the blades. The exhaust gas temperature was found to impact the turbine creep life usage, as the turbine creep life decreases with increasing EGT, in line with sections B and D above.

This research revealed that, for a uniform speed single shaft gas turbine installed and operated in Tropical savanna climate, the turbine creep life usage was lowest in the months of August, September and May respectively as shown in Fig. 12: Turbine Creep Life of a Gas Turbine in Benin, with the atmospheric conditions being investigated, impacting most on the turbine creep life of the unit in the month of June.

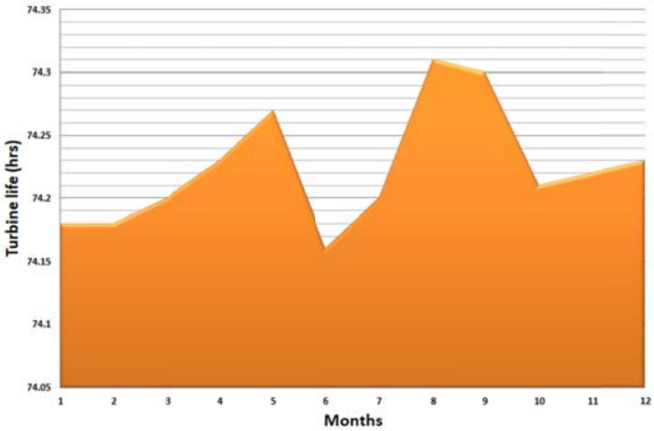

Fig. 12: Turbine Creep Life of a Gas Turbine in Benin City

IV. CONCLUSION

A single shaft gas turbine simulator (known as GPAL) from Gas Path Analysis ltd was successfully employed to investigate the performance of a uniform speed single shaft gas turbine under the variation of atmospheric conditions in Benin City. The study reveals that it is most efficient and productive to operate the gas turbine in Benin City in the month of June whereas it is worse off, in the month of December. The CO emission was found to be relatively low and uniform throughout the year whereas the specific fuel consumption was found to be highest in the months of March and April. It could also be established that the combined effect of ambient temperature and relative humidity on the gas turbine is at variance with other effect of individual climatic condition.

REFERENCES

[1] C. B. Richard and E. Sonntag (2017). Introduction to Engineering Thermodynamics, Energy Conversion, Second Edition.

[2] E. A. Abhulimen, (2013). Frequency and Load Control in Power Generation., *NAPTIN NGSDP Project,* pp. 13–15.

[3] E. A. Abhulimen, M. U. Bonet, S. O.Oyekunle, N. Achara and W. C. Solomon (2020). An Inquisition on the Combined Effects of Ambient Temperature and Relative Humidity on The Performance of a Uniform Speed Single Shaft Gas Turbine in Tropical Monsoon Climate, using GPAL, EJERS vol. 5, no. 6,

[4] word meaning - What do they mean by ambient condition? - English Language Learners Stack Exchange. https://ell.stackexchange.com/questions/198329/what-do-they-mean-by-ambient-condition. Accessed, May 31, 2023.

[5] Ambient condition| Grundfos. Retrieved from https://www.grundfos.com/service-support/encyclopedia-search/ambient-condition.html. Accessed, Apr. 24, 2020.

[6] Y. Liu, A. Banerjee, A. Kumar, A. Srivastava, and N. Goel (2017). Effect of ambient temperature on performance of gas turbine engine, *PHM*, Prognostics and Health Management Society, pp. 503–509.

[7] A. T. Baheta, and S. I. U. H. Gilani (2012). The Effect of Ambient Temperature on a Gas Turbine Performance in Part load Operation. Retrieved from https://www.researchgate.net/publication/258570724 Accessed Apr. 22, 2020.

[8] Ambient temp 2. Retrieved from https://searchdatacenter.techtarget.com/definition/ambient-temperature. Access, May 24, 2023.

[9] A. M. Y. Razak, (2007). Industrial gas turbines Performance and operability. Woodhead Publishing Limited, Abington Hall, Abington, Cambridge CB21 6AH, England. Pp431-563

[10] Tropical savanna climate. Retrieved from https://en.wikipedia.org/wiki/Tropical_savanna_climate Accessed May 31, 2023.

[11] Weather Information for Tegucigalpa, Country: HONDURAS," *WMO*, Available: https://worldweather.wmo.int/133/c00283.htm. Accessed: May 31, 2023

[12] *World Weather Information Service — Banjul.* Available: http://worldweather.wmo.int/en/city.html?cityId=140. Accessed: May 31, 2023

[13] T. L. H McKnight and I. Darre, (2000). Climate Zones and Types, a Landscape Appreciation, Available: https://archive.org/details/physicalgeographmckn/page/205. Accessed: May 31, 2023.

[14] Climate Classification and Climatic Regions of the World. Retrieved from http://www.physicalgeography.net/fundamentals/7v.html. Accessed Apr. 24, 2020.

[15] O. O. Jegede, (2014). Variation of Rainfall and Humidity in Nigeria. Journal of Environment and Earth Science vol. 4, no. 2, pp29–37.