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Modelling Compressor's Initial Operating Conditions Effect on Turbine Performance in the Tropical Rainforest

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ABSTRACT: *The Gas Turbine performance in terms of power output and efficiency are often determined by many factors, among which the compressor inlet temperature and humidity are major factors. The research power plant is located in the tropical rainforest within the delta region of Nigeria and hence, its performance is highly influenced by compressor inlet temperature. It showed that the higher the compressor inlet temperature, the lesser the power output. And the lower the inlet temperature, the higher the output power of the plant. At the current average operational compressor inlet temperature of 31^{0}C, the net power output of the plant is 125.5MW which is far less than the designed rated capacity of 138.29MW. However, at a lower temperature of 18^{0}C, the power output was analysed to be 138.26MW which is quite close to the 138.29MW rated capacity, and at a much lower temperature of 10^{0}C, a better output was obtained. It was also observed that the thermal efficiency of 33.1% at 31^{0}C inlet air temperature improved impressively to 36.10 at 18^{0}C. Analysis further showed that a reduction in temperature from 31^{0}C to 18^{0}C resulted to 0.78% increase in power output for every 1^{0}C decrease compressor inlet temperature. Investigation of the effect of humidity on turbine performance revealed that at inlet air temperature of 31^{0}C and a humidity of 80%, a power output of 128.406MW was generated. This represent an increase of 2.096MW or 1.67% above the 125.5 MW obtained at the same temperature without humidity effect consideration. The overall result indicates an inverse proportionality between the compressor inlet air temperature and the turbine power output and a proportional correlation between humidity and the power output.*

KEYWORDS: *Gas Turbine, Humidity, Compressor Work, Thermal Efficiency, Power Output, Turbine Work, Compressor Inlet Temperature.*

I. INTRODUCTION

Gas turbine engine is a heat engine in which hot combustion gases, generated by burning a fuel, drives a turbine which generates power. It has basic configurations which consist of a compressor, combustor and a turbine. The turbine shaft is coupled to a generator which produces electrical energy through the rotary action of the shaft system. Gas turbine plays a very important role in aircraft, power generation and marine power plant usage [1].

Gas turbines are key components in combined cycle power plants. There are many economic advantages in using gas turbine for power generation. These include high reliability and flexibility in operation; they are compact, light weighted and efficient. Other unique features include its capability of rapid start-up and can be remotely operated.

Gas turbine compact size of high power-to- weight ratio and high reliability makes it the ideal power plant for use to drive aviation and marine systems, etc. Gas turbines use a wide variety of gaseous and liquid fuels, depending on the design and application. Fuel nature and ambient conditions of inlet air into the system also affect its power output. It has been shown that the cooler the compressor inlet air, the better the engine performance [2].

Despite the fact that gas turbines have many attractive features which makes it one of the most preferred power generations, one of the parameters that affect its performance is the ambient conditions of the inlet air into the compressor. Power output, which is directly dependent on the mass flow for a fixed cycle varies directly with air density which is a function of air pressure and temperature [3]. Variation in the initial operating conditions of the compressor affects the engine operating characteristics, especially the power output and efficiency which are some of the indices of engine performance. Previous works have revealed that the cooler the inlet air, the more the mass flow rate, and hence more power will be generated by the turbine. It has also been shown from research that a typical turbine plant experiences a capacity reduction of up to 1% for every 1^0C rise in compressor inlet temperature above typical ISO conditions of 15^0C and 60% relative humidity [4]. [1] Revealed that the power output can drop by about 0.5% to 1% rise in ambient temperature and an increase of about 0.623% for every 1^0C rise in inlet air temperature.

The work of [5] revealed that the turbine power output decreases as the inlet air temperature increases. His conclusion was based on the experimental aero-derivative turbine, which showed that the power output of the turbine decreased by 73% when its inlet air temperature was increased from 15^0C to 37.8^0C. Also about 27% power loss was prevented when the temperature was reverted from 37.8^0C to 15^0C. In a similar investigation within Los Angeles vicinity, another turbine plant of 42MW output showed that temperature rise from 15^0C to 17.8^0 C resulted to a power drop of 34.1MW, representing about 19% power loss [3].

According to [6] humidified air was injected into the air stream at the upstream of the combustor and downstream of the compressor. This improvement technique resulted into a tremendous power improvement without increasing the compressor work load. It also shows a double advantage by reducing the level of Nitrogen oxide compounds in the turbine system, and eliminates the possibility of compressor blades corrosion and distress. It was indicated that the mass flow rate of air entering into the gas turbine varies with their specific mass, which means that it depends on the temperature and the relative humidity of the ambient air [7].

Gas turbine performance is critically limited by the predominating ambient temperature, mainly in hot and dry regions. It occurs because the power output is inversely proportional to the ambient temperature [8]. The temperature drop provides an augment in the air density and consequently elevates air mass flow rate; this behavior increase the power output and efficiency by about 0.7% per degree Celsius for heavy duty gas turbine [9].

In the presentation by [10], the result from the study of combined cycle power plant operated from 35^0C to ISO-rated condition which increases the power output of a gas turbine by 10.6% and the combined cycle power plant by 6.24% annually.

Further analysis has been carried out such as performance analysis and components irreversibility of a (25MW) gas turbine power plant modeled with a spray cooler. In this work the potentials benefits of improving the performance of the current gas turbine plant into a more advanced cycle with high efficiency and power output through inlet air cooling were analysed. In the study, performance characteristics were determined for a set of actual operational conditions including ambient temperature, relative humidity, and turbine inlet temperature and pressure ratio [11].

Investigate the temperature inlet effect on the gas turbine performance. And it show that during the summer in Saudi, the turbine suffer a 24% decrease in their capacity due to ambient temperature up to 50^0C [12].

According to [12], it revealed that most turbines suffer as high as 50% capacity loss at 45^0C by cooling the inlet air to as low as 15^0C. He added that cooling the inlet air also lowers the heat rate by 10%, therefore saving fuel costs and reducing pollution. He further explained that for a combined cycle gas turbine plant operating at full load, with 45^0C inlet temperature, the thermal efficiency is about 42%, while if the inlet air of the same plant was cooled to 15^0C, a 53% thermal efficiency was achieved.

In the research work of [13], it was revealed that at high relative humidity, about 1.5 to 1.9 times higher cooling thermal loads was achieved than plants with low relative humidity of about 30% and below.

In this research modeling the initial operating conditions of the compressor in the tropical rainforest was carried out. Various procedures for the collation of data from service records, field measurement, simulation of systems and thermodynamic analysis of results were presented.

II. MATERIALS AND METHODS

2.1 Theoretical Formulation

For this research, data collections were made by direct measurement via the human machine interface (HMI) and operational result from the log book for a period of two years. The data collection methods were designed to produce facts about some aspects of the research. The daily operational log data were used to determine those factors that influence the gas turbine performance.

In the treatment and collection of data, mean values of daily parameters were computed by the use of statistical method while the objective functions were modeled by MATLAB software, followed by monthly average and the overall average for the research period. Some of the phenomena of the operation of the set could not be investigated directly by field measurement, various thermodynamics theories were employed to model the performance of the plant under considerable conditions.

2.1.1 The Energy Model

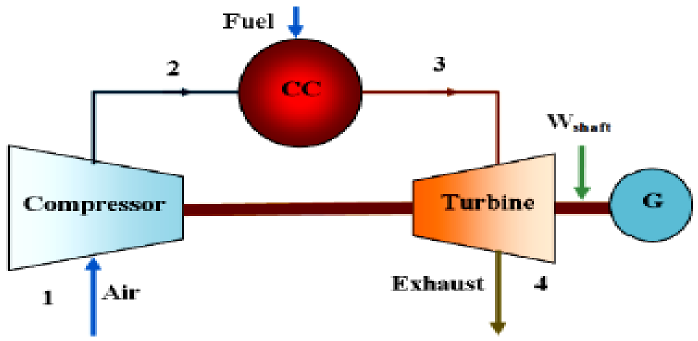

Figure 1: Schematic of the typical gas turbine cycle

The figure above represents a single shaft gas turbine engine and the expressions for the efficiency and work ratio of the Brayton Cycle was employed.

A simple cycle gas turbine is comprised of three major components, which are compressor, combustor and turbine as shown in figure 1. Air at ambient temperature and pressure enter the compressor. The ratio of the compressor exit pressure to the ambient pressure inlet defined the pressure ratio. For the compression process which is adiabatic, the temperature of the compressed air is higher than the ambient temperature of the inlet air.

The compressed air from the compressor enters the combustor, where it is mixed with high pressure gaseous fuel. The fuel and air are burned at constant pressure, and the high pressure, hot gases (product of combustion) enter the turbine. In the turbine, the gases are reduced in pressure, resulting in to a corresponding reduction in temperature. The heat removal process associated with expansion and cooling of the hot gases in the turbine, results in energy transfer from the gases to shaft work, leading to shaft rotation.

The compressor power can be modeled using the first law of thermodynamic as follows

$$\text{Compressor power transfer } \dot{W}_c = m_a c_{pa}(T_2 - T_1) \quad 1$$

where m_a = air mass flow rate, c_{pa} = the specific heat of the dry air

$$\text{Turbine power output } \dot{W}_T = m_a c_{pg}(T_3 - T_4) \quad 2$$

$$\text{Heat supplied during cyle } \dot{Q}_s = m_a c_{pg}(T_3 - T_2) \quad 3$$

$$\text{Heat rejected by the cycle } \dot{Q}_r = m_a c_{pg}(T_4 - T_1) \quad 4$$

where c_{pg} = the flue gas specific heat

$$\text{Thermal efficiency} = \frac{(T_3 - T_2) - (T_2 - T_1)}{T_3 - T_2} = 1 - \frac{1}{(r_p)^{\gamma-1/\gamma}} \quad 5$$

where r_p is the pressure ratio.

2.1.2 The Humidity Function Model

Air contains water vapour in varying degrees, and at a very low partial pressure. At this low pressure and atmospheric temperature, the water vapour behaves like a perfect gas [4]. Humidity describes the amount of water vapour in the atmospheric air. Since air is essential in the burning of the fuel that is used for the production of gas turbine power, the quantity of water vapour contained in the air obviously affects its characteristics as it is delivered to the turbine plant for fuel burning. This effect can be looked at from the laws governing humidity, and the relationship between humidity and gas turbine power output

The Gibbs-Dalton's theory is used to model the characteristic impact of humidity in this research.

The Dalton's Law relation show that

$$P = P_v + P_a \tag{6}$$

Where P is the total pressure of the atmospheric air, P_v, the partial presure of water vapour

P_a is the partial pressure of the dry air in the mixture.

Applying the characteristic gas equation for the water vapour and dry gas gives

$$\frac{M_v}{M_a} = \frac{P_v}{P_a} \times \frac{R_a}{R_v} \tag{7}$$

Where R_a = Gas constant for dry air =0.287kJ/kgK

R_v = Gas constant for water vapour = 0.462kJ/kgK

P = Barometric pressure of the atmosphere

P_a = Partial pressure of dry air

P_V = Partial pressure of water vapour

M_a = Mass of dry air in kg

M_v = Mass of water vapour in kg

$$\omega = 0.622\frac{P_v}{P - P_v} \text{ or } \omega = 0.622\left(\frac{P - P_a}{P_a}\right) \tag{8}$$

Where ω is the humidity

$$\text{The Relative humidity } \emptyset = \frac{P_v}{P_s} \tag{9}$$

$$\text{Therefore } \omega = \frac{0.622\ \emptyset P_s}{P - P_v} \tag{10}$$

$$\text{The mass flow rate } M = m_a + m_v = m_a\left(1 + 0.622\emptyset\frac{P_s}{P_a}\right) \tag{11}$$

Equation 10 shows that the specific humidity and relative humidity are directly proportional to each other, while other quantities remain constant. This represent an increase in one translates to an increase in the other

III. RESULTS AND DISCUSSION

The parameters in table 1 were obtained from the installation manual of SIEMENS V94.2 gas turbine and its operational data. The application of the thermodynamics theories was used to model the objective parameters.

Table 1: Design and average operational data

S/NO	PARAMETER	DESIGN VALUE	OPERATIONS VALUE
1	Turbine Power Output	138.29kW	125kW
2	Exhaust Gas Flow	498kg/s	477kg/s
3	Fuel Flow Rate	12.4kg/s	9.3kg/s
4	Compressor Pressure Ratio	8.9	8.89
5	Turbine Pressure Ratio	9.68	8.89
6	Thermal Efficiency	36.2%	33.1%
7	Air Flow Velocity	200m/s	200m/s

3.1. Effect of Inlet –Air Temperature on Turbine Performance

The research was carried out in order to determine the effect of compressor initial operating conditions on turbine performance as well as the efficiency of the power plant. To do this, we set temperature at which the design net power output of 138.29MW could be attained, while we used operating values between 31^0C and 10^0C inlet air temperatures for numerical modeling of the various air mass flow rates, heat supplied, compressor power input, turbine power, net power output and the efficiency of the plant.

The research revealed that the lower the inlet air temperature, the higher the air mass flow rate, and therefore improve performance.

Table 2: Impact of operating temperature on net power outputs and efficiencies without humidity consideration.

Case	Inlet air temp. $T_1{}^0C$	Air mass flow rate (kg/s)	Compressor Power input P_C (MW)	Turbine Power output P_T (MW)	Turbine Net Power Output P_N (MW)	Thermal Efficiency η (%)	% Increase in Net Power Output
1	31	467.70	125.50	251.50	125.50	35.44	-
2	25	478.04	124.27	256.55	132.28	35.93	5.4
3	20	486.66	124.39	261.18	136.79	36.06	9.0
4	18	490.04	124.41	263.18	138.07	36.10	10.44
5	15	495.27	124.39	265.80	141.41	36.19	12.68
6	10	503.9	124.40	270.43	146.03	36.30	16.36

Table 3: Summary of inlet- air temperature impact on net power outputs at 70% relative humidity

S/N	Inlet Air Temperature, $T_1{}^0C$	Mass flow rate (m) kg/s	Net Power output P_N (MW)
1	10	505.59	146.59
2	15	497.34	142.10
3	18	443.03	139.61
4	20	486.47	136.76
5	25	483.83	133.89
6	31	477.17	128.04

3.2 Impact of Specific Humidity and Relative Humidity on the Turbine Performance at various inlet air temperatures.

Humidity has direct effect on gas turbine performance. This could be explained from the fact that when a moist inlet air passes through the compressor of the gas turbine, the water vapour in the air evaporates. In the process of evaporation, it takes its latent heat of vaporization from the air. This cools the air which in turn produces the effect of increasing the air mass flow rate into the system. Tables 3.4 – 3.5 show the results of the evaluation of specific and relative humidity on turbine performance at various inlet air temperatures.

Table 4: Specific and relative humidity effect on turbine output at inlet air temperature of 31^{0}C

S/N	Relative Humidity (%)	Vapour Mass (kg)	Dry Air Mass (kg)	Total Mass Flow (kg)	Specific Humdity	Net Power Output (MW)
1	40	5.4251	467.7	473.12	0.01157	126.96
2	50	6.7653	467.7	474.47	0.01447	127.31
3	60	8.119	467.7	475.83	0.01736	127.68
4	70	9.470	467.7	477.17	0.02025	128.04
5	80	10.8240	467.7	478.52	0.02314	128.41

Table 5: Specific and relative humidity effect on turbine output at inlet air temperature of 10^{0}C

S/N	Relative Humidity (%)	Vapour Mass (kg)	Dry Air Mass (kg)	Total Mass Flow (kg)	Specific Humdity	Net Power Output (MW)
1	40	1.539	503.9	505.44	0.00305	146.48
2	50	1.923	503.9	505.82	0.00382	146.59
3	60	2.308	503.9	506.21	0.00458	146.70
4	70	2.693	503.9	506.59	0.00534	146.81
5	80	3.077	503.9	506.99	0.00611	146.93

3.3 Comparative Results of Net power Outputs and Efficiencies with and without Humidity Consideration

The research analysed the turbine performance and efficiencies with humidity and without humidity. The comparative result from the analysis is shown in Table 6.

Table 6: Turbine power output and efficiency with and without humidity effect

S/N	Inlet Air Temp. (^{0}C)	Turbine Net Power Outputs P_N (MW) without Humidity	Turbine Net Power Outputs P_N (MW) with Humidity	Thermal Efficiency η(%) without Humidity	Thermal Efficiency η(%) with Humidity
1	31	125.5	At $\emptyset$ =40% P_N = 126.96 At $\emptyset$ =80% P_N = 128.41	35.44%	At $\emptyset$ =80% η =35.51%
2	10	145.6	At $\emptyset$ =40% P_N = 146.48 At $\emptyset$ =80% P_N = 146.93	36.30%	At $\emptyset$ =80% η =36.85%

IV. RESULTS AND DISCUSSION

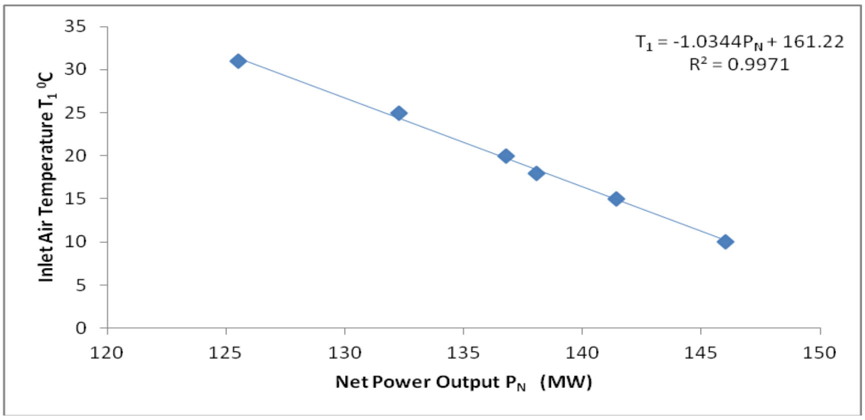

Figure 2: Effect of inlet air temperature on power output

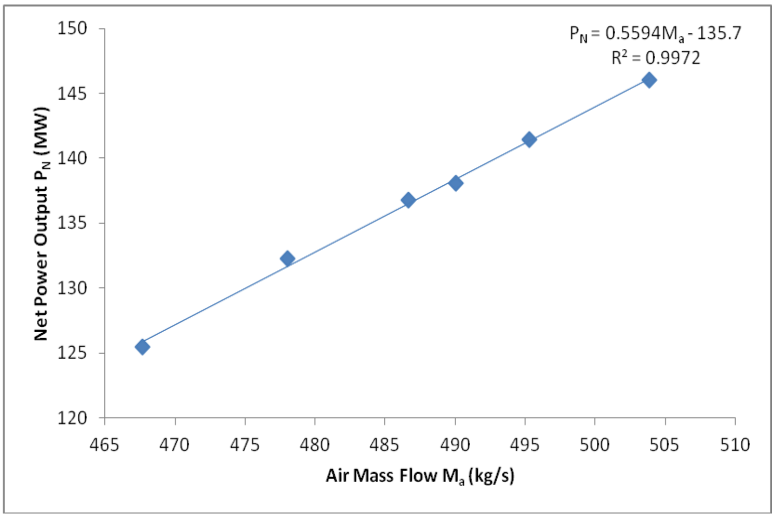

Figure 3: Effect of air mass flow on power output

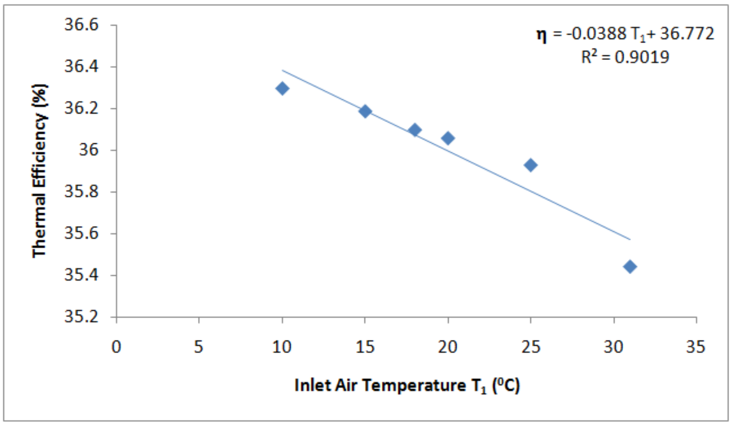

Figure 4 Effect of inlet air temperature on thermal efficiency

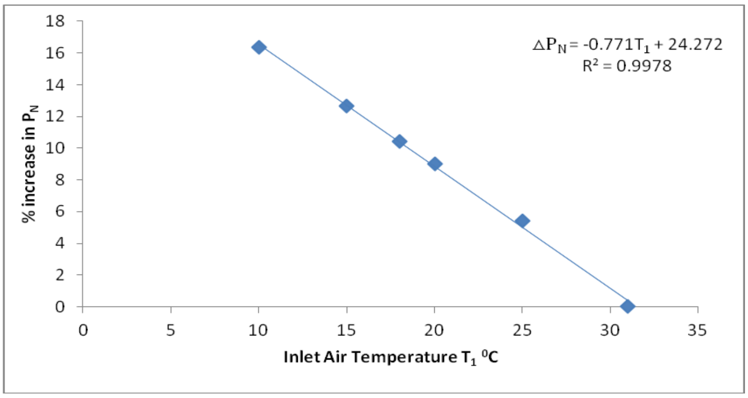

Figure 5: Effect of inlet air temperature on power drop

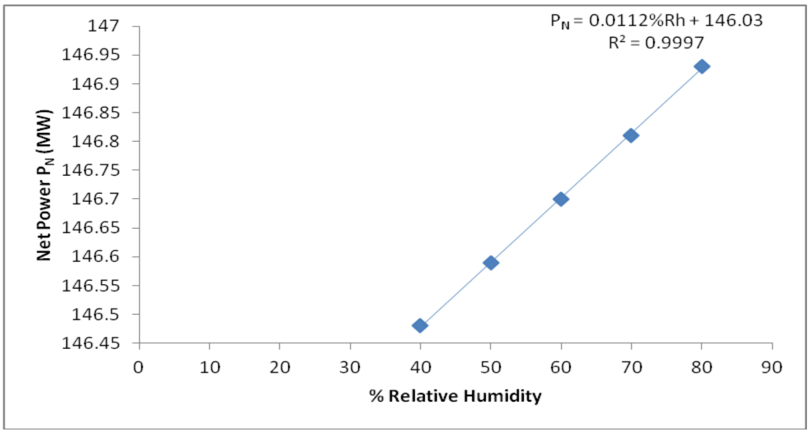

Figure 6: Effect of relative humidity on power output

Table 2 shows that between 31^{0}C and 10^{0}C the temperature difference is 21^{0}C and there is a percentage increase in power output of about 16.36%. This represents an increase in power output of 0.78% for every 1^{0}C reduction in the inlet air temperature. The analysis carried out which investigate the effect of inlet air temperature on power output shows that the cooler the inlet air entering the compressor, the more power output was obtained from the plant, this is clearly indicated in Table 2 and Figure 2

The research analysis was done within the range of 10^{0}C and 31^{0}C. This gave a corresponding net power output between 146.03MW and 125.50MW respectively. This is in line with the operational data of 125MW obtained at 31^{0}C by the plant operator. From Figure 2, it can be seen that the plant rated capacity of 138.29MW design value could be achieved if the inlet air temperature is reduced to about 18^{0}C. Also it can be seen that the plant efficiency progressively increased as the inlet temperature decreased. Figure 4 shows that at inlet air temperature of 18^{0}C, the efficiency of 36.10% almost equal that of the designed value of 36.20%. On the whole the analyses showed that there is 0.78% power gain for every 1^{0}C reduction in inlet air temperature.

The analysis carried out to investigate the effect of the humidity on the gas turbine power output and performance show the power output increase as humidity increases. At higher temperature and higher humidity of the inlet air, the power output was low compared with the result obtained when a lower inlet air temperature and same humidity was analysed. It shows that the best result was obtained at 80% humidity, 10^{0}C inlet air temperature. This gave a power output of 146.92Mw. On the other hand, the lowest power output was obtained when a humidity of 40% was used with the highest inlet air temperature of 31^{0}C. This gave a power output of 126.96MW.

Table 3, 4, 5 and Figure 3-6 clearly illustrate these humidity effects on the turbine performance at various inlet air temperatures. A comparative analysis of power outputs at different humidity but at the same temperature was carried out at 10^{0}C and 31^{0}C inlet air temperatures respectively. The results show that at 31^{0}C, 80% relative humidity, the power output obtained was 128.41. At the humidity of 40%, 10^{0}C, the power output obtained was 146.48MW, and at the highest humidity of 80%, 10^{0}C, the power output increased by 0.37% to 146.92MW. The above clearly establishes that the turbine power output and performance increases as the inlet air temperature decreases.

In the analysis, 138.26MW was obtained at 18^{0}C, without humidity consideration, and 139.61MW power output was achieved when a relative humidity of 70% was applied at the same 18^{0}C inlet air temperature condition. This represents an additional 0.97% increase power output. The result above affirmed clearly that the plant's designed net power output of 138.29MW could be achieved with the application of a higher relative humidity of the inlet air temperature.

In achieving the above application of higher relative humidity in a tropical weather where this plant operates, a suitable air temperature reduction system is employed. The process could be any of the evaporative cooling methods which include wetted media/ over-spraying, inlet fogging, wet compression and humid air injection.

V. CONCLUSION

The research was to analyse the influence of the initial operating condition of the compressor on the turbine performance of V94.2 power plant. The research work was able to establish that at 18^{0}C DBT, the plant's rated capacity of 138.29MW could be achieved and sustained. The low inlet temperature also increased the efficiency of the plant. It was established that there is an increase of 0.78% in power output for 1^{0}C reduction in the inlet air temperature of the plant. The research analysis further established that the higher the relative humidity, the greater the net power output from the turbine as well as the performance. At 40% relative humidity and the inlet air temperature of 18^{0}C, a power output of 138.37MW was achieved. This is greater than the output of 138.26MW obtained when the analysis was done at the same temperature but without humidity consideration. It also can be seen that the efficiency of 36.17% obtained at 18^{0}C inlet temperature without humidity consideration increase to 36.21% at the same temperature on application of a relative humidity of 80%. This obviously shows a strong positive correlation between the compressor initial operating parameters and turbine power output.

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