Thermodynamics Performance Evaluation of a Two-Shaft Gas Turbine Power Plant

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Abstract

In this work, the performance of a two-shaft Gas Turbine power plant was evaluated based on the efficiencies of the plant from the year 2002 to 2007.The parameters used in the evaluation are the ambient conditions, thermal efficiencies, and the inlet and outlet temperatures of the power turbine. The results showed that the highest thermal efficiency of the turbine was obtained in the year 2006 when the average compressor inlet temperature of the turbine and the power turbine outlet (exhaust) temperature are the least. With the increase in thermal efficiency of 42.62%, rise in value of compressor pressure ratio of 7.78 and least compressor inlet temperature of 25.08^{0}C as seen in table 2. The research shows that gas turbine plants perform better in temperate regions than tropical. Therefore, to increase the efficiency of an existing gas turbine plants in high temperature climates, retrofitting an air cooler that will always reduce the temperature back or close to the design temperature before compression is necessary.

Keywords: Power Turbine, Gas Generator, Thermal Efficiency, Thermodynamics Performance Evaluation, Two-Shaft Gas Turbine Plant

Nomenclature

C_p	= *Specific Heat Capacity (KJ/KgK)*
$\eta_{thermal}$	=*Thermal Efficiency*
W_{12}	= *Compressor Power (KJ/Kg)*
PR	= *Pressure ratio*
W_{out}	= *Specific Work Output (KJ/kg)*
y	= *Isentropic index*
W_{12}	= *Compressor Power(KJ/Kg)*
p	= *Pressure (bar)*
W_t	= *Isentropic TurbineWork(KJ/Kg)*
T	= *Temperature (^{0}C)*
C_{pg}	= *Specific Capacity of the Gas(KJ/KgK)*
Q_{23}	= *Heat Input (KJ/Kg)*
m_a	= *Mass of the air (Kg/s)*
m_g	= *Mass of the gas (Kg/s)*
η_{pt}	= *Isentropic Efficiency of the Power Turbine*
P_{pt}	= *Power Turbine Power (KJ/Kg)*
C_{pa}	= *Specific Capacity of the air(KJ/KgK)*
Δp	= *Pressure drop in the combustion chamber*
η_m	=*Mechanical Transmission Efficiency*

1. Introduction

Gas turbine plants which started from its simplest form that operates on Brayton's cycle have undergone tremendous modifications. These different metamorphoses in gas turbine plants were made possible as a result of researches that were carried out on plant performance and subsequently proffering the outputs of these researches that has led to the improvement of gas turbines.

One of the products of such researches is the two-shaft gas turbine. The two-shaft gas turbine unlike the simple gas turbine that operates on Brayton's cycle has two turbines [1], the compressor turbine that drives the compressor and the power turbine that produces the power.

However, in spite of the improvements and modifications of gas turbine plants, their performance to a very large extent depends on the operational environments. This in effect means that the power outputs and efficiencies of gas turbine plant depend on the ambient temperatures of the operating environment.

The compression work clearly shows the difference between the compressor inlet and exit temperatures, therefore, the higher the compression work, the higher the compressor power. The implication of this is that gas turbine plants operating in tropical environment have higher compression ratios and therefore, seem to need more power to drive the compressor.

Since gas turbine plants take in air directly from the atmosphere, the prevailing environmental conditions affect their performance. The power rating can drop as much as 20 to 30% with respect to international standard organization (ISO) design conditions, when ambient temperature gets to 35 to 40^{o}C [2].

Therefore, where the temperature of the operating environment is higher than the design temperature, initial conditions could be restored by adding an air cooler at the compressor inlet. The air cooling system serves to raise the turbine performance to a peak power level during the warmed periods when the high atmospheric temperature could cause the turbine to work at off-design conditions, with reduced power output [3].This paper takes a comparative study of the efficiencies of a typical two-shaft gas turbine plant shown in fig 1 in prevailing environmental temperatures that are generally higher than the design temperature of the plant for specified periods of years. The purpose of this paper is aim at bringing to the fore the thermodynamic advantages of retrofitting a heat exchanger and an air cooler to a typical gas turbine plant operating in a tropical region.

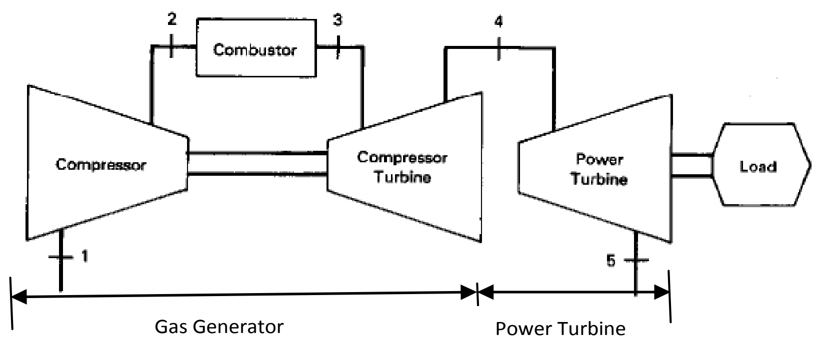

Fig.1: *Diagram of two-shaft gas turbine*

2. Materials and Methods

For a given compression ratio, the power consumed in the compressor is directly proportional to the inlet temperature. If the compressor inlet temperature is reduced, the power required to drive the compressor will be reduced whereas the net turbine cycle power delivered will be increased [4]. Therefore, a study of the operation environmental temperatures becomes imperative for optimal turbine performance.

The compressor turbine, combustor and the gas generator combined is called the gas generator or the gasifier. This is because, it functions to produce enough hot, high pressure gas needed to drive the power turbine, whereas the compressor turbine drives solely the compressor.

The data for this study were obtained from an operational Rolls Royce, Industrial Olympus-SK 30 two-shaft gas turbine plant located at Imiringi, Bayelsa State, Nigeria. The plant is the major source of electricity in the State. The parameters used for this work were obtained from the logsheet over certain numbers of years.

However, where certain data could not be sourced, standard thermodynamic values were used. In other to make the data workable, statistic is used to arrive at the values used for the studies. This is done by computing the average of the daily, weekly, monthly and then yearly turbine readings. These procedures are repeated for the years covered by this work. And finally the average of the five years values was computed.

A summary of the processes carried out in order to arrive at the values used for the computations is shown in table 1. This table just as the ones that were used for the actual calculations, shows the actual values from the plant's log sheets and the calculated values.

Fig. 2 shows the T-s diagram of the plant. In other to arrive at a better understanding of this work, thermodynamic equations are derived which are then used for subsequent calculations. The reasons for deriving the thermodynamic equations are the thermal efficiency and its relationship with parameters such as the temperatures and pressure ratios.

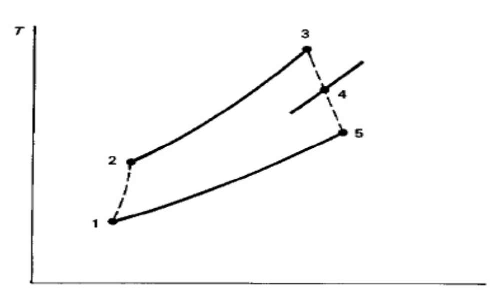

Fig.2*: T-S Diagram of the two-shaft gas turbine*

Compressor Power,

$$W_{12} = m_a Cp_a (T_2 - T_1) \quad 1$$

$$= m_a Cp_a T_1 \left({}^{T_2}/_{T_1} - 1\right) \quad 2$$

In terms of pressure ratio, equation 2 becomes

$${}^{T_2}/_{T_1} = PR^{r_a - 1}/_{r_a} \quad 3$$

$$W_{12} = m_a Cp_a T_1 \left(PR^{r_a - 1}/_{r_a} - 1\right) \quad 4$$

Heat energy added to combustion chamber,

$$Q_{23} = m_g\, Cp_g (T_3 - T_2) \quad 5$$

Noting that,

$$T_3 = T_4\, PR^{r_g - 1}/_{r_g} \quad 6$$

and

$$T_2 = T_1\, PR^{r_a - 1}/_{r_a} \quad 7$$

Equation 5 becomes

$$Q_{23} = m_g\, Cp_g \left(T_3 - T_1\, PR^{r_a - 1}/_{r_a}\right) \quad 8$$

In this particular plant, it is the power turbine that produces the power that drives the electric motor.

The power turbine power output is,

$$P_{pt} = m_g\, Cp_g (T_4 - T_5) \quad 9$$

Therefore, the thermal efficiency of the cycle is:

$$\eta_{thermal} = \frac{Net\ Power}{Heat\ supplied}$$

$$\eta_{thermal} = \frac{Power\ Turbine\ Power\ Output}{Heat\ Supplied}$$

Table 1:*Summary of overall average of the working parameters (from 2002 to 2007).*

Components	**Parameters**	**Units**	**Actual Values From Log Sheets**	**Calculated Values**
Low Pressure Compressor	*Inlet Temperature, T_1* *Outlet Temperature, T_2* *Inlet Pressure, P_1* *Outlet Pressure, P_2* *Mass flow rate, m_a* *Compressor Work, W_c*	*K* *K* *Bar* *Bar* *Kg/s* *Kj/kg*	*298.81* *-* *1.013* *6.43* *82.14* *-*	*-* *533.95* *-* *-* *-* *247.47*
Combustion Chamber	*Inlet Temperature, T_2* *Maximum Temperature, T_3* *Inlet Pressure, P_2* *Outlet Pressure, P_3* *Mass flow rate, m_g*	*K* *K* *Bar* *Bar* *Kg/s*	*-* *-* *6.43* *-* *3.05*	*533.95* *869.97* *-* *6.22* *-*
HP Turbine	*Inlet Temperature, T_3* *Outlet Temperature, T_4* *Inlet Pressure, P_3* *Outlet Pressure, P_4* *Mass flow rate, m_g*	*K* *K* *Bar* *Bar* *Kg/s*	*-* *665.16* *-* *-* *85.19*	*869.97* *-* *6.22* *2.11* *-*
Power Turbine	*Inlet Temperature, T_4* *Outlet Temperature, T_5* *Inlet Pressure, P_4* *Outlet Pressure, P_5= Patm.* *Mass flow rate, m_g* *Power Output, P*	*K* *K* *Bar* *Bar* *Kg/s* *MW*	*665.16* *-* *-* *1.013* *85.19* *10.79*	*-* *564.85* *2.11* *-* *-* *9.77*
Exhaust	*Exhaust gases temperature, T_5* *Exhaust gases temperature, P_5* *Mass flow rate, m_g*	*K* *Bar* *Kg/s*	*-* *1.013* *85.19*	*564.85* *-* *-*

3. Results and Discussion

The parameters relevant for this study are actually the compressor turbine inlet temperature, power turbine inlet and exit temperatures, as well as the power turbine power output. Also, of utmost importance is the thermal efficiencies calculated in the periods under study. Table 1 shows the summary of both the actual working and calculated data used for the compilation of table 2.

Table 2.*Table showing the turbine parameters with years under study*

Year	**Parameters**											
	T_2(k)	**T_3(K)**	**T_3-T_2 (K)**	**T_4(K)**	**T_5(K)**	**T_4-T_5 (K)**	**P_2/P_1**	**AFR**	**P_5/P_3**	**T_1(°C)**	**P_{pt}(MW)**	**η_{therm}(%)**
2002	*539.26*	*867.88*	*328.62*	*698.73*	*586.51*	*112.22*	*5.89*	*1.55*	*0.48*	*25.48*	*11.04*	*34.15*
2003	*537.81*	*985.36*	*447.55*	*658.38*	*566.21*	*92.17*	*5.91*	*1.18*	*0.49*	*26.00*	*9.07*	*20.15*
2004	*531.27*	*885.61*	*354.34*	*671.58*	*573.20*	*92.38*	*5.93*	*1.57*	*0.50*	*25.60*	*9.68*	*27.76*
2005	*533.83*	*845.46*	*311.63*	*686.64*	*585.56*	*101.08*	*5.75*	*1.63*	*0.48*	*25.50*	*9.45*	*32.40*
2006	*540.08*	*768.74*	*228.66*	*596.37*	*498.91*	*97.46*	*7.78*	*2.22*	*0.45*	*25.08*	*9.59*	*42.62*
2007	*521.43*	*866.76*	*545.33*	*679.28*	*578.69*	*100.59*	*6.83*	*1.47*	*0.48*	*27.16*	*10.00*	*29.43*

4. Discussion

Figure 3 clearly shows the chart of the various operational parameters against the years under consideration. From the chart, it can be seen that the lower the ambient temperature, the higher the cycle efficiency. Also, the greatest efficiency is obtained in the year 2006, when the ambient temperature is least.

This shows that as gas turbines are designed with respect to temperate climates, higher efficiency of gas turbine plants are obtained with lower temperatures. The reason adduced to this is that the density of air increases when ambient temperature decreases which then causes an increase in the air mass flow rate [5].

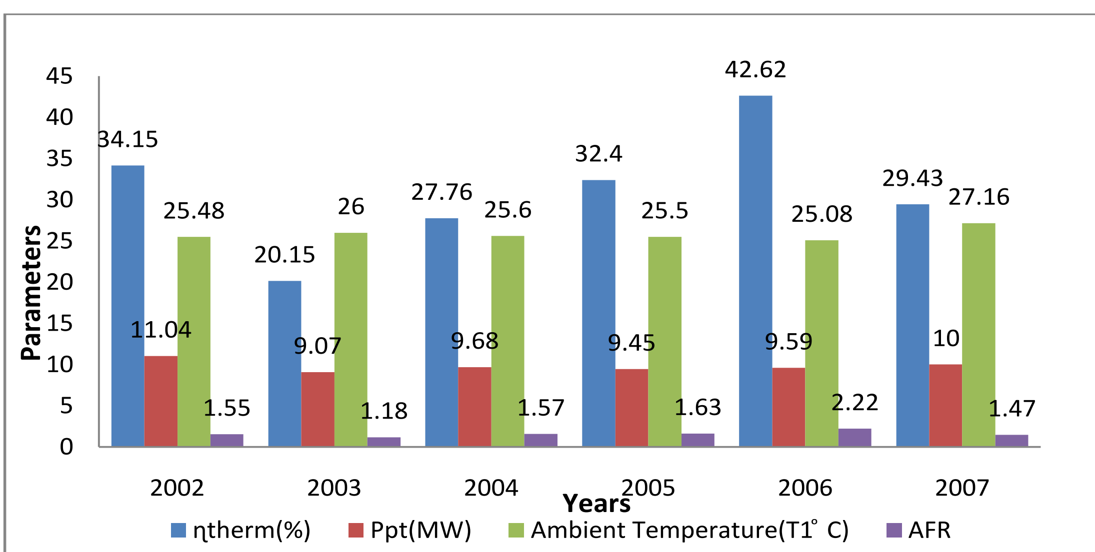

Fig. 3:*Various operational parameters against the years*

Figure 4 illustrates clearly the changes of the turbine efficiencies with ambient temperatures. The obvious observation here is that the change in thermal efficiencies did not depend much on the power turbine output but can be deduced as a function of the compressor inlet pressures. Another major contributor to change in thermal efficiencies can be attributed to the variations in the compression ratio as seen in the table 2 and also, as illustrated in the thermal efficiencies versus the compression ratios shown in figure 5 below.

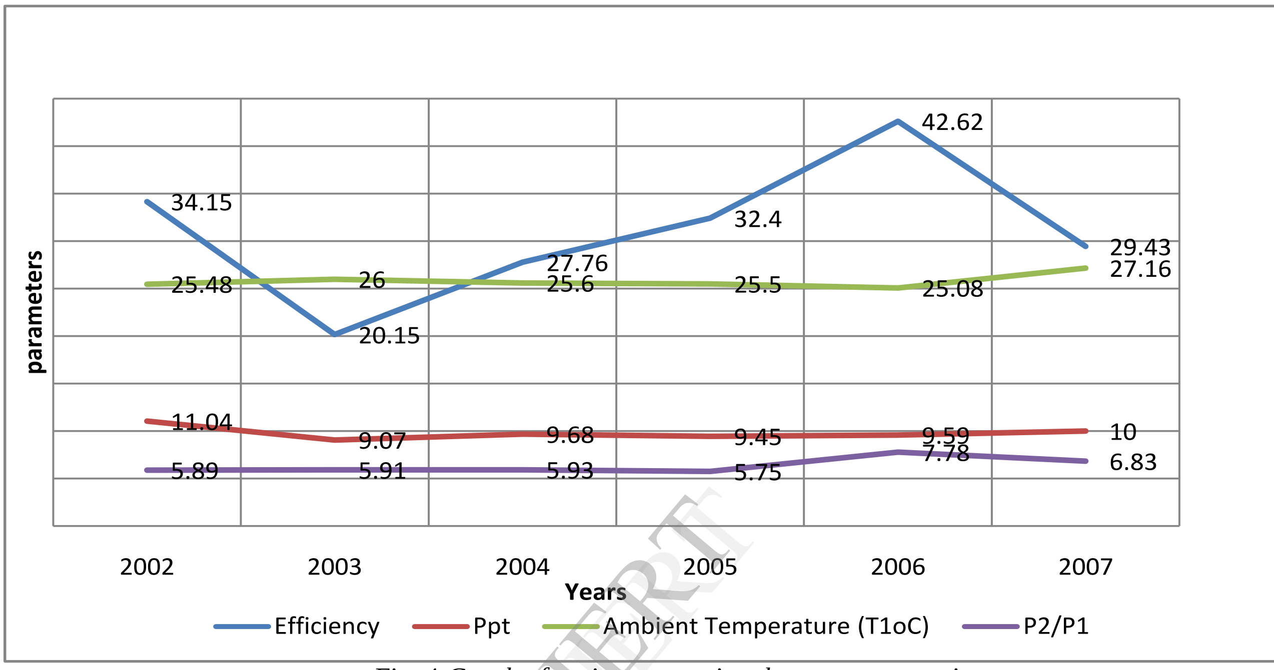

Fig. 4:*Graph of various operational parameters against years*

Figure 5 illustrate the variations of the thermal efficiencies with the compression ratios over the years the research was carried out. From the graph, it can be seen that the peak compression ratio was attained in the year 2006 and the also corresponds to the highest efficiency ever attained. There is a direct relationship between compression ratios and power output as well as the thermal efficiencies [6]. That is, as the compression ratio increases, the power output increases and so the thermal efficiency also increases.

However, the highest compression ratio here does not give the maximum power output. The reasons are, the ambient temperature was the least whereas, the compression exit temperature was the highest obtained of five years considered.

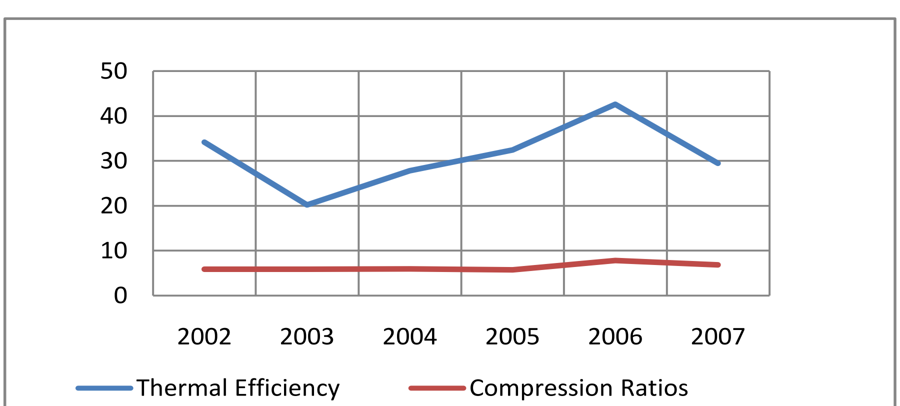

Fig. 5:*Graph showing the thermal efficiencies and the compression ratios (P_2/P_1).*

A thorough examination of fig.6 shows that the greatest of the thermal efficiencies was attained at the point where the turbine exit temperature is the least and where the compressor outlet temperature is the highest. The reasons to this is simply the fact that gas turbines that operates in simple cycles have low efficiencies because the turbine exhaust gases come out very hot and the energy contained in these hot gases is lost to the atmosphere [7].

Therefore, better performance is reached with advanced cycles that take advantage of the energy contained in the turbine exhaust gases to improve the cycle efficiency [8]. The power turbine as a separate component from the gas generator has made it possible for this gas turbine plant to have taken advantage of the energy content of the hot gases from the high pressure turbine.

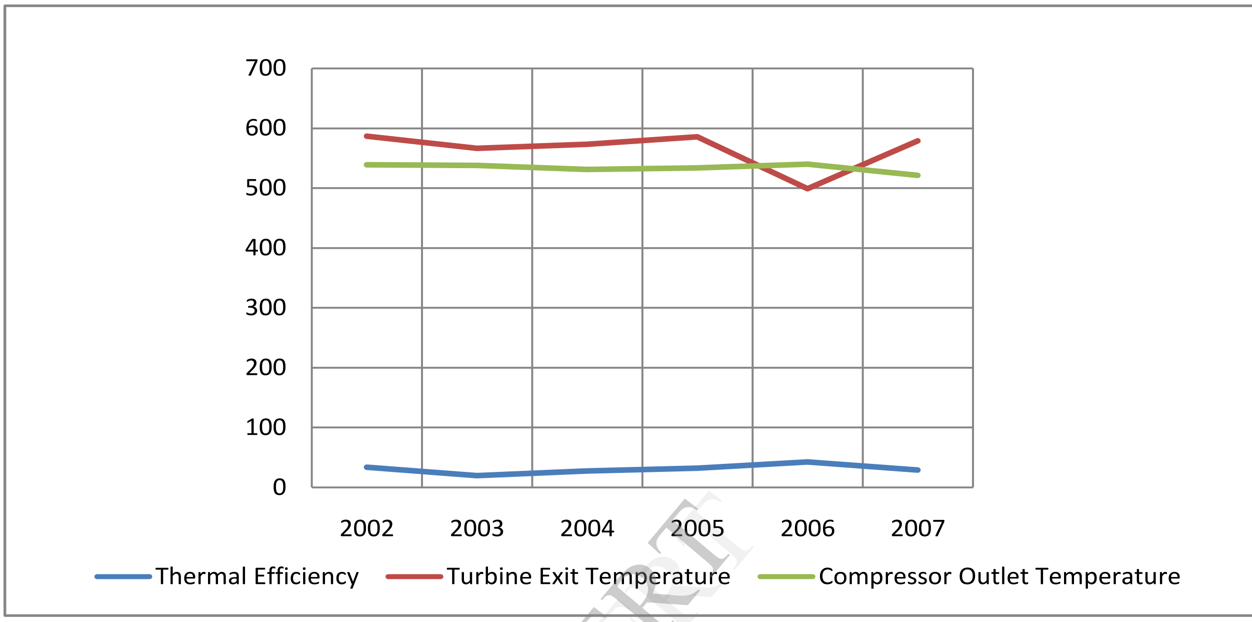

Fig. 6:*A graph showing the variations of compressor outlet temperature, turbine exit temperature and the thermal efficiency.*

5. Conclusion

This gas turbine power plant as with any other gas turbine plant is highly dependent on several parameters. These parameters played vital roles as to the efficient performance of the turbine. The parameters considered in this paper are the ambient temperatures, compression ratios, combustion chamber inlet pressure and the turbine outlet temperature.

The evaluation of the performance parameters showed that:

i. As the environmental temperature decreases, the density of the air taken into the compressor increases and this causes an increase in the air mass flow rate. Also, less work is required from the turbine to drive the compressor. These all contributes to the increase in efficiency and the power output of the turbine.

ii. The gas turbine plant performs better when the compressor outlet temperature and the compressor pressure ratios are high. This was confirmed in this work as the highest efficiency was attained when the combustion chamber inlet pressure and compressor pressure ratios were the highest.

iii. The efficiency increases with decrease in power turbine pressure ratios (P_5/P_4) and maximum efficiency is attained when the power turbine temperature and pressure are the least.

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References

[1] Ogbonnaya, E.A (2004). Thermodynamics of Steam and Gas turbines, Oru's Press Limited, Port Harcourt, Nigeria, ISBN 978-2631-760, PP 68-102

[2] Ibrahim, T. K., Rahman, M. M. and Abdalla, A. N. (2010). Improvement of gas turbine performance based on inlet air cooling system: A

technical review. International Journal of Physical Sciences, Vol. 6(4), pp. 620-627.

[3] Hart, H. I. (1998). Thermodynamic Appraisal of Gas Turbine Performance in the Niger Delta. Ph.D's Dissertation, Mechanical Engineering, University of Nigeria, Nsuka, Nigeria.

[4] Ogbonnaya, E. A., Johnson, C. A. N., Poku, R. (2012). Model-Based Advantages of Cogeneration in Marine Power Plants.

[5] Rahman, M. M., Ibrahim, T. K. and Abdalla, A. N. (2011). Thermodynamic performance analysis of gas-turbine power-plant. International Journal of the Physical Science. Vol. 6(14), pp. 3539-3550. Retrieved 20 July, 2012 from the World Wide Web: http://academicjournals.org/ijps/PDF/pdf2011/18Jul/Rahman%20et%20al.pdf

[6] Elsaied, W. K. and Abdulkarim, Z. A. (2010). Effects of Inlet Air Cooling and Gas Turbine Performance. Retrieved August 5, 2012 from the World Wide Web: http://eprints.utp.edu.my/1040/2/HFT_ID_0356.pdf

[7] Liu, K. et al., (2004). Performance Evaluation of H-25 Gas Turbine. Retrieved 5 July, 2012 from the World Wide Web: http://www.hitachi.com/ICSFiles/afieldfile/2004/06/01/r2003_02_104.pdf

[8] Obodeh, O., and Isaac, F. O. (2011). Performance Analysis of Sapele Power: Case Study of Nigeria. *Journal of Emerging Trends in Engineering and Applied Sciences* (JETEAS) 2(1): 166-171.