HEFAT2014
10th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
14 – 16 July 2014
Orlando, Florida

EXERGETIC AND EXERGOECONOMIC ANALYSIS OF SELECTED GAS TURBINE POWER PLANTS IN NIGERIA

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ABSTRACT

Analysis of power generation systems is of scientific interest and also essential for the efficient utilization of energy resource. The most commonly used method for analysis of the energy conversion process is the first law of thermodynamics - especially for computation of work and heat exchanges as well as thermal efficiency. However, there is increasing interest in combined utilization of both the first and second laws, using such concepts as exergy and exergy destructions in order to evaluate the efficiency with which the available energy is utilized. In this study, a thermodynamic analysis and performance of eleven selected gas turbine power plants in Nigeria was carried out using the first and second laws of thermodynamics and economic concepts. Thermodynamic modelling of industrial gas turbines in power plant applications was performed using a computer code developed specifically for simulation purposes with the Matlab software. Exergetic and exergo-economic analyses were conducted using operating data obtained from the power plants to determine the exergy destruction and exergy efficiency of each major component of the gas turbine in each power plant. The exergy analysis confirmed that the combustion chamber is the most exergy destructive component compared to other cycle components as expected. Furthermore, the exergy efficiency of the combustion chamber is less than that of any other components of the gas turbines studied, which is due to the high temperature difference between working fluid and burner temperatures. The percentage exergy destruction in combustion chamber varied between 86.05 and 94.6%. In addition, it was found that by increasing the gas turbine inlet temperature (GTIT), the exergy destruction of this component can be reduced. Exergo-economic analysis showed that the cost of exergy destruction is high in the combustion chamber and that increasing the GTIT effectively decreases this cost. The exergy costing analysis revealed that the unit cost of electricity produced in the plants ranged from 3.78 cents/kWh (N5.67/kWh) to 5.86 cents/kWh (N8.79/kWh). An examination of the effects of design parameters on exergy efficiency showed that an increase in the air compressor pressure ratio and GTIT increases the total exergy efficiency of the cycle.

Key Words: Exergy, Exergo-economic, Gas Turbine, Exergy efficiency

1.0 INTRODUCTION

The importance of developing thermal systems that effectively use energy resources such as natural gas is apparent. Effective use of energy resources is determined with both the first and second laws of thermodynamics. Energy cannot be destroyed. The idea that something can be destroyed is useful in the analysis of power plants and thermal systems [1]. This idea does not apply to energy, however, but to exergy.

Many researchers suggested that the impact of energy resource utilization on the environment and the achievement of increased resource-utilization efficiency are best addressed by considering exergy [2 – 4]. The exergy of an energy form or a substance is a measure of its usefulness or quality. It is the maximum quantity of work extractable from flows of material and energy, when these are brought under a state of equilibrium with the environment. The energy content of a plant is the difference between energy input and output. Exergy is based on the first and second laws of thermodynamics, and combines the principles of conservation of energy and non-conservation of entropy. The essence of exergy analysis is primarily for optimization. If properly done it reveals where in the plant the largest energy wastage occurs and therefore the need for design improvements [5-6].

Recently, exergy analysis has been used by many researchers in thermal systems, especially for power plants. It is well-known that the exergy can be used to determine the location, type and true magnitude of exergy destructions and losses. Therefore, it can play an important role in developing strategies and providing guidelines for more effective use of energy in the existing power plants. Some key points about exergy are well explained in the literature [7- 9]:

- Exergy has become increasingly important across a diverse array of fields and throughout developing and developed world in order to increase efficiency, reduce wastes and losses, and improve processes and systems.
- Exergy has become more integrated with economics and applications as a new discipline like thermoeconomics or exergoeconomics.
- Exergy has been a tool to foster sustainability and contribute to making development more sustainable.
- Exergy has become more broadly covered in educational programs, and used as a basis for explaining and giving practical meaning to the second-law of thermodynamics.
- Exergy has also been used in assessing environmental impact of thermal plant in exergoenvironomic.

These remarks clearly show the importance of exergy in thermal engineering, especially for power plants analysis.

Combination of the first and second laws of thermodynamics with concepts of economics represents a very powerful tool for the systematic study of energy systems. This combination forms the basis of the relatively new field of thermoeconomics or exergoeconomics. Exergoeconomics combines exergy analysis with conventional cost analysis in order to evaluate and optimize the performance of energy systems [10]. Exergoeconomics is a tool used for improving overall system efficiency and lowering life cycle costs of a thermodynamic system.

Exergoeconomic analysis allows evaluation of cost incurred by irreversibility, which may include the capital cost and operating cost of each component of energy conversion systems [11 – 12]. A complete exergoeconomic analysis consists of (a) an exergetic analysis, (b) an economic analysis, and (c) an exergoeconomic evaluation.

A number of studies on exergy and exergoeconomic analyses of energy systems have been carried out by several researchers [13 – 16]. Tsatsaronis and Moran [16] showed how certain exergy related variables can be used to minimize the cost of a thermal system. Vieira et al., [17], presented the development and automated implementation of an iterative methodology for exergoeconomic improvement of thermal systems integrated with a process simulator, so as to be applicable to real, complex plants. Colpan and Yesin [18] analyzed the energetic, exergetic and thermoeconomic aspects of the Bilkent combined cycle cogeneration plant. Cardona and Piacentino [19] presented a new method to exergoeconomic analysis and design of variable demand energy systems. Also Baghernejad and Yaghoubi [20] presented exergoeconomic analysis and optimization of an Integrated Solar Combined Cycle System (ISCCS) using genetic algorithm.

Most of the past studies on exergy and exergoeconomic analyses of gas turbine plants were based on a single gas turbine unit. In the present work, exergy and exergoeconomic analyses is performed on eleven (11) gas turbine units at three different stations in Nigeria.

The prime objectives of this study are:

- To evaluate the performance of the selected gas turbine power plants by analyzing the exergetic parameters of each components based on the actual operational data
- To establish exergy consumption and destruction in the same components of the gas turbine power plants using the second law of thermodynamics.
- To identify the most significant sources (s) of exergy destruction in the power plants and the location(s) of occurrence.
- To evaluate exergoeconomic performance of the selected gas turbine power plants in Nigeria by analyzing exergetic cost parameters of each components of the power plants
- To determine the unit cost of electricity in the selected gas turbine power plants using exergy costing analysis.

2.0 SYSTEM DESCRIPTION

Gas turbine power plants in Nigeria operate on simple gas turbine engine. The simple gas turbine power plant mainly consists of a gas turbine coupled to a rotary type air compressor and a combustor (or combustion chamber) which is placed between the compressor and turbine in the fuel circuit. Auxillaries, such as cooling fan, water pumps, etc. and the generator itself are also driven by the turbine. Other auxillaries are starting device, lubrication system, duct system, etc.

For ease of analysis, the steady state model of simple gas turbine is presented in Figure 1.

3.0 METHODOLOGY

Exergoeconomics combines the exergy analysis with the economic principles and incorporates the associated costs of the thermodynamic inefficiencies in the total product cost of an energy system. Exergoeconomic analysis estimates the unit cost of product such as electricity and quantifies monetary loss due to irreversibility. At present, such analysis is in great demand because proper estimation of the production costs is essential for companies to operate profitably. In this study, performance evaluation of eleven selected gas turbine power plants in Nigeria was carried out using exergy and exergoeconomic analyses.

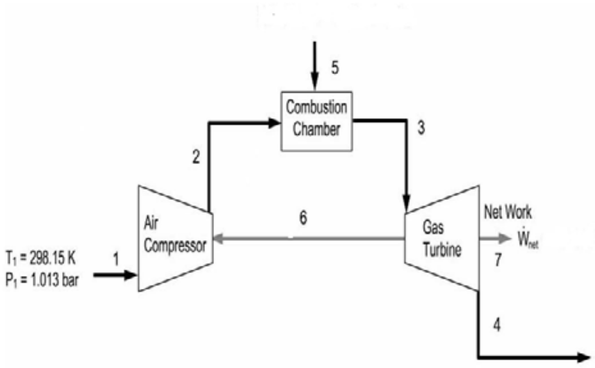

Figure 1: A schematic diagram for a simple GT cycle

3.1 Exergoeconomic Analysis

Exergoeconomics based on the concept that exergy is the only rational basis for assigning monetary costs to the interactions that a system experiences with its surroundings and to the sources of thermodynamic inefficiencies within it. There are different exergoeconomic methodologies discussed in the literatures [11, 13, 15, 21 – 22]. Specific Exergy Costing (SPECO) method is used in this study. This method is based on specific exergies and costs per exergy unit, exergetic efficiencies, and the auxiliary costing equations for components of thermal systems.

In the exergoeconomic analysis of energy conversion system, four steps proposed by Tsatsaronis [23] were followed in this study. These steps are: (i) exergy analysis, (ii) economic analysis of each of the plant component, (iii) estimation of exergetic costs associated with each flow and (iv) exergoeconomic evaluation of each system component.

3.1.1 Exergy Analysis

In steady state, exergy balance for control volume is given as [24 - 25]:

$$\dot{E}_x = \sum_j \left(1 - \frac{T_0}{T_j}\right)\dot{Q}_j + \dot{W}_{CV} + \sum_i m_i e_i - \sum_e m_e e_e \tag{1}$$

The subscripts i, e, j and 0 refer to conditions at inlet and exits of control volume boundaries and reference state. Equation (1) can be written as:

$$E_i^{tot} - E_e^{tot} - E_D = 0 \tag{2}$$

Equation (2) implies that the exergy change of a system during a process is equal to the difference between the net exergy transfer through the system boundary and the exergy destroyed within the system boundaries as a result of irreversibilities.

The exergy-balance equations and the exergy destroyed during each process and for the whole gas turbine plant are written as follows:

Air Compressor

$$\dot{E}^{WAC} = \left(\dot{E}_1^T - \dot{E}_2^T\right) + \left(\dot{E}_1^P - \dot{E}_2^P\right) + T_0\left(\dot{S}_1 - \dot{S}_2\right) \tag{3a}$$

$$\dot{E}_{DAC} = T_0\left(\dot{S}_2 - \dot{S}_1\right) = \dot{m}T_0\left[c_{p1-2} ln\left({}^{T_2}/_{T_1}\right) - Rln\left({}^{P_2}/_{P_1}\right)\right] \tag{3b}$$

Combustion Chamber

$$\dot{E}^{CHE} + \left(\dot{E}_2^T + \dot{E}_5^T - \dot{E}_3^T\right) + \left(\dot{E}_2^P + \dot{E}_5^P - \dot{E}_3^P\right) + T_0\left(\dot{S}_3 - \dot{S}_2 + \dot{S}_5 + \frac{\dot{Q}_{CC}}{T_0}\right) = 0 \tag{4a}$$

$$\dot{E}_{DC} = T_0\left[\dot{S}_3 - \dot{S}_2 + \dot{S}_5 + \frac{\dot{Q}_{CC}}{T_0}\right] = \dot{m}T_0\left\{\left(c_{p2-3} ln\left({}^{T_3}/_{T_2}\right) - Rln\left({}^{P_3}/_{P_2}\right)\right) + \left(c_{p5} ln\left({}^{T_5}/_{T_0}\right) - Rln\left({}^{P_5}/_{P_0}\right)\right) + \frac{c_{p2-3}(T_3 - T_2)}{T_{in\,CC}}\right\} \tag{4b}$$

Gas Turbine

$$\dot{E}^{WGT} = \left(\dot{E}_3^T - \dot{E}_4^T\right) + \left(\dot{E}_3^P - \dot{E}_4^P\right) + T_0\left(\dot{S}_3 - \dot{S}_4\right) \tag{5a}$$

$$\dot{E}_{DGT} = \dot{m}T_0\left[c_{p3-4} ln\left({}^{T_4}/_{T_3}\right) - Rln\left({}^{P_4}/_{P_3}\right)\right] \tag{5b}$$

3.1.2 Economic Analysis of Gas Turbine Components

The economic analysis, conducted as part of the exergoeconomic analysis, provides the appropriate monetary (cost) values associated with the investment, operating and maintenance and fuel costs of the system being analyzed [8]. These values are used in the cost balances [25].

The annualized (levelized) cost method of Moran [2] is used to estimate the capital cost of system component in this work.

The amortization cost for a particular component may be written as [26]:

$$PW = PEC - (SV)PWF(i,n) \tag{6}$$

where the salvage value (SV) at the end of the nth year is taken as 10% [27] of the initial investment for component (or purchase equipment cost, PEC). The present worth (PW) of the component may be converted to the annualized cost by using the capital recovery factor *CRF (i,n)* [28], i.e

$$\dot{C}(\$/year) = PW \times CRF(i,n) \tag{7}$$

where $CRF(i,n) = i/1 - (1+i)^{-n}$, $PWF = (1+i)^{-n}$, i is the interest rate and it is taken to be 17% [27], n is the total operating period of the plant in years and was obtained from the selected plants. PEC is the purchased-equipment cost.

Equations for calculating the purchased-equipment costs for the components of the gas turbine power plant are as follows [25]:

Air Compressor

$$PEC_{ac} = \left[\frac{71.1\dot{m}_a}{0.9-\eta_{sc}}\right]\left[\frac{P_2}{P_1}\right] ln\left[\frac{P_2}{P_1}\right] \quad (8)$$

Combustion Chamber

$$PEC_{cc} = \left[\frac{46.08\dot{m}_a}{0.995-{}^{P_3}/_{P_2}}\right][1 + exp(0.018T_3 - 26.4)] \quad (9)$$

Gas Turbine

$$PEC_{gt} = \left[\frac{479.34\dot{m}_g}{0.92-\eta_{st}}\right] ln\left[\frac{P_3}{P_4}\right][1 + exp(0.036T_3 - 54.4)] \quad (10)$$

Dividing the levelized cost by annual operating hours, N, we obtain capital cost rate for the kth component of the plant [28]:

$$\dot{Z}_k = \frac{\phi_k \dot{C}_k}{3600 \times N} \quad (11)$$

The maintenance cost is taken into consideration through the factor ϕ_k =1.06 for each plant component [27, 28].

3.1.3 Estimation of Exergy Costing

In order to perform exergy costing calculations, gas turbine components (Fig.1) must be combined into suitable control volumes, on which exergetic cost balance equation was then applied, on individual basis. The component in each control volume (CV) with their input and output streams are given as follows:

CV 1: Air Compressor (AC) - Input streams: 1, 6; Output stream: 2

CV 2: Combustion Chamber (CC) - Input Streams: 2, 5; Output Stream: 3

CV 3: Gas Turbine (GT) - Input Stream: 3; Output Streams: 4,6, 7

For a component that receives heat transfer and generates power, cost balance equation may be written as follow [27, 29]:

$$\sum\left(c_e\dot{E}_e\right)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}_{q,k} + \sum\left(c_i\dot{E}_i\right)_k + \dot{Z}_k \quad (12)$$

$$\dot{C}_j = c_j\dot{E}_j \quad (13)$$

The cost – balance equations for all the components of the system construct a set of nonlinear algebraic equations, which was solved for $\dot{C}_j$ and c_j.

The formulations of cost balance for each component and the required auxiliary equations are as follows:

Air Compressor

$$\dot{C}_2 = \dot{C}_1 + \dot{C}_6 + \dot{Z}_{ac} \quad (14)$$

Where subscript 6 denotes the power input to the compressor

Combustion Chamber

$$\dot{C}_3 = \dot{C}_2 + \dot{C}_5 + \dot{Z}_{cc} \quad (15)$$

Gas Turbine

$$\dot{C}_4 + \dot{C}_6 + \dot{C}_7 = \dot{C}_3 + \dot{Z}_{gt} \quad (16)$$

The auxiliary equation for gas turbine is given as:

$$\frac{\dot{C}_3}{\dot{E}_3} = \frac{\dot{C}_4}{\dot{E}_4} \quad (17)$$

Additional auxiliary equation is formulated assuming the same unit cost of exergy for the net power exported from the system and power input to the compressor:

$$\frac{\dot{C}_6}{\dot{W}_{AC}} = \frac{\dot{C}_7}{\dot{W}_n} \quad (18)$$

The cost rate associated with fuel (methane) is obtained from [30]:

$$\dot{C}_f = c_f\dot{m}_f \times LHV \quad (19)$$

where the fuel cost per energy unit (on an LHV basis) is c_f = 0.004\$/MJ [30], $\dot{m}_f$ is mass flow rate of fuel and LHV is the lower heating value of fuel.

A zero unit cost is assumed for air entering the air compressor i.e,

$$\dot{C}_1=0 \quad (20)$$

Implementing Equation (12) for each component together with the auxiliary equations forms a system of linear equations as follows:

$$\left[\dot{E}_k\right] \times [c_k] = \left[\dot{Z}_k\right] \quad (21)$$

where, $[\dot{E}_k]$,$[c_k]$ and $[\dot{Z}_k]$ are the matrix of exergy rate which were obtained in exergy analysis, exergetic cost vector (to be evaluated) and the vector of $\dot{Z}_k$ factors (obtained in economic analysis), respectively.

The above set of equations was solved using MATLAB to obtain the cost rate of each line in Figure 1

The amount of exergy loss rate per unit power output as important performance criteria is given as:

$$\xi = \frac{\dot{E}_{D\,Total}}{\dot{W}_{net}} \quad (22)$$

where ξ is the exergetic performance coefficient.

Exergy destruction rate and efficiency equations for the gas turbine power plant components and for the whole cycle are summarized in Table 1.

Table 1: The exergy destruction rate and exergy efficiency equations for gas turbine

Component	Exergy Destruction Rate	Exergy Efficiency
Compressor	$\dot{E}_{DC} = \dot{E}_{in} - \dot{E}_{out} + \dot{W}_C$	$\varepsilon = \frac{\dot{E}_{out} - \dot{E}_{in}}{\dot{W}}$
Combustion Chamber	$\dot{E}_{DCC} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_{fuel}$	$\varepsilon = \frac{\dot{E}_{out}}{\dot{E}_{in} - \dot{E}_{fuel}}$
Gas Turbine	$\dot{E}_{DT} = \dot{E}_{in} - \dot{E}_{out} - (\dot{W}_{net} + \dot{W}_C)$	$\varepsilon = \frac{\dot{W}_{net} + \dot{W}_C}{\dot{E}_{in} - \dot{E}_{out}}$
Total exergy destruction rate	$\dot{E}_{DTotal} = \sum \dot{E}_D = \dot{E}_{DC} + \dot{E}_{DCC} + \dot{E}_{DT}$	

The overall exergetic efficiency of the entire plant is given as:

$$\psi_i = \frac{\dot{W}_{net}}{\dot{E}_{x\,fuel}} \tag{23}$$

3.1.4 Exergoeconomic Variables for Gas Turbine Components Evaluation

In exergoeconomic evaluation of thermal systems, certain quantities play an important role. These are the average cost of fuel ($c_{F,k}$), average unit cost of product ($c_{P,k}$), the cost rate of exergy destruction ($\dot{C}_{D,k}$), relative cost difference r_k and exergoeconomic factor f_k.

Then the average costs per unit of fuel exergy ($c_{F,k}$)and product exergy ($c_{P,k}$) are calculated from[31] :

$$c_{F,k} = \frac{\dot{C}_{F,k}}{\dot{E}_{F,k}} \tag{24}$$

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{25}$$

The cost rate associated with exergy destruction is estimated as:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{26}$$

Relative cost difference r_k is given as [32]:

$$r_k = \frac{c_{P,k} - c_{F,k}}{c_{F,k}} = \frac{1-\varepsilon_k}{\varepsilon_k} + \frac{\dot{Z}_k}{c_{F,k}\dot{E}_{p,k}} \tag{27}$$

One indicator of exergoeconomic performance is the exergoeconomic factor, f_k. The exergoeconomic factor is defined as [27, 31]:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \tag{28}$$

4.0 RESULTS AND DISCUSSION

The average operating data for the selected gas turbine power plants for the period of six years (2005 – 2010) is presented in Table 2.

4.1 Results of Exergy Analysis

The exergy flow rates at the inlet and outlet of each component of the plants were evaluated based on the values of measured properties such as pressure, temperature, and mass flow rates at various states. These quantities were used as input data to the computer program (MATLAB) written to perform the simulation of the performance of the components of the gas turbine power plant and the overall plant.

Table 3 presented results of the net exergy flow rates crossing the boundary of each component of the plants, exergy destruction, exergy defect, exergetic performance coefficient and exergy efficiency of each component of the plants. The two most important performance criteria, exergy efficiency and exergetic performance coefficient (ξ) vary from 18.22 – 32.84% and 1.32 – 2.01 respectively for the considered plants. Since the condition of good performance is derived from a higher overall exergetic efficiency but lower exergetic performance coefficient for any thermal system, hence, it can be inferred that AF2, DEL3 and DEL4 gas turbine plants have good performance.

The exergy analysis results also show that the highest percentage exergy destruction occurs in the combustion chamber (CC) and followed by the air compressor in range of 86.05 – 94.67% and 4.75 – 9.21% respectively.

To illustrate the effect of operating parameters on the second law efficiency of the components of the gas turbine, the AES1 (PB204) plant is considered as a typical case. The simulation of the performance of plant and components was done by varying the air inlet temperature from 290 to 320°K; and the turbine inlet temperature from 1000 to 1400*K*, respectively. Figure 2 compares the second-law efficiencies of the air compressor, combustion chamber, gas turbine and the overall plant when the ambient temperature increases. The exergy efficiency of the turbine component and the overall exergetic efficiency of plant decreased with increased ambient temperature, whereas the exergy efficiencies of the compressor and turbine increased with increased ambient temperature. The overall exergetic efficiency decreased from 18.53 to 17.26% for ambient temperature range of 290 - 320K. It was found that a 5°K rise in ambient temperature resulted in a 1.03% decrease in the overall exergetic efficiency of the plant. The reason for the low overall exergetic efficiency is due to large exergy destruction in the combustion chamber [24].

4.2 Results of Exergoeconomic Analysis

Solving the linear system of equations (14 – 20), the cost rates of the unknown streams of the system are obtained. For these systems, the exergy costing method gave the unit cost of electricity produced in each plant as : 3.90 cent/kWh (N5.85/kWh) for AES1 (PB204), 4.45 cents/kWh(₦6.68/kWh) for AES 2(PB209), 4.64 cents/kWh(₦6.96/kWh) for AES 3(PB210), 3.69 cents/kWh (₦5.54/kWh) for AF1(GT 17), 3.78 cents /kWh (₦5.67/kWh) for AF2(GT 18), 5.86 cents/kWh

(₦8.79/kWh) for AF3 (GT 19), 5.76 cents/kWh (₦8.64/kWh) for AF4(GT 20), 5.31 cents/kWh (₦7.97/kWh) for DEL1(GT9), 5.43 cents/kWh (₦8.15) for DEL2 (GT10), 5.18 cents/kWh (₦7.77/kWh) for DEL 3(GT18) and 5.14 cents/kWh (₦7.71).

The exergoeconomic parameters considered in this study include average costs per unit of fuel exergy C_F and product exergy C_P, rate of exergy destruction $\dot{E}_D$, cost rate of exergy destruction $\dot{C}_D$, investment and O &M costs rate $\dot{Z}$ and exergoeconomic factor f. In analytical terms, the components with the highest value of $\dot{Z}_k + \dot{C}_{Dk}$ are considered the most significant components from an exergoeconomic perspective. This provides a means of determining the level of priority a component should be given with respect to the improving of the system.

For all the plants considered, the combustion chamber and air compressor have the highest value of the sum $\dot{Z}_k + \dot{C}_{Dk}$ and are, therefore, the most important components from the exergoeconomic viewpoint. The low value of exergoeconomic factor, f, associated with the combustion chamber suggests that the cost rate of exergy destruction is the dominate factor influencing the component. Hence, it is implied that the component efficiency is improved by increasing the capital investment. This can be achieved by increasing gas turbine inlet temperature (GTIT). The maximum GTIT is limited by the metallurgical considerations [27, 33].

The gas turbine has the highest f value in all the plants investigated except plant AF4 (GT20) with f value 33.87%. The cost effectiveness of the entire system of the plants investigated can be improved if the $\dot{Z}$ value of gas turbine is reduced. According to equation (10) of the cost model, the capital investment and O & M costs of the gas turbine depend on temperature T_3, pressure ratio P_3/P_4, and turbine isentropic efficiency η_{st}. To reduce the high $\dot{Z}$ value associated with the gas turbine, we need to consider reduction in the value of at least one of the variables.

The results of the exergoeconomic analysis of the plants investigated show that the combustion chamber (CC) exhibits the greatest exergy destruction cost. The next highest source of exergy destruction cost is the air compressor. In comparing the results of exergy and exergoeconomic analyses, similar trends are revealed. Increasing gas turbine inlet temperature effectively decreases the cost associated with exergy destruction. Further comparisons between related results are consistent with those reported by Ahmadi et al [34], and confirm that the most significant parameter in the plant is GTIT. The finding establishes the concept that the exergy loss in the combustion chamber is associated with the large temperature difference between the flame and the working fluid. Reducing this temperature difference reduces the exergy loss. Furthermore, cooling compressor inlet air allows the compression of more air per cycle, effectively increasing the gas turbine capacity.

To illustrate the effect of GTIT on the exergy destruction cost of combustion chamber of the selected plants, AES1 (PB204) plant is considered as sample. The simulation was done by varying the gas turbine inlet temperature from $950 - 1500K$. Figure 3 shows the effect of variation in GTIT on combustion chamber exergy destruction cost. This figure shows that, like the exergy analysis results, the cost of exergy destruction for the combustion chamber decreases with an increase in the gas turbine inlet temperature (TIT). This is due to the fact that the cost of exergy destruction is proportional to the exergy destruction. Hence, an increase in the gas turbine inlet temperature can decrease the cost of exergy destruction. Furthermore, from Figure 3, an increase in the TIT of about 200 K can lead to a reduction of about 29% in the cost of exergy destruction. Therefore, TIT is the best option to improve cycle losses.

5 CONCLUSIONS

In the present study, exergy and exergo-economic analyses were performed for eleven selected gas turbine power plants in Nigeria.

The results from the exergy analysis show that the combustion chamber is the most significant exergy destructor in the selected power plants, which is due to the chemical reaction and the large temperature difference between the burners and working fluid. Moreover, the results show that an increase in the turbine inlet temperature (TIT) leads to an increase in gas turbine exergy efficiency due to a rise in the output power of the turbine and a decrease in the combustion chamber losses.

The results from the exergoeconomic analysis, in common with those from the exergy analysis, show that the combustion chamber has the greatest cost of exergy destruction compared to other components. In addition, the results show that by increasing the turbine inlet temperature (TIT) the gas turbine cost of exergy destruction can be decreased. The finding solidifies the concept that the exergy loss in the combustion chamber is associated with the large temperature difference between the flame and the working fluid. Reducing this temperature difference reduces the exergy loss. Furthermore, cooling compressor inlet air allows the compression of more air per cycle, effectively increasing the gas turbine capacity. The results of this study revealed that an increase in the TIT of about 200 K can lead to a reduction of about 29% in the cost of exergy destruction. Therefore, TIT is the best option to improve cycle losses.

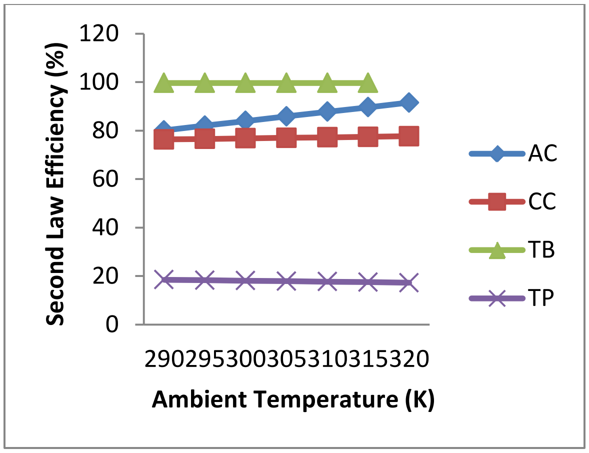

Figure 2 - Variation in second-law efficiency with Ambient Temperature

AC - Second law efficiency of Compressor,
CC- Second law efficiency of combustion chamber,
TB – Second law efficiency of turbine,
TP – Second law efficiency of entire plant

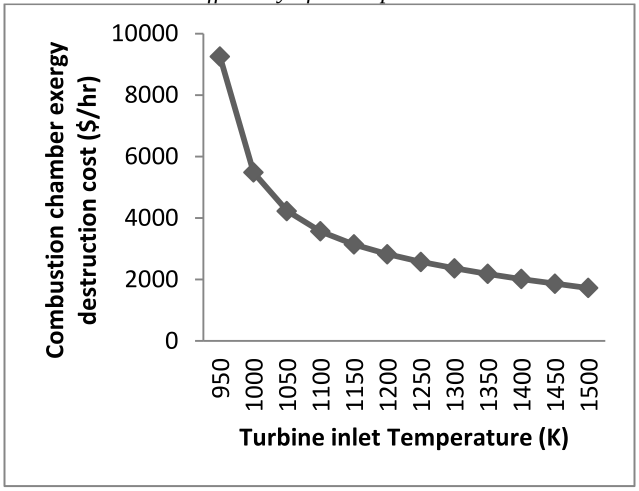

Figure 3: Combustion chamber exergy destruction cost and TIT

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Table 2: Average Operating Data for Selected Gas Turbine Power Plants

Plant/Average Operating Data	AES Station			Afam Station				Delta Station			
	PB204 (AES1)	PB209 (AES2)	PB210 (AES3)	GT17 (AF1)	GT18 (AF2)	GT19 (AF3)	GT20 (AF4)	GT9 (DEL1)	GT10 (DEL2	GT18 (DEL3)	GT20 (DEL4)
Ambient temperature, T_1(K)	303.63	302.31	305.28	300.34	301.48	300.38	300.9	300.55	301.41	301.15	301.79
Compressor outlet temperature, T_2(K)	622.31	627.48	636.28	593.73	595.82	610.90	618.32	613.73	619.07	634.32	630.32
Turbine inlet temperature, T_3(K)	1218.62	1256.86	1222.45	1133.4	1192.82	1200.15	1215.65	1226.15	1224.73	1233.57	1234.73
Turbine outlet temperature, T_4(K)	750.00	755.00	827.05	712.73	723.75	770.07	807.32	710.56	707.48	730.15	705.07
Temperature of exhaust gas, T_{exh}(K)	715.40	750.52	746.48	731.45	664.65	707.23	741.48	622.65	649.90	635.65	636.73
Compressor inlet pressure, P_1(bar)	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013	1.013
Compressor outlet pressure, P_2(bar)	9.8	9.86	9.60	9.50	9.80	9.60	9.60	11.05	10.98	10.82	10.84
Pressure ratio	9.00	9.14	9.48	9.38	9.67	9.48	9.48	10.91	10.84	10.68	10.70
Mass flow rate of fuel (kg/s)	2.58	2.54	2.81	5.50	6.4	8.1	8.4	3.08	3.10	8.15	8.13
Inlet mass flow rate of air(kg/s)	122.16	122.20	121.93	359.00	359.00	470	470	140	140	375	375
Power output (MW)	29.89	29.37	31.52	49.90	58.00	132	135.4	19.42	20.8	92.8	93.42
LHV of fuel (kJ/kg)	47,541.57	47,541.57	47,541.57	48,948.3	48,948.3	48,948.3	48,948.3	46,778	46,778	46,778	46,778

Table 3: Result of Exergy Analysis

Exergy Performance Indicator	PB204 (AES1)	PB209 (AES2)	PB210 (AES3)	GT17 (AF1)	GT18 (AF2)	GT19 (AF3)	GT20 (AF4)	GT9 (DEL1)	GT10 (DEL2)	GT18 (DEL3)	GT20 (DEL4)
Installed Rated Power (MW)	33.5	33.5	33.5	75.0	75.0	138.0	138.0	25.0	25.0	100.0	100.0
Fuel exergy flow rate (MW)	220.53	235.23	237.68	327.96	363.28	459.15	449.06	274.85	276.78	441.20	440.24
Exergy destruction rate of A.C (MW)	4.69	4.98	5.64	8.62	8.09	13.14	14.80	3.14	3.63	13.36	12.48
Exergy destruction of C.C (MW)	56.55	56.58	55.35	139.42	159.84	176.78	180.83	62.52	61.76	171.84	173.33
Exergy destruction rate of Turbine (MW)	0.29	0.52	0.23	5.99	1.47	9.39	14.50	0.39	0.14	0.70	1.80
Total exergy destruction rate (MW)	61.54	62.09	61.23	154.02	169.40	199.31	210.13	66.04	65.53	185.91	187.61
Exergy destruction of A.C (%)	7.62	8.03	9.21	5.59	4.78	6.60	7.04	4.75	5.54	7.19	6.65
Exergy destruction of C.C (%)	91.90	91.13	90.39	90.51	94.36	88.70	86.05	94.67	94.25	92.43	92.39
Exergy destruction rate of Turbine (%)	0.48	0.84	0.41	3.89	0.87	4.71	6.90	0.58	0.21	0.38	0.96
Efficiency defect of A.C (%)	14.01	14.83	16.83	9.15	8.43	12.46	14.03	7.79	9.05	12.52	11.69
Efficiency defect of C.C (%)	66.11	66.26	64.63	58.31	58.05	58.35	56.20	73.45	72.43	56.11	56.97
Efficiency defect of Turbine (%)	0.38	0.68	0.32	3.05	0.68	4.08	6.50	0.42	0.15	0.29	0.74
Total efficiency defect (%)	80.50	81.77	81.78	70.51	67.16	74.89	76.73	81.66	81.63	68.92	69.40
Exergy efficiency of A.C (%)	85.99	85.17	83.17	90.85	91.57	87.54	85.97	95.21	90.95	87.48	88.31
Exergy efficiency of C.C (%)	74.36	75.95	76.71	57.49	56.00	61.50	59.73	77.25	77.69	61.05	60.63
Exergy efficiency of Turbine (%)	99.62	99.32	99.67	96.86	99.32	95.75	93.09	99.57	99.85	99.71	99.25
Overall exergetic efficiency (%)	19.50	18.23	18.22	29.49	32.84	25.11	23.27	18.34	18.37	31.08	30.60
Exergetic performance coefficient (ξ)	1.43	1.45	1.46	1.59	1.32	1.73	2.01	1.47	1.59	1.36	1.39