Nigerian Research Journal of Engineering and Environmental Sciences 6(1) 2021 pp. 387-397

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

Performance Evaluation of the Afam VI Combined Cycle Power Plant System using Energy and Exergy Analysis Approach

***Eke, M.N., Akogwu, J.N. and Enibe, S.O.**

Department of Mechanical Engineering, Faculty of Engineering, University of Nigeria, Nsukka, Enugu State, Nigeria.
*mkpamdi.eke@unn.edu.ng

ARTICLE INFORMATION

Article history:
Received 17 Mar, 2021
Revised 18 May, 2021
Accepted 03 Jun, 2021
Available online 30 June, 2021

Keywords:
Combined cycle
Heat recovery steam generator
Gas turbine
Exergy destruction
Mean exergy efficiency

ABSTRACT

Performance evaluation of the 685MW Afam VI combined cycle power plant (CCPP) in Nigeria was carried out using energy and exergy analyses approach. The data used were the plant's design data and operating data for 2013-2015. The plant is made up of three gas turbine generation sets of 165 MW each and a condensate-type steam turbine of 190 MW. Each sub-component of the plant was analyzed separately with a view of pinpointing the component with highest source of exergy destruction. The results showed that the combustion chamber (CC) had mean exergy efficiency of 14.02% and highest mean exergy destruction value of 11363986 kW. The least mean exergy destruction of 56.378 kW was found in the pump.

1. INTRODUCTION

Nigeria is a rapidly developing economy endowed with both conventional and the non-conventional energy resources. The conventional energy resources comprise mostly of the non-renewable resources such as crude petroleum oil, natural gas, coal, tar sand and uranium (Nnaji, 2012). The country needs efficient use of energy such as electricity to secure a sustainable future. Therefore, exergy analysis is the answer for proper utilization of energy resources for improved systems efficiency particularly thermal power plants for sustainable power generation. The most commonly-used method for evaluating the efficiency of an energy-conversion process is the energy or first-law analysis. However, there is increasing interest in the combined utilization of both the first and second laws of thermodynamics, using such concepts as exergy (availability, available energy), entropy generation and irreversibility (exergy destruction) in order to evaluate the efficiency with which the available energy is consumed (Vosough, 2012; Bakhshesh and Vosough, 2012). Exergy analysis is based on the laws of thermodynamics, especially the second law, which acknowledges that whereas energy may neither be created nor destroyed, its quality may be so degraded as it come to equilibrium with the surroundings that its use for performing tasks is limited (Dincer and Rosen, 2007; Njoku et al., 2019).

Exergy is the maximum theoretical useful work derivable with an energy carrier under the conditions imposed by an environment at a given pressure (P_o) temperature (T_o) and constituted of specified amounts of chemical elements. The purpose of an exergy analysis is generally to identify the location, sources, and magnitudes of true thermodynamic inefficiencies in a system (Dincer and Rosen, 2007). One of the most widely used energy conversion system for power generation are thermal power plants. Thermal power plants are the kind of facilities transforming chemical energy inherent in solid, liquid and gaseous fuels into thermal energy, which is then converted to electrical energy (Bolatturk et al., 2015).

Among thermal power plants, the combined cycle power plant is one of the sources of electricity in Nigeria. In conventional power plants, a large amount of heat is produced but not used. Only a small portion of fuel energy is converted into electricity and the remaining is lost as a waste heat. These losses are reduced by designing systems that can use the waste heat and then increase the efficiency of energy production from current levels to a higher level. Combined cycle power plant is the simultaneous production of electricity and usable heat using air and steam from the same energy source.

Today, many electrical generation utilities are striving to improve efficiency and the heat rate at their existing thermal electric generating stations, many of which are over 25 years old. Often, a heat rate improvement of only a few percent appears desirable, as it is thought that the costs and complexity of such measures may be more manageable than more expensive options (Ahmadi and Dincer, 2011; Jodat, 2016). Thus, a better understanding is attained when a more complete thermodynamic view is taken, which uses the second law of thermodynamics in conjunction with energy analysis, via exergy methods (Rashad and Maily, 2009). This paper is aimed at evaluation of the Afam VI combined cycle power plant system using energy and exergy approach.

2. METHODOLOGY

2.1. System Description

The Afam VI combined power plant is located in Rivers State, Nigeria. It has a design capacity of 685 MW and is an integrated combined cycle power plant composed of three gas turbine generation sets, 1 GT 13 E2, GT-2 GT 13 E2 and GT-3 GT 13 E2 of 165 MW each and a condensate-type ST-1 turbine capacity steam turbine of 190 MW (one boiler/Heat recovery steam generator (HRSG) as shown in the process diagram in Figure 1. The plant uses natural gas as its fuel type sourced from Shell Petroleum and Development Cooperation (SPDC) Okoloma gas plant located in Oyibo area of the State. The natural gas characteristics composition is shown in Table 1. Air at pressure of 1.01 bar and temperature of 303.90 K enters the compressor of the gas turbine with a constant mass flow rate of 493 kg/s and leaves at pressure of 8.80 bar and a temperature of 676 K. Heat addition takes place in the combustion chamber at constant pressure and temperature of 1773 K. The fuel and air mixture is burned at the combustion chamber, where the combustion products after doing work in the turbine are exhausted at a pressure of 1.1 bar and a temperature of 823K. Hot exhaust gases from the gas turbine are the waste heat sources for process heat production. The quantity and quality of process heat produced depend on the temperature of the hot exhaust gases entering the heat recovery system and the resulting temperature of the steam produced.

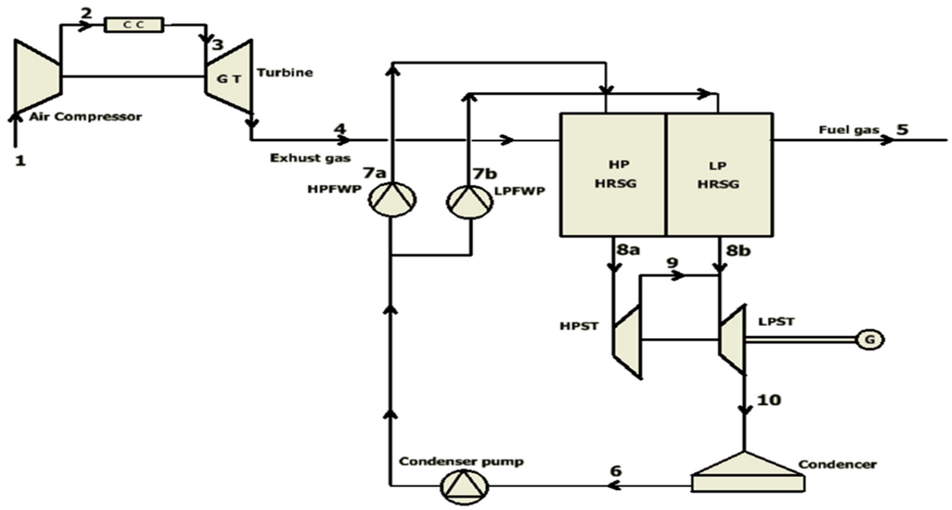

Figure 1: Schematic diagram of Afam VI combined cycle power plant

Table 1: Characteristics of natural gas composition for the Afam VI power plant

Component	Molecular formula	Molar mass	Mole fraction (y_i)	Mass fraction (M_f)
Carbon (IV) oxide	CO_2	44	0.004050	0.008549
Nitrogen	N_2	28	0.000100	0.000134
Methane	CH_4	16	0.826090	0.634064
Ethane	C_2H_6	30	0.066770	0.096092
Propane	C_3H_8	42	0.057610	0.116074
Iso-butane	C_4H_{10}	58	0.009520	0.026488
n-butane	C_4H_{10}	58	0.016900	0.047022
Iso-pentane	C_5H_{12}	72	0.005250	0.018133
n-pentane	C_5H_{12}	72	0.004480	0.015474
n-hexane	C_6H_{14}	86	0.003510	0.014481
n-heptane	C_7H_{16}	100	0.003270	0.015687
n-octane	C_8H_{18}	114	0.001100	0.006016
n-nonane	C_9H_{20}	128	0.000180	0.001105
Decane	$C_{10}H_{22}$	142	0.000100	0.000681
				$\sum=1.000000$

2.2. Method of Analysis

In other to carry out the performance evaluation of the power plant using energy and exergy analysis approach, thermodynamic models were developed for each component. The components include the compressor, combustion chamber, gas turbine, heat recovery steam generator (HRSG), high pressure steam turbine (HPST), low pressure steam turbine (LPST), air ejector and condensate extraction pump and other power plant accessories. The parameters investigated in this research were energy efficiency, exergy efficiency, exergy destruction and thermal efficiency of the plant. Thermodynamic models based on mass, energy and exergy balance equations were formulated. The data used in this study are the plant's design data shown in Table 2 and actual operating data. Thermodynamic data for other properties such as enthalpy and entropy were found with known thermodynamic intensive properties from properties tables (Rogers and Mayhew, 2003a). This information which was fed into Scilab scientific computing software code for result computation (Baudin, 2011).

M.N. Eke et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(1) 2021 pp. 387-397

Table 2: Design input data

State	Substance	Mass flow rate (kg/s)	Temperature (K)	Pressure (bar)	Specific enthalpy (kJ/kg)	Specific entropy (kJ/kgK)
1	Air	493.5	303.9	1.01	305.42	6.89
2	Air	493.5	676.0	8.80	679.38	7.09
3	Fuel	9.6	333.0	29.00	48.81	1.56
4	Combustion product	503.1	1773.0	13.00	1781.87	2.99
5	Combustion product	503.1	823.0	1.01	910.16	1.12
6	Flue gas	503.1	373.0	1.01	412.50	0.25
7	Water	228.0	328.0	25.00	231.82	0.84
8	Water	228.0	333.7	18.80	273.62	0.89
9	Steam	175.7	787.0	123.00	3435.78	6.78
10	Steam	228.0	523.0	4.10	2964.56	7.38
11	Condensed water	228.0	301.5	0.05	2552.88	8.48

2.3. Modeling Approach

The combined cycle power plant models are developed on the basis of the following assumptions.

1. Plant performance parameters at design and operating conditions are evaluated.
2. Each component in the combined cycle power plant model is considered as a control volume.
3. Steam and water are working fluids on the steam side.
4. Air and combustion products are working fluids on the gas side.
5. Each component is regarded as operating at steady state.
6. The combustion process is complete.
7. Ideal gas mixture principles apply for air and combustion products.
8. Generator efficiency is 99%.
9. Kinetic, potential, electrical and nuclear components of exergy are neglected.
10. The values for both P_o and T_o used throughout a particular analysis are normally taken as typical environmental conditions as 1 bar and 25 ^oC respectively.

2.4. Combined Cycle Power Plant Model Equations

Model equations for mass, energy and exergy balances were performed in each component of the combined cycle power plant.

2.4.1. Mass balance

The mass balance at steady state becomes:

$$\sum \acute{m}_i = \sum \acute{m}_e \quad (1)$$

Where $\dot{m}$ is mass flow rate and subscripts í and e refer to inlet and exit conditions respectively

2.4.2. Energy balance

The first law energy equation for a flow process is given by Equation (2) as:

$$Q_{cv} - W_{cv} = \sum_e \acute{m}_e \, h_e - \sum_i \acute{m}_i \, h_i \quad (2)$$

Where$\acute{Q}_{cv}$, $\acute{W}_{cv}$, h_i and h_e are heat transfer rate, rate of energy transfer by work, enthalpy at inlet and enthalpy at exit, respectively.

2.4.3. Energy efficiency of the compressor

The energy efficiency of the compressor sub-system is given by Equation (3).

$$\eta_1 = \frac{W_{\mathrm{AC}_{isen}}}{W_{\mathrm{AC}}} \quad (3)$$

M.N. Eke et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(1) 2021 pp. 387-397

Where W_{AC} is actual work input and $W_{\mathrm{AC}_{isen}}$ isentropic work input

2.4.4. Energy efficiency of the combustion chamber

The energy or first law efficiency ($\eta_{1,cc}$) of the combustion chamber is given as:

$$\eta_{1,cc} = \frac{\acute{m}_t Cp_g\,(\mathrm{T}_3 - T_2)}{\acute{m}_f * LCV} \tag{4}$$

Where $\acute{m}_f * LCV$ and $\acute{m}_t Cp_g\,(\mathrm{T}_3 - T_2)$ are energy input and output of the system respectively.

2.4.5. Energy efficiency of the gas turbine

The energy efficiency of the turbine sub-system is given as:

$$\eta_{1,} = \frac{W_{GT}}{W_{GT_{isen}}} \tag{5}$$

Where W_{GT} is the actual work output and $W_{GT_{isen}}$ is the isentropic work output of the gas turbine sub-system.

2.4.6. Energy efficiency of steam generator

The energy efficiency η_{hrsg} of the steam generator is given by Equation (6).

$$\eta_{hrsg} = \frac{\text{actualenergy recovered}}{\text{maximumenergyinput}} = \frac{Q_{actual}}{Q_{max}} \tag{6}$$

Where Q_{max} is the maximum heat input to the steam generator and Q_{actual} is the actual energy recovered from the steam generator.

2.4.7. Energy efficiency of high-pressure steam turbine (HPST)

The energy efficiency of the high pressure steam turbine, η_{HPST} is given by Equation (7).

$$\eta_{HPST} = \frac{(W_{HPST})_{isen}}{W_{HPST}} \tag{7}$$

Where W_{HPST} is the actual work output and $W_{HPT_{isen}}$ is the isentropic work output of the high pressure steam turbine, respectively.

2.4.8. Energy efficiency of low-pressure steam turbine (LPST)

The energy efficiency of the low pressure steam turbine is calculated using Equation (8).

$$\eta_{\mathrm{LPST}} = \frac{\mathrm{W}_{\mathrm{PT}_{\mathrm{isen}}}}{W_{LPST}} \tag{8}$$

Where W_{LPST} is the actual work output and $\mathrm{W}_{\mathrm{LPT}_{\mathrm{isen}}}$ is isentropic work output of the low pressure steam turbine.

2.4.9. Energy efficiency of the air-cooled condenser

The energy efficiency of the air-cooled condenser is determined using Equation (9).

$$\eta_{\mathrm{cond}} = \frac{E_{\mathrm{outlet}}}{E_{\mathrm{inlet}}} \tag{9}$$

Where E_{inlet} energy inlet to the air-cooled condenser, and E_{outlet} is energy outlet from the air-cooled condenser.

2.4.10. Energy efficiency of pumps

The pump consists of two feedwater pumps. The actual work input W_P and the isentropic pump work $w_{P_{isen}}$ of the combined cycle power plant based on Rogers and Mayhew, (2003b) for a liquid undergoing an isentropic process is determined using Equation (10).

$$w_{P_{isen}} \approx \acute{K}\frac{v_f}{2}\frac{c_v}{c_p}(P_7^2 - P_6^2) \quad (10)$$

Where $\acute{K}$ is the mean coefficient of compressibility $\approx 5X\frac{10^{-9}}{Pascal}$, c_v= 4. 2kJ/(kgK)

The energy efficiency of the pump was calculated using Equation (11).

$$\eta_p = \frac{w_{P_{isent.}}}{W_P} = \frac{\acute{K}\frac{v_f c_v}{2\ c_p}(P_2^2 - P_1^2)}{m_6(h_6 - h_7)} \quad (11)$$

2.4.11. Energy efficiency of the combined power plant

The total energy input to the plant is given by Equation (12) as:

$$\mathrm{Q_{in}} = \mathrm{m_f LHV} \quad (12)$$

The net work ($\mathrm{W_{net}}$) of the combined power plant is given by Equation (13).

$$\mathrm{W_{net}} = \mathrm{W_{gt}} + \mathrm{W_{hpst}} + \mathrm{W_{lpst}} - \mathrm{W_{comp}} - \mathrm{W_{pump}} \quad (13)$$

Hence, the thermal efficiency of the plant is determined using Equation (14).

$$\eta_{ov} = \frac{W_{net}}{Q_{\mathrm{in}}} \quad (14)$$

2.5. Exergy Performance Analyses

Generally, the exergy balance for steady flow processes is given by Equation (15).

$$\sum_j \left(1 - \frac{T_0}{T_j}\right)\acute{Q}_J - \acute{W}_{cv} + \sum_i \acute{m}_i\, e_i - \sum_e \acute{m}_e\, e_e - \acute{E}x_D = 0 \quad (15)$$

$\acute{W}_{cv}$ is rate of exergy transfer accompanying work, ($\acute{Q}_J$) is rate exergy transfer accompanying heat, e_i, e_e are specific exergy in and out of the system and $\acute{E}x_D$ rate of exergy destruction. T_0 is ambient temperature and T_j is the temperature of the system boundary.

2.5.1. Exergy efficiency of the air compressor

The exergy efficiency η_{2C} of the compressor is given as:

$$\eta_{2C} = 1 - \frac{Ed_{AC}}{W_C} \quad (16)$$

Where E_{dAC} is exergy destruction and W_C is work input of the compressor.

2.5.2. Exergy efficiency of the combustion chamber

The exergy efficiency of the combustion chamber $\eta_{2,CC}$ is given by Equation (17).

$$\eta_{2,CC} = 1 - \frac{E_{D,CC}}{(\dot{m}e)_{f+a}} \quad (17)$$

Where m_{f+a} is the sum of the mass of fuel and air, $E_{D,CC}$ is the exergy destruction in the combustion chamber.

The chemical exergy component of the air and fuel were determined from Equation (18) by substituting the standard chemical exergy data reported in Kotas (2013). If the compounds can be treated as perfect gases, then the chemical exergy of the mixture can be calculated from Equation (18).

$$\in_0 = \sum_{i=1}^{n} x_i \in_{oi} + RT_0 \sum_{i=1}^{n} x_i log\ (x_i) \quad (18)$$

Where x_i is the mole fraction of component i and $\in_{oi}$ is the standard chemical exergy of the component. The fuel is composed of 14 gases (CO_2, N_2, CH_4, etc) and their mass fraction are shown in Table 3. The combustion products per mole of the fuel are shown in Table 4.

Table 3: Fuel composition and other reactants in the combustion chamber

Component	Molecular formula	Molar mass	Moles of fuel only	Mole of reactants per mole of fuel	Equivalent constituent for specific heat estimation	Source	Standard chemical exergy of formation (kJ/kmol)
Carbon (IV) oxide	CO_2	44	0.0041	0.0041	CO_2	Fuel	20140
Nitrogen	N_2	28	0.001	0.001	N_2	Fuel	720
Methane	CH_4	16	0.8261	0.8261	CH_4	Fuel	836510
Ethane	C_2H_6	30	0.0668	0.0668	C_2H_6	Fuel	1504360
Propane	C_3H_8	42	0.0576	0.0576	C_3H_8	Fuel	2163190
Iso-butane	C_4H_{10}	58	0.0095	0.0095	C_4H_{10}	Fuel	2818930
n-butane	C_4H_{10}	58	0.0169	0.0169	C_4H_{10}	Fuel	2818930
Iso- pentane	C_5H_{12}	72	0.0053	0.0053	C_5H_{12}	Fuel	3477050
n-pentane	C_5H_{12}	72	0.0045	0.0045	C_5H_{12}	Fuel	3477050
n-hexane	C_6H_{14}	86	0.0035	0.0035	C_6H_{14}	Fuel	4130570
n-heptane	C_7H_{16}	100	0.0033	0.0033	C_7H_{16}	Fuel	4786300
n-octane	C_8H_{18}	114	0.0011	0.0011	C_8H_{18}	Fuel	5440030
n-nonane	C_9H_{20}	128	0.0002	0.0002	C_9H_{20}	Fuel	6093550
Decane	$C_{10}H_{22}$	142	0.0001	0.0001	$C_{10}H_{22}$	Fuel	6749750
Oxygen	O_2	32	0	x*0.21*(1+xe)	O_2	Air	3970
Nitrogen	N_2	28	0	x*0.79*(1+xe)	N_2	Air	720

Table 4: Fuel composition of products in the combustion chamber

Name	Chemical symbol	Molar mass	Mole of product per mol of fuel	Standard chemical exergy of formation (kJ/kmol)
Carbon (IV) oxide	CO_2	44.00	y	20140
Nitrogen	N_2	28.00	0.001+0.79*x*(1+xe)	720
Oxygen	O_2	32.00	0.21*xe*x	3970
Water vapour	H_2O	18.00	z	11710

Note: x = Stoichiometric air/fuel ratio, xe =excess air fraction

2.5.3. Exergy efficiency of turbine

The exergy efficiency of the gas turbine sub system is given by Equation (19).

$$\eta_{2,T} = 1 - \frac{E_{D,T}}{\acute{m}_p(e_3 - e_4)} \quad (19)$$

Where $\acute{m}_p(e_3 - e_4)$ is the rate of change of exergy stream and $E_{D,T}$ is the exergy destruction in the gas turbine sub-system.

2.5.4. Exergy efficiency of heat recovery steam generator

The exergy efficiency is then given by Equation (20).

$$\eta_{2hrsg} = 1 - \frac{E_{xdhrsg}}{m_4 e_{x4}} \quad (20)$$

Where E_{xdhrsg} is the exergy destruction in the heat recovery steam generator and $m_4 e_{x4}$ is the exergy stream into the steam generator.

2.5.5. Exergy efficiency of the high pressure steam turbine (HPST)

The exergy efficiency of the high pressure steam turbine ($\eta_{2_{HPST}}$) is given by Equation (21).

$$\eta_{2_{HPST}} = 1 - \frac{E_{dHPST}}{Ex_{8a} - Ex_9} \quad (21)$$

Where $Ex_{8a} - Ex_9$ is exergy in and out of the system and E_{dHPST} is the exergy destruction in the high pressure steam turbine.

2.5.6. Exergy efficiency of the low pressure steam turbine (LPST)

The exergy efficiency of the low pressure steam turbine ($\eta_{2_{LPST}}$) is given by Equation (22).

$$\eta_{2_{LPST}} = 1 - \frac{E_{dLPST}}{(Ex_9 + Ex_{8b}) - Ex_{10}} \quad (22)$$

Where $(Ex_9 + Ex_{8b}) - Ex_{10}$ is the exergy flow as it enters and exit the component and E_{dLPST} is the exergy destruction in the system.

2.5.7. Exergy efficiency of the air cooled condenser

The exergy efficiency of air cooled compressor (η_{2airc}) is given by Equation (23).

$$\eta_{2airc} = 1 - \frac{E_{dairc}}{Ex_{10}} \quad (23)$$

Where E_{dairc} is the exergy destruction of the air cooled condenser and Ex_{10} is the exergy stream into the system.

2.5.8. Exergy efficiency of the pump

The exergy efficiencies of the pump is given by Equation (24).

$$\eta_{2_{pump}} = 1 - \frac{E_{d_p}}{\mathrm{W_P}} \quad (24)$$

Where $\mathrm{W_P}$ is work input and E_{d_p} is the exergy destruction of the pump.

2.5.9. Plant overall exergy analysis

The exergy input to the plant is given by Equation (25).

$$E_{xin} = E_{xair} + E_{fuel} \quad (25)$$

Where E_{xin} is the sum of exergies in the system E_{xair} and E_{fuel} are the exergy of air and fuel in the system. The total exergy destruction (E_{xdtot}) in the plant is the sum of the exergy destruction in the eight (8) major components considered in the analysis as given by Equation (26).

$$E_{xdtot} = \sum_{i=1}^{8} E_{xd}(i) \quad (26)$$

The overall exergy efficiency of the plant is given by Equation (27).

$$\eta_{2_{Overall}} = 1 - \frac{E_{xdtot}}{E_{xin}} \quad (27)$$

2.5.10. Computational algorithm

All the equations resulting from the energy and exergy analysis were solved using the high performance computational software, SCILAB, version 5.5.2. In general, all the equations for each major component were handled by a function given a name derived from that of the component. The entire analysis is directed by a main programme as shown in the flowchart in Figure 2. The code for this programme was first written to execute before executing main programme. This short code was designed to provide basic information to the main programme, such as the directory path. It also loads all the user-defined functions into memory. Each of the user-defined functions was compiled to produce a binary code for faster execution like an inbuilt SCILAB function. This is accomplished by the short programme genlib file which is only necessary to execute it if a function has been edited or if another version of SCILAB is to be used. Once compiled and binary codes created, the programme can run in any computing system with SCILAB installed.

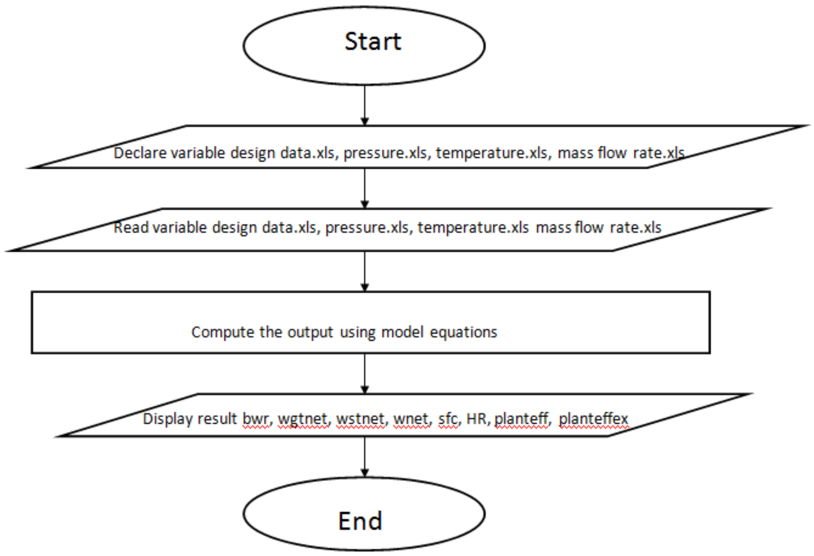

Figure 2: Flow chart for the main programme

3. RESULTS AND DISCUSSION

The performance evaluation of 685 MW combined cycle power plant comprising three gas turbine generation sets of 165 MW each and a condensate- type steam turbine of 190 MW was analyzed using the foregoing and noting that the environment reference temperature and pressure are 25 ^{o}C and 1 bar respectively. The thermodynamic properties of water, steam, air and combustion products at indicated nodes shown in the process diagram were calculated using the SCILAB codes. The complete energy and exergy equations were also solved using the associated SCILAB codes. The results of energy and exergy efficiencies of components investigated are shown in Table 5. From Table 5, the compressor energy and exergy efficiencies were in the range of 83- 88% and 92- 95 % respectively for the period; the combustion chamber energy and exergy efficiencies were in the range of 17.57 – 25.01% and 13.48 – 14.01%. Other components, gas turbine, heat recovery steam generator, high pressure steam turbine, low pressure steam turbine, air cooled condenser and pump had energy and exergy efficiencies in the range 79 -99 % and 61- 75%, 0.23 - 0.27% and 21.19 – 29.14%, 41- 59 % and 50 – 66 %, 42-59 % and 45-69 %, 0.27- 0.3 % and 81 – 91 %, 94 – 96 % and 39 – 48 % respectively. The plant overall energy and exergy efficiencies were in the range 24 – 39 % and 13 – 14 % respectively. The low exergy efficiency of the combustion chamber was an indication that exergy destruction was on the increase.

The mean exergy destruction and percentage contribution of each component to the total exergy destruction in the system is shown in Table 6. From Table 6, the combustion chamber contributes 98.786% of the total exergy destruction in the plant. This is due to high temperature difference during chemical reaction of reacting substances. The heat recovery steam generator had 0.755% of the total exergy destruction and the pump had the least exergy contribution of 0.001% of the entire exergy destruction indicating reduction in irreversibilities during pumping process.

M.N. Eke et al. / Nigerian Research Journal of Engineering and Environmental Sciences
6(1) 2021 pp. 387-397

Table 5: Mean, maximum, minimum and standard deviation of efficiencies of the system components

Component	Mean	Maximum	Minimum	Standard deviation
		Compressor		
Energy efficiency	0.8575071	0.8823409	0.8272429	0.0151707
Exergy efficiency	0.9342291	0.9458933	0.9204706	0.0068744
		Combustion chamber		
Energy efficiency	0.2500489	0.3161270	0.1757361	0.0457529
Exergy efficiency	0.1401514	0.1554987	0.1347612	0.0065386
		Gas turbine		
Energy efficiency	0.8949751	0.9907322	0.7859716	0.0620794
Exergy efficiency	0.6881749	0.7527149	0.6134897	0.0446403
		Heat recovery steam generator		
Energy efficiency	0.02500036	0.0270965	0.0236971	0.0012407
Exergy efficiency	0.2575410	0.2913615	0.2118692	0.0307491
		High pressure steam turbine		
Energy efficiency	0.5369512	0.5915244	0.4180892	0.0430526
Exergy efficiency	0.6130056	0.6633298	0.5013896	0.0405617
		Low pressure steam turbine		
Energy efficiency	0.5369512	0.5915244	0.4180892	0.0430526
Exergy efficiency	0.6111567	0.6854894	0.4501100	0.0706844
		Air cooled condenser		
Energy efficiency	0.953470	0.9666119	0.9451462	0.0059426
Exergy efficiency	0.4248505	0.4772902	0.3894332	0.026119
		Pump		
Energy efficiency	0.0029750	0.0032625	0.0027525	0.0001989
Exergy efficiency	0.8769742	0.9057479	0.8013525	0.0281895
Plant overall energy efficiency	0.3171705	0.3883070	0.2386343	0.0490648
Plant overall exergy efficiency	0.1294525	0.1416468	0.1247763	0.0050192

Table 6: Mean exergy destruction and percentage contribution of components to total exergy destruction

Component	Mean (kW)	Percentage (%)
Compressor exergy destruction	11651.105	0.101
Combustion chamber exergy destruction	11363986	98.786
Gas turbine exergy destruction	9505.032	0.083
Heat recovery steam generator exergy	86846.643	0.755
High pressure steam turbine exergy destruction	11062.562	0.096
Low pressure steam turbine exergy destruction	1295.091	0.011
Air cooled condenser exergy destruction	19205.304	0.167
Pump exergy destruction	56.378	0.001

4. CONCLUSION

A detailed energetic and exergetic analysis of a 685 MW combined cycle power plant comprising three gas turbine generation sets of 165 MW each and a condensate- type steam turbine of 190 MW has been carried out. The thermodynamic data were extracted from the combined power plant's design data and three years' operating period, Thermodynamic properties of water, steam, air and combustion products at indicated nodes shown in the process diagram were calculated and employed in solving the energy and exergy model equations of all the components. From the results of the analysis for the various components and plant, it was observed that combustion chamber has the highest exergy destruction in the plant contributing 98.786%

of the total exergy destruction in the plant. This is as a result of high temperature difference, spontaneous chemical reaction and mixing of reacting substances. The heat recovery steam generator is the component that represents second major percentage exergy destruction contribution of 0.755% in the plant. This which may be attributed to temperature difference among the streams and heat dissipated during the process to the surroundings. The air-cooled condenser was the third source of irreversibility largely due to high energy loss to the coolant during the condensation process in order to continue the cycle. The exergy destruction in other components occurs in the decreasing order namely compressor, high pressure steam turbine, gas turbine, low pressure steam turbine, and pumps. The pump constitutes the lowest source of irreversibility hence lowest exergy destruction.

5. ACKNOWLEDGMENT

The authors sincerely acknowledge the management of Afam VI combined power plant and particularly the staff of efficiency department for providing design data from their handbook and operating data from their log book.

6. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

REFERENCES

Ameri, M., Ahmadi, P. and Khanmohammadi, S. H. (2008). Exergy analysis of a 420 MW combined cycle power plant. *International. Journal of Energy Research*, 32, pp. 175–183.

Ahmadi, P. and Dincer, I. (2011). Thermodynamic and exergoenviromental analyses and multi-objective optimization of a gas turbine power plant. *Applied. Thermal Engineering,* 31, pp. 2529-2540.

Bakhshesh, M. and Vosough, A. (2012). Boiler parametric study to decrease irreversibility. *Indian Journal of science and technology*, *5*(4), pp. 2534-2539.

Baudin, M. (2011). Introduction to Scilab. Consortium SCILAB, Cedex, France. Available online at http://forge.scilab.org/index.php/p/docintroscilab/

Bolatturk, A., Coskun, A. and Geredelioglu, C. (2015). Thermodynamic and exergoeconomics analysis of Cayirhan thermal power plant. *Energy Conversion and Management,* 101, pp. 371-378.

Dincer, I. and Rosen, M.A. (2007). *Exergy, Energy, Environment and Sustainable Development*. Elsevier Science, Oxford.

Jodat, A. (2016). Exegoeconomic Analysis of Gas Turbine Cogeneration Systems. *Journal of Engineering and Applied Sciences,* 11, pp. 2545 – 2550.

Kotas, T. J. (2013). *The Exergy Method of Thermal Plant Analysis*. Elsevier: Amsterdam, The Netherlands.

Njoku, H. O., Egbuhuzor, L.C., Eke, M.N., Enibe, S.O. and Akinlabi, E.A. (2019) Combined Pinch and Exergy Evaluation for Fault Analysis in a Steam Power Plant Heat Exchanger Network. *Journal of Energy Resource Technology*, 141, pp. 1-10

Nnaji, B. (2012). Annual Report of Federal Ministry of Power, 2011, Federal Secretariat Phase I Annex III 4th and 5th Floor, Shehu Shagari Way Abuja, Nigeria.

Rashad, A. and Maily, E. L. (2009). Energy and exergy analysis of a steam power plant in Egypt". *13th International Conference on Aerospace Sciences and Aviation Technology, Asat-13,* May 26-28. Military Technical College, Kobry Elkobbah, Cairo, Egypt.

Rogers, G.F.C. and Mayhew, Y.R. (2003a). En*gineering Thermodynamics, Work and Heat Transfer*. Pearson Educational Ltd, London.

Rogers, G.F.C. and Mayhew, Y.R. (2003b). *Thermodynamic and Transport Properties of Fluids*. Blackwell Publishing Ltd, Oxford.

Vosough, A. (2012). Thermodynamic parametric study of a supercritical power plant. *Journal of thermophysics and heat transfer*, 26 (4), pp. 629 – 637.