Exergoeconomic Evaluation of Transcorp Power Plant Ughelli

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Abstract - *Fundamentally, energy from fuel is low grade energy and all of it cannot be converted to high grade energy (shaft work). Gas turbine's (GT's) thermal efficiency is further reduced due to operational instabilities from protracted part-load operations and high environment temperatures besides those arising due to component inefficiencies. When these occur, power plant operates below its rated capacity; increasing specific cost of energy produced. In this study, exergoeconomic evaluation of Transcorp power plant Ughelli, Nigeria were carried out to determine the location and magnitude of exergy destruction and the cost of exergy destruction associated with each component for the two GE frame 9 engines (GT16 and GT19 units) in the plant. The results obtained from exergoeconmic analysis show that combustion chamber has the highest energy destruction cost of 2351.81$/h GT16, 2315.93$/h GT19 as compared to turbine with 277.36$/h GT16 and 274.46$/h GT19, also compressor with 556.31$/h GT16, 547.60$/h GT19. This shows high level of irreversibility and degradation in the combustion chamber.*

***Key Words*: Exergy, Destruction, Irreversibities, Efficiency, Exergoeconmic, Cost rates.**

1. INTRODUCTION

Developing thermal systems for effectively use energy resources is of paramount interest. Engineers and industries are faced with efficient design and cost effective thermal systems [1,2]due to the uncertainty in energy prices and increase in demand coupled with stringent emission regulation, that seek more efficient energy systems with reduced thermal losses [3-6]. Exergy is highest available shaft work, which in a certain circumstance could be acquired from a certain thermal system as it proceeds to a specified final state in equilibrium with its surroundings [7-8]. Exergy is conserved when the process in a system and the environment is reversible, while it is destroyed in an irreversible process [9].The exergy analysis based on the second law of thermodynamics has found as useful method in design, evaluation, optimization and improvement of thermal power plants [10-11].

It is useful to combine second law of thermodynamic with economic principles for the systematic study of thermal energy systems. This combination forms the basis of thermodynamics thermoeconomics or exergoeconomics. Exergoeconomics combines exergy analysis with conventional cost analysis in order to evaluate and optimize the performance of energy systems. Exergoeconomics is a tool used for improving overall system efficiency and lowering life cycle costs of a thermodynamic system. It incorporates the associated costs of the thermodynamic inefficiencies in the total product cost of an energy system [12-13]. Exergoeconomic analysis estimates the associated unit cost losses due to irreversibility.

Exergoeconomic based on the concept that exergy is rests on the notion 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 [1,12]. Exergoeconomic accounting means determining and assigning economic values to the exergy flows in an energy systems [1,14]. Exergy accounting gives a good picture of the monetary flows inside the total system and is a way to analyze and evaluate very complex installations [1].

Many researchers have carried out work on the exergy and exergoeconomics of energy systems for better design and cost effective operation of the energy systems [13,15-17]. Mousafarash and Ameri (2013) [18] carried out a research study on energy, exergy and exergo-economic analysis of Montazer Ghaem gas turbine power plant which is located near Tehran, capital city of Iran at different loads and ambient temperatures. Abusoglu and Kanoglu [6,19] used the SPECO method to find specific exergy cost to analyze diesel engine powered cogeneration plant. Gorji-Bandpy and Goodarzian [1] carried out an exergoeconomic optimization for 140MW gas turbine power plant using Genetic Algorithms. Tsatsaronis and Winhold [20] proposed thermoeconomic optimization of thermal system. Modesto and Nebra (2006) [21] applied the Theory of Exergetic Cost and Thermoeconomic Functional Analysis to the power plant, generating power from the waste heat of a steel mill plant. Aguilar, Uson, Szyszka and Espinosa (2007) [22] analyzed steam turbine using exergetic cost theory. Shiran, Shitzer and Degani (1982) tried to apply thermodynamic analysis based on first law and economic analysis in combination to Aqua Ammonia Vapour Absorption (AAVAR) system and tried to optimize the system thermoeconomically. Rosen and Dincer [24] carried out exergoeconomic analysis of power plants operating on various fuels. Usón, Kostowski, Stanek and Gazda carried [25] out thermoecological cost of electricity, heat and cold generated in a trigeneration module fuelled with selected fossil and renewable fuels. Sahoo [26] carried out the exergoeconomic analysis and optimization of a cogeneration system using evolutionary programming.

From past research works on exergoeconomic analysis of thermal systems only a single unit plant was considered. In this study, exergoeconomics analysis were applied on two units (GT16 and GT19) that produce 100MW of electricity at Transcorp Power Plant located at Ughelli, Delta State, Nigeria.

2. MATERIALS AND METHOD

2.1 PLANT OVERVIEW

The plant under consideration is a 100MW (GT16 and GT19) GE Frame 9 single shaft open cycles operated at 50Hz located at Ughelli, Nigeria. Each generates electricity to the National Grid and use natural gas as fuel. The simplified schematic diagram of the plant is shown in Fig-1. The plant consists of three (3) main components, namely; axial flow air compressor (C), combustion chamber (CC), turbine (T) and W_{net} is available energy for generator.

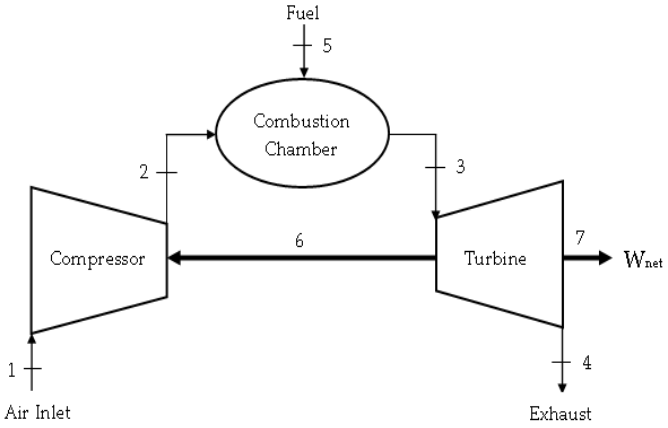

Fig-1: Schematic Diagram of the Power Plant

2.2 EXERGOECONOMIC ANALYSIS

Exergoeconomic 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 [1,12]. There are different exergoeconomic methodologies discussed in the literatures [15-17,27]. In this study Specific Exergy Costing (SPECO) method is used. This method is based on specific exergies and costs per exergy unit, exergetic efficiencies, and the auxiliary costing equations for components of thermal system [12].

Exergoeconomic analysis of energy conversion system, Tsatsaronis [15] proposed four steps which were followed in this study. These steps are:

- Exergy analysis.
- Economic analysis of each of the plant component.
- Estimation of exergetic costs associated with each flow and
- Exergoeconomic evaluation of each system component.

2.2.1 ECONOMIC ANALYSIS

The economic analysis, conducted as part of the exergoeconomic analysis, provides the appropriate monetary (cost) values associated with the investment, operating (excluding fuel), maintenance and fuel costs of the system being analyzed[15,28]. These values are used in the cost balances. The annualized (levelized) cost method of Moran [29] is used to estimate the investment (capital) cost of various plant components in this study. The amortization cost for a particular plant component may be written [16] as:

$$PW = PEC - (SV)\,PWF(i,n) \qquad (1)$$

The salvage value (SV) at the end of the nth year is taken as 10% of the initial investment for component or purchase equipment cost (PEC). The present worth of the component may be converted to the annualized cost by using the capital recovery factor $CRF(i,n)$ [16,30], i.e.

$$\dot{C}(\$/year) = PW \times CRF(i,n) \qquad (2)$$

Where, $CRF(i,n) = i(1+i)^n/[(1+i)^n - 1]$

The capital recovery factor (CRF) depends on the interest rate as well as estimated equipment lifetime [31], i is the interest rate and n is the total operating period of the plant in years.Equations for calculating the purchase equipment costs (PEC) for the components of the power station are as follows [1,12,32]:

Compressor, PEC_C:

$$PEC_C = \left(\frac{71.1\dot{m}_a}{0.9 - \eta_{sc}}\right)\left(\frac{P_2}{P_1}\right) \qquad (3)$$

Combustion Chamber, PEC_{CC}:

$$PEC_{cc} = \left(\frac{46.08\dot{m}_a}{0.995 - P_3/P_2}\right) \times [1 + exp(0.018T_3 - 26.4)] \quad (4)$$

Turbine, PEC_T:

$$PEC_T = \left(\frac{479.34\dot{m}_g}{0.92 - \eta_T}\right) \ln\left(\frac{P_3}{P_4}\right) \times \ [1 + exp(0.036T_3 - 54.4)] \quad (5)$$

For converting capital investment cost into cost per time unit, one may write [31] as:

$$\dot{Z}_k = \frac{\dot{C}_k \varphi_k}{N} \quad (6)$$

N is the annual number of operation hours of the unit and maintenance cost is taken into consideration through the factor $\varphi_k = 1.06$ for each plant component [30].

The cost associated with fuel is obtained from

$$\dot{C}_f = c_f \dot{m}_f LHV \quad (7)$$

Where the fuel cost per energy unit (on an LHV basis) is c_f =0.004 \$/MJ [32].

2.2.2 EXERGY COSTING

The exergy analysis yields the desired information for a complete evaluation of the design and performance of an exergy system from the thermodynamic viewpoint. With this, the plant operator needs to know how much the exergy destruction in a plant component costs and knowing this cost is very useful in improving the cost effectiveness of the plant [15].

To perform exergy costing calculations, the schematic diagram of the gas turbine power plant components (Fig-1), must be considered under control volumes, on which exergetic cost balance equation been applied on individual component. For a component that receives heat and produces work, the exergetic balance may be written [18,33] as follows:

$$\sum_e \dot{C}_{e,k} + \dot{C}_{w,k} = \dot{C}_{q,k} + \sum_i \dot{C}_{i,k} + \dot{Z}_k \quad (8)$$

$$\sum (c_e \dot{E}_e)_k + c_{w,k}\dot{W}_k = c_{q,k}\dot{E}_{q,k} + \sum (c_{i,k}\dot{E}_i)_k + \dot{Z}_k \quad (9)$$

$$\dot{C}_j = c_j \dot{E}_j \quad (10)$$

The cost balance for each component and the required auxiliary equations of Fig. 1 are as follows:

Compressor:

$$\dot{C}_2 = \dot{C}_1 + \dot{C}_6 + \dot{Z}_C \quad (11)$$

Combustion Chamber:

$$\dot{C}_3 = \dot{C}_2 + \dot{C}_5 + \dot{Z}_{CC} \quad (12)$$

Turbine:

$$\dot{C}_4 + \dot{C}_6 + \dot{C}_7 = \dot{C}_3 + \dot{Z}_T \quad (13)$$

The numbers in subscripts denote the states of material streams described in Fig-1. The cost-balance equations are (11) – (13) and we have 7 unknowns. Auxiliary equations for exergy costing can be obtained by applying fuel (“F”) and product (“P”) rules to each component [34]. These are:

$$\frac{\dot{C}_3}{\dot{E}_3} = \frac{\dot{C}_4}{\dot{E}_4} \ or \ c_3 = c_4 \quad F - rule \quad (14)$$

$$\frac{\dot{C}_6}{\dot{W}_C} = \frac{\dot{C}_7}{\dot{W}_{net}} \ or \ c_6 = c_7 \quad P - rule \quad (15)$$

$$\dot{C}_f = \dot{C}_5 = c_f \dot{m}_f LHV \quad (16)$$

A zero unit cost is assumed for air entering the air compressor, which is:

$$\dot{C}_1 = 0 \quad (17)$$

Solving the equations (11) – (17) simultaneously, one may obtain the cost flow rate and average unit cost at each inlet and outlet of the kth component.

2.2.3 EXERGOECONOMIC EVALUATION OF EACH PLANT COMPONENT

In a complete exergoeconomic evaluation of a plant, certain variables play an important role which is based on the following variable calculated for the kth component. These are the average cost of fuel $(c_{F,k})$, average cost of product $(c_{P,k})$, cost rate exergy destruction $(\dot{C}_{D,k})$, relative cost difference r_k and exergoeconomic factor f_k.

Tsatsaronis [15] expressed the average cost per unit of fuel exergy $(c_{F,k})$ and the average cost per unit of exergy of the product $(c_{P,k})$ for the kth component as:

$$c_{P,k} = \frac{\dot{C}_{P,k}}{\dot{E}_{P,k}} \tag{18}$$

The cost rate associated with exergy destruction is given as:

$$\dot{C}_{D,k} = c_{F,k}\dot{E}_{D,k} \tag{19}$$

The exergoeconomic factor is defined as [1]:

$$f_k = \frac{\dot{Z}_k}{\dot{C}_{D,k} + \dot{Z}_k} \tag{20}$$

3. RESULTS AND DISCUSSION

3.1 EXERGOECONOMIC RESULTS

Table-1 shows the average operating data of the plant. Table-2 and 3 show the exergy flow rates at various state points of Fig-1 for GT16 and GT19. Table-4 and 5 present the economic cost of each component the plant units. Table-8 and 9 present the exergoeconomic parameters for each component of the plant units. The levelized cost rates and average unit exergy cost at various state points of the plant were solved using equations (11–17) simultaneously and results are shown in Table-7 and 8. For these plant units, the unit cost of electricity produced in each plant units is given as 9.00$/GJ GT16 and 8.99$/GJ GT19. The exergoeconomic parameters considered in this study include average costs per unit of fuel exergy C_F and product exergy C_P, rate of destruction $\dot{E}_D$, cost rate of exergy destruction $\dot{C}_D$, investment cost rate $\dot{Z}$, and exergoeconomic factor f. The components with the highest value of $\dot{Z}_k + \dot{C}_{D,k}$ and lowest exergoeconomic factor f are considered the most important components from an exergoeconomic viewpoint. This provides a means of determining the level of priority a component should be given attention with respect to improving of the plant.

For the two units considered, the combustion chamber has the highest value of $\dot{Z}_k + \dot{C}_{D,k}$ and lowest value of exergoeconomic factor f, this implies that the component accounts for the highest cost rate of exergy destruction. Hence, the component efficiency should be improved by increasing the capital investment costs$\dot{Z}_k$. This can be achieved by increasing the turbine inlet temperature T_3. The maximum turbine inlet temperature (TIT) of the combustion chamber is limited by the metallurgical conditions [1,12]. A relatively high value of the exergoeconomic factor f in the turbine and compressor for GT16 and GT19 suggest a reduction in the capital investment cost of these components. The cost effectiveness of the total system of the plant units investigated can be improved if the $\dot{Z}$ value of the gas turbine is reduced.

From the results of the exergoeconomic analysis of the plant units investigated show that the combustion chamber gives the highest exergy destruction cost. The next source of exergy destruction is the compressor. The exergy destruction cost for compressor for GT16 and GT19 are high and also need improvement. From the results it shows that high exergy destruction occurred in the combustion due to incomplete chemical reaction and large temperature difference and can be reduced by preheating the combustion air and reducing the air-fuel ratio. By reducing the temperature difference reduces the exergy destruction of the plant.

Table-1: Average Operating Data for the Gas Turbine Power Plant

Plant/Average Operating Data	GT16	GT19
Power output (MW)	75.10	80.15
Pressure of inlet air to compressor, (P_1 (MPa)	0.1013	0.1013
Temperature of inlet air to compressor, T_1 (K)	298	298
Mass flow rate of air, $\dot{m}_a$ (kg/s)	412	414
Outlet pressure of air from compressor, P_2 (MPa)	0.981	0.985
Pressure ratio	9.68	9.72
Outlet temperature of air from compressor, T_2 (K)	655	654
Inlet temperature to gas turbine, T_3 (K)	1328	1330
Temperature of exhaust gas, T_4 (K)	824	821
Pressure of exhaust gas, P_4 (MPa)	0.1075	0.1075
Mass flow rate of fuel, $\dot{m}_f$ (kg/s)	7.858	7.843
Inlet temperature of fuel, T_f (K)	296.9	297
Inlet pressure of fuel , P_f (MPa)	2.05	2.03
LHV of fuel (kJ/kg)	47.285	47.285
Turbine speed (rpm)	3000	3000

Table-2: Thermal, mechanical and chemical exergy flow rates at various state for GT16

State	$\dot{m}\ (kg/s)$	$T\ (K)$	$P\ (MPa)$	$\dot{E}^{T}\ (MW)$	$\dot{E}^{P}\ (MW)$	$\dot{E}^{CHE}\ (MW)$	$\dot{E}^{TOT}\ (MW)$
1	412	298	0.1013	0.0000	0.0000	0.0000	0.0000
2	412	655	0.981	50.6447	80.0045	0.0000	130.6492
f	7.858	296.9	2.05	0.00003	3.6481	420.3069	423.9550
3	419.858	1328	0.9516	287.2185	81.2774	0.0000	368.4959
4	419.858	824	0.1075	109.5015	2.1554	0.0000	111.6569

Table-3: Thermal, mechanical and chemical exergy flow rates at various state for GT19

State	$\dot{m}\ (kg/s)$	$T\ (K)$	$P\ (MPa)$	$E^{T}\ (MW)$	$E^{P}\ (MW)$	$E^{CHE}\ (MW)$	$\dot{E}^{TOT}\ (MW)$
1	414	298	0.1013	0.0000	0.0000	0. 0000	0.0000
2	414	654	0.985	50.6639	80.5369	0.0000	131.2009
f	7.843	297	2.03	0.00003	3.6293	419.5976	423.2269
3	421.843	1330	0.9555	289.3422	81.8100	0. 0000	371.1522
4	421.843	821	0.1075	110.0192	2.1656	0.0000	112.1848

Table-4: ***Economic costs GT16***

Component	Annual Levelized Cost $\dot{C}_k$ $(\$/year)$	Purchase Equipment Cost (PEC) ($)	Capital Cost Rate $\dot{Z}_k$ $(\$/hour)$
C	$5.500\mathrm{x}10^{6}$	$32.204\mathrm{x}10^{6}$	728.75
CC	$1.404\mathrm{x}10^{5}$	$0.822\mathrm{x}10^{6}$	18.60
T	$2.502\mathrm{x}10^{6}$	$14.649\mathrm{x}10^{6}$	331.49

Table-5: ***Economic costs GT19***

Component	Annual Levelized Cost $\dot{C}_k(\$/year)$	Purchase Equipment Cost (PEC)($)	Capital Cost Rate $\dot{Z}_k$ $(\$/h)$
C	$5.559\mathrm{x}10^{6}$	$32.551\mathrm{x}10^{6}$	736.59
CC	$1.415\mathrm{x}10^{5}$	$0.828\mathrm{x}10^{6}$	18.74
T	$2.519\mathrm{x}10^{6}$	$14.747\mathrm{x}10^{6}$	333.71

Table-6: ***Levelized cost rates and average unit exergy cost at various state point GT16***

State Points	$\dot{c}$ $(\$/h)$	c $(\$/GJ)$	c $(\$/kWh)$
1	0	0	0
2	5668.0723	12.051	0.043384
3	11037.212	8.320	0.029952
4	3344.2753	8.320	0.029952
5	5350.54	3.506	0.012621
6	4939.3223	9.003	0.032412
7	3085.1007	9.003	0.032412

Table-7: *Levelized cost rates and average unit exergy cost at various state points GT19*

State Points	$\dot{C}$ ($/h)	c ($/GJ)	c ($/kWh)
1	0	0	0
2	5676.6342	12.019	0.043267
3	11035.704	8.259	0.029734
4	3343.8184	8.259	0.029734
5	5340.3300	3.505	0.012618
6	4940.0442	8.986	0.032351
7	3085.5516	8.986	0.032351

Table-8: Exergoeconomic Parameters of Gas Turbine Components of GT16

Component	c_P ($/GJ)	c_F ($/GJ)	$\dot{E}_D$ (MW)	$\dot{C}_D$ ($/h)	$\dot{Z}$ ($/h)	$\dot{C}_D+\dot{Z}$ ($/h)	f (%)
C	12.05	9.00	17.17	556.31	728.75	1285.06	56.71
CC	8.32	3.51	186.12	2351.81	18.60	2370.41	0.78
T	9.00	8.32	9.26	277.36	331.49	608.85	54.45

Table-9: Exergoeconomic Parameters of Gas Turbine Components of GT19

Component	c_P ($/GJ)	c_F ($/GJ)	$\dot{E}_D$ (MW)	$\dot{C}_D$ ($/h)	$\dot{Z}$ ($/h)	$\dot{C}_D+\dot{Z}$ ($/h)	f (%)
AC	12.02	8.99	16.92	547.60	736.59	1284.19	57.46
CC	8.26	3.51	183.28	2315.93	18.74	2334.67	0.80
T	8.99	8.26	9.23	274.46	333.71	608.17	54.82

3. CONCLUSIONS

In this study, the exexergoeconomic analysis was performed for the two 100MW gas turbine units at Transcorp Power Limited, Ughelli.

The exergoeconomic analysis results from two plant units show that combustion chamber has the highest exergy destruction as compare to other components and cost of exergy destruction of turbine and compressor are lower compare to the combustion chamber that has the highest cost of exergy destruction. Also the exergonomic factor of turbine and compressor far better than the combustion chamber with lowest value of exergoeconomic factor f. In order to reduce the exergy destruction cost of the combustion chamber and improved the component efficiency is by increasing the capital investment costs $\dot{Z}_k$ which will as well increase the exergoeconomic factor f.

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