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iJET International
Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 4 No. 8, August, 2014

Exergoeconomic Analysis of A 100MW Unit GE Frame 9 Gas Turbine Plant in Ughelli, Nigeria.

D. I. Igbong[1] and D.O. Fakorede[2]
[1]Department of Mechanical Engineering, Cross River University of Technology, Calabar Nigeria
[2]Department of Mechanical Engineering, Cross River University of Technology, Calabar Nigeria

ABSTRACT

A 100 MW gas turbine power plant at Ughell, Nigeria was evaluated using exergoeconomic analysis method. These optimization was performed on engineering equation solver (EES) software to estimate the cost rate associated with all the exergy streams at cycle state points and the cost of plant final product which is electricity. Two parameters were chosen as decision variables: turbine inlet temperature, T_3 and compressor pressure ratio, r_p. Studies were carried out on the effect of variation of these parameters on the unit cost of the final product of the plant. Results establishes a relation between variation in decision variables and unit cost of product. The unit cost of product decreases to a minimum point as the decision variables increases, beyond which, it increases with further increase in the value of the parameters.. Thus, the least unit cost of product was achieved at T_3 = 1474 K and r_p = 11.4. The plant thermal efficiency is 31.05%, and overall exergy efficiency of 30.81%, identified the combustion chamber with the lowest exergetic efficiency of 54.05% accounting for the component with the largest total inlet exergy destruction value of 238.681 MW.

Keywords: *Gas turbine, exergoeconomic analysis, exergy analysis, exergy cost rates.*

1. INTRODUCTION

The rapid increase in global energy demand, couple with the challenges of limited energy resources and environmental concerns have spurred research efforts towards the efficient utilization of available energy resources as well as the development of renewable forms of energy. Pursuance of the former, have led to the combined utilization of energy, exergy and economic principles in the evaluation of energy consumption efficiency and exploring cost minimization potential in thermal process systems. Exergy analysis asserts the fact that energy cannot be destroyed, but the quality can be degraded such that it reduces its ability to do useful work [1].

Exergoeconomic analysis is a system optimization tool that uses both the second-law of thermodynamics (Exergy concept) and economic principles to evaluate thermal energy systems , in order to provide designers with useful information for system improvement and cost-effective operations. The method predicts energy system's thermodynamic performance and inefficiencies (irriversibilities), estimates cost of product from the system and associate cost rate to irriversibilies [2]. These concept of system cost optimization became popular among researchers in the 80'es, with works by Antonio Valero, El-sayed Yehia, Tadeusz Kotas, Richard Gaggioli, and others [3]. In recent times, comprehensive work have been done on the application of exergoeconomic concept in the analysis and optimization of energy systems for better design and cost effective operation [2,3,4,5,6,7,8]. In this study, exergoeconomic analysis were applied on 100 MW unit GE Frame 9 gas turbine plant in Ughelli, Nigeria.

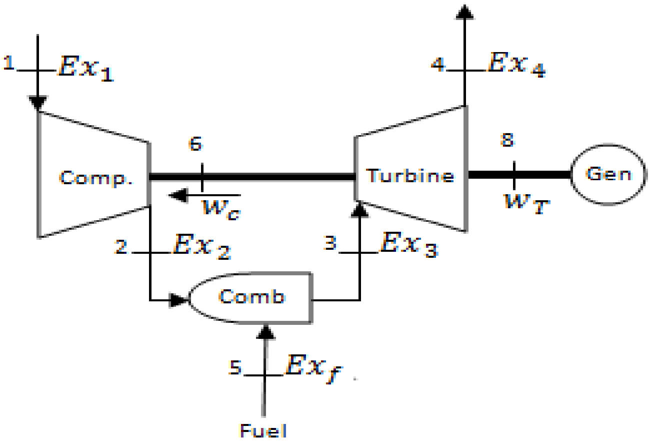

Figure 1: Schematic diagram of Gas turbine plant

1.2 Plant Description

The system under consideration, is a 100MW Unit single-shaft open cycle active gas turbine plant located at Ughelli in Nigeria. It uses natural gas of low heating value (LHV = 43,000KJ/Kg) and its been evaluated from a reference base condition of T_{ref}= 298K and P_{ref} =1.013bar. As shown in Fig. 1, the plant consists of an air-compressor (AC), combustion chamber (CC), and gas turbine (GT).

2. MATERIALS AND METHODS

2.1 Energy Analysis

The thermodynamic characterization of the plant is obtained from the operating parameters at various state point. The decision variables used for the plant optimization are compression ratio (r_p), and turbine inlet temperature (T_3).

Air-compressor exit pressure and temperature are

$$P_2 = P_1 \times r_p \quad (1)$$

$$T_2 = T_1(1 + R_{p,c}) \quad (2)$$

Where $R_{p,c} = \left[\frac{r_p^{\left(\frac{\gamma a-1}{\gamma a}\right)} - 1}{\eta_c}\right]$

Work required to drive the compressor per unit mass is

$$W_c = \frac{c_{pa}(T_2 - T_1)}{\eta_m} \quad (3)$$

From combustion chamber energy balance equation [9]

$$m_a c_{pa} T_2 + m_f LHV + m_f c_{pf} T_f = m_g c_{pg} T_3$$

(4)

Fuel air ratio is expressed as

$$f = \frac{c_{pg}T_3 - c_{pa}T_1(1+R_{pg})}{LHV + c_{pf}T_f - c_{pg}T_3} \quad (5)$$

Heat supplied to the combustion chamber

$$Q_{add} = m_g LHV \quad (6)$$

Work done by the turbine per unit mass

$$W_T = c_{pg}(T_3 - T_4)\eta_T \quad (7)$$

From computations with the models above, the state-point characterization of plant with reference base decision variables; air-compressor ratio (r_p) of 10.336, turbine inlet temperature of 1324K, isentropic compressor and turbine efficiencies of 88% and 89% respectively, are presented in Table 1. A combustion chamber pressure drop of 4% have been consider during the analysis.

Table 1: State point for the simple gas turbine

State Point	Temperature (K)	Pressure (bar)	Mass flow rate (Kg/s)
1	298	1.013	427
2	619.4	10.47	427
3	1324	10.05	436
4	805.7	1.358	436
5	308	30	8.997

2.2 Exergy Analysis

The limitations of energy analysis to properly account for energy losses due to irreversibilities in systems, have led to the application of the second-law or exergy (availability) concept to optimize energy utilization efficiency in thermal systems. Exergy, defined as the maximum theoretical useful work obtainable from the an energy carrier, assesses the quality of an energy carrier to be converted into work, and account for component irriversibilities in gas turbine plant. Exergy in a flow stream consist of physical, chemical, potential and kinetic exergy components. If we assume the potential and kinetic component of exergy to be negligible, the physical and chemical energy in the stream are properly accounted for by the models presented below.

Exergy flow rate of air stream exiting the compressor.

$$Ex_2 = m_a\left[c_{pa}(T_2 - T_{ref}) - T_{ref}\left(c_{pa} ln\left(\frac{T_2}{T_{ref}}\right) - R ln\left(\frac{P_2}{P_{ref}}\right)\right)\right] \quad (8)$$

Exergy destruction rate or irriversibilities in compressor exit stream

$$I_c = W_c - Ex_2 \quad (9)$$

The exergy - balance in the combustion chamber is expressed as

$$Ex_f + Ex_2 = Ex_3 + I_{cc}$$

(10)

Exergy rate in fuel is expressed as [10].

$$Ex_f = m_f.\left[c_p^{-h}(T_3 - T_{ref}) - T_{ref} c_p^{-s} ln\left(\frac{T_3}{T_{ref}}\right) + \tilde{R} T_{ref} ln\left(\frac{P_3}{P_{ref}}\right) + \sum_j x_j e_{jo}\, \tilde{R} T_1 \sum_j ln\, \gamma_j x_j\right] \quad (11)$$

Exergy destruction rate in the combustion chamber exit stream

$$I_{cc} = m_g T_{ref}\left[c_p^{-s} ln\left(\frac{T_3}{T_2}\right) - \tilde{R} ln\left(\frac{P_3}{P_2}\right)\right]$$

(12)

The plant overall exergetic efficiency expresses the ratio of the useful work output to the maximum obtainable work input [11].

$$\xi_{all} = \frac{\dot{W}_{net}}{\dot{Ex}_{fuel}} \quad (13)$$

The rate of exergy destroyed in a component accounts for the component efficiency defects and can be represent by the component exergy destruction ratios

$$y_{D,k} = \frac{I_k}{Ex_{in}} \qquad (14)$$

Table 2: Exergy Stream of the Plant

Component	Exergy Flow Rate (MW)	Exergy Destroyed (MW)	Exergy Efficiency (%)
Air Compressor	129.6	9.66	93.07
Combustion Chamber	280.8	238.7	54.05
Gas Turbine	116.7	27.97	65.27
Fuel	389.803	-	-
Overall Exergetic Efficiency = 30.81%		Thermal Efficiency of plant = 31.05%	

2.3 Economics Analysis

The economics of gas turbine assess the non-exergy related cost; which is the cost of the various components of the system. This cost comprise of the cost of ownership and operations of the plant, its value is dependent on the component life expectancy, capital requirement, financing structure, etc. The Annual levelized cost of system kth component is expressed as follows:

$$\dot{C}_k = \left(PEC - \frac{0.1}{(1+i)^n}\right)\left(\frac{i}{1-\frac{1}{(1+i)^n}}\right) \quad (\$/\text{year})$$

(15)

where PEC is the purchase equipment cost for the kth components, i is the interest rate and n, the time period . For gas turbine power plant, the purchase equipment cost for the components are computed from the models bellow according to Bejan et al., 1996.

Air compressor;

$$PEC_{ac} = \left(\frac{71.1m_a}{0.9-\eta_{ac}}\right)\left(\frac{P_2}{P_1}\right) ln\frac{P_2}{P_1} \qquad (16)$$

Combustion Chamber;

$$PEC_{cc} = \left(\frac{46.08m_a}{0.995-\frac{P_3}{P_2}}\right)\left(1 + exp(0.081T_3 - 26.4)\right) \qquad (17)$$

Gas Turbine;

$$PEC_{gt} = \left(\frac{479.34m_g}{0.92-\eta_{gt}}\right) ln\left(\frac{P_3}{P_4}\right)\left(1 + exp(0.036T_3 - 56.4)\right) \qquad (18)$$

Therefore, the cost rate for the kth component of the plant is expressed as

$$\dot{Z}_k = \frac{\phi_k \dot{C}_k}{H} \quad (\$/\text{hours}) \qquad (19)$$

where H is the plant operating hour and ϕ_k is the maintenance cost factor for the kth component of the plant.

Table 3: Plant non-exergy associated costs

Component	Annual Levelized Cost $\dot{C}_k$ ($/year)	Purchased Equipment Cost (PEC)$	Capital Cost Rate, $\dot{Z}_k$ ($/hour)
Air Compressor (AC)	$3.134\text{x}10^6$	$18.32\text{x}10^6$	415.2
Combustion Chamber (CC)	$1.035\text{x}10^5$	$0.605\text{x}10^6$	13.72
Gas Turbine (GT)	$2.336\text{x}10^6$	$13.65\text{x}10^6$	309.5

2.4 Exergoeconomic Analysis

This analysis assess the costs of all the flows involve in the plant and associates cost to each exergy stream in individual plant component. This is achieved by formulating a cost balance equation for each component of the plant. The general equation according to Bejan, 1996 [12], is expressed as

$$\sum_{out} \dot{C}_{o,k} = \sum_{in} \dot{C}_{i,k} + \dot{Z}_k \qquad (20)$$

Auxiliary equations, which are formulations of cost balance equations for individual components of the plant are based on the following principles

F-Principle: The cost of exergy removal from a stream must be equal to the cost of supplying the exergy to the same stream in a component located upstream.

P-Principle: Associates the same average cost to any exergy unit supplied to any stream that is related to the product.

Air compressor:

$$\dot{C}_2 = \dot{C}_1 + \dot{C}_6 + \dot{Z}_{ac} \qquad (21)$$

$$\dot{C}_1 = 0$$

Combustion chamber:

$$\dot{C}_3 = \dot{C}_2 + \dot{C}_5 + \dot{Z}_{cc} \qquad (22)$$

Gas Turbine:

$$\dot{C}_4 + \dot{C}_6 + \dot{C}_7 = \dot{C}_3 + \dot{Z}_{gt} \qquad (23)$$

F-rule: $\frac{\dot{C}_4}{\dot{Ex}_4} = \frac{\dot{C}_5}{\dot{Ex}_5}$ or

$$c_4 = c_5 \qquad (24)$$

But $\dot{Ex}_5 = \dot{Ex}_{fuel}$

P-rule: $\frac{\dot{C}_7}{\dot{W}_T} = \frac{\dot{C}_6}{\dot{W}_{ac}}$ or

$$c_7 = c_6 \qquad (25)$$

where c_2, c_3, c_4, c_5, c_6 *and* c_7 are average cost per unit exergy in dollar gigajoule ($/GJ).

Another cost associated with components is the hidden cost or cost associated with the rate of exergy destruction $\dot{C}_{D,k}$. This, alongside with other exergoeconomic variables like average cost of fuel per unit exergy $c_{f,k} = \dot{C}_{f,k}/\dot{Ex}_{fuel}$, the average unit cost of product $c_{p,k} = \dot{C}_{p,k}/\dot{Ex}_{p,k}$, and the exergoeconomic factor, f_k are very vital in the analysis of the system.

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}} \qquad (26)$$

3. RESULTS AND DISCUSSION

Table 4: Average unit exergy cost and levelized cost rates associated with various state point

State points	$\dot{C}$, $/h	c, $/KWh	c, $/GJ
1	0	0	0
2	1,769	0.01363	3.786
3	6,092	0.02170	6.026
4	2,532	0.02170	6.026
5	4,311	0.01106	3.072
6	1,352	0.009705	2.695
7	2,518	0.009705	2.695

Table 5: Gas Turbine Components Exergoeconomic Parameters

Component	c_p, $/GJ	c_f, $/GJ	$\dot{E}_D$, MJ	$\dot{C}_D$, $/h	$\dot{Z}$, $/h	$\dot{C}_D$+$\dot{Z}$, $/h	f, %
Air Compressor	3.786	2.695	9.66	26.0337	415.2	441.234	94.099
Combustion Chamber	6.026	3.072	238.7	733.286	13.72	747.006	1.836
Gas Turbine	2.695	6.026	27.97	168.547	309.5	478.047	64.74

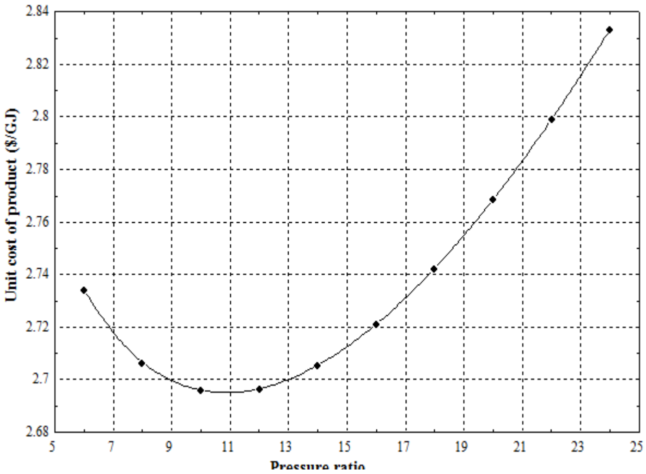

Figure 2: Pressure ratio Vs Unit Cost of

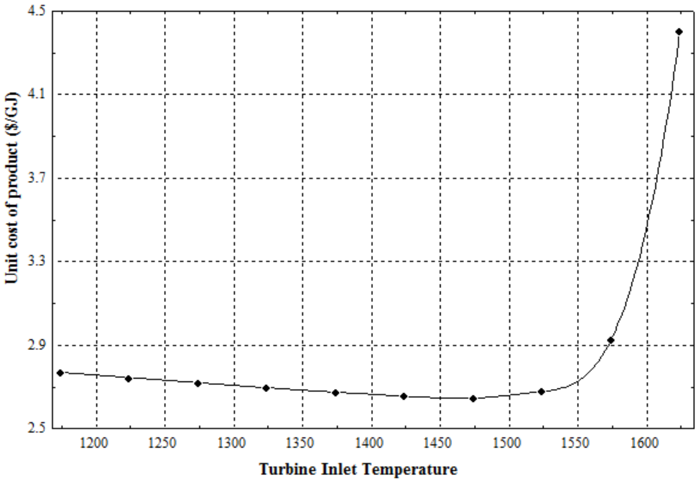

Figure 3: Gas Turbine Inlet Temperature Vs Unit Cost of Product

This study looks at the exergoeconomic analysis of one of the Gas turbine power plants operating in Nigeria. Table 1 shows the state point characteristics of the plant calculated based on the design point ISO data, such as ambient temperature, mass flow rate entering the compressor, turbine inlet temperature, compressor ratio, compressor isentropic efficiency, and turbine isentropic efficiency. In Table 2, the exergy flow rate, exergy destroyed or irriversibility and the exergetic efficiency of the various components of the plant are given. The combustion chamber recorded the lowest efficiency of 54.05% , accounting for the component with the largest total inlet exergy destroyed value of 238.681MW. This results in a low plant overall exergy efficiency of 30.81%.

Table 3 presents the non-exergy associated costs of the plant; initial investment (purchased equipment) costs, capital cost rates, and the annual levelized costs for each component of the plant. The average unit cost of exergy and the levelized cost rates associated with every state point in the plant is shown in Table 4. The cost of exergy associated with the product of the plant; which is electricity is given as 2.695$/GJ. And Table 5 presents the exergoeconomic parameters for each component of the plant. The combustion chamber component which has the highest value of $\dot{C}_D$+$\dot{Z}$ and lowest exergoeconomic factor f is the component of interest. This values implies that the component accounts for the highest cost rate of exergy destroyed in the system, thus the isentropic efficiency should be improved by increasing capital investment costs. For other components (compressor and turbine) with high values of f, and lower value of $\dot{C}_D + \dot{Z}$, figure 1 shows that a low exergy cost rate is achieved through reduction in component isentropic efficiencies, which implies a reduction in capital investment.

Further analysis, examines the effect of the decision variables on the unit cost of product. Figure 2 and 3, shows that increasing pressure ratio and turbine inlet temperature decreases the unit cost of product to a minimum point beyond which further increase in decision variables increases the unit cost of product. Increase in decision variable implies an increase in the investment cost. Therefore, increasing capital investment cost on the combustion chamber (which has the highest exergy destruction cost value) by increasing turbine inlet temperature, leads to an increase in the exergoeconomic factor, decreases exergy destruction cost rate and a corresponding decrease in unit cost of product. The turbine inlet temperature that gives the least unit cost of product is $T_3 = 1474\ K$. In the other hand, increase in pressure ratio (in compressor and turbine) decreases the exergy destruction cost and a decrease in unit cost of product. The pressure ratio that gives the least unit cost of product is 11.4.

4. CONCLUSION

The unit cost of product for the 100MW gas turbine power plant was estimated through the exergoeconomic analysis of the plant. The effect of the turbine inlet temperature and the pressure ratio on the unit cost of product was investigated, and result shows that the unit cost of product decreases to a minimum point as the decision variables increases, beyond which, it increases with further increase in the value of the parameters. Thus, the value of the turbine inlet temperature and compression ratio where the least cost of product is achieved are $T_3 = 1474K$ and r_p 11.4 , respectively.

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