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Effects of Incorporating Air Pre-Heater after the Compression Process to Exergy Destruction and Exergy Efficiency of a Gas Turbine Plant

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ABSTRACT

Exergy formally known as available energy is very useful in analyzing the performance of plants. Exergy analysis is different from energy analysis because it is able to quantify and locate components with irreversibilities and further suggest ways to improve plant efficiency. This paper uses exergy analysis technique to analyze incorporating air pre heater to a simple gas turbine plant in order to reduce exergy destruction and improve efficiency of plant components. Data was collected from the gas turbine control room of Warri Refining and Petrochemical Company and analysed using exergy balance equations. The result showed that by incorporating air pre-heater after the compression stage efficiency of the combustion improved from 22.41% to 22.67% while the exergy destroyed in the combustion chamber dropped 96.224MW to 81.3224MW while that of the turbine decreased from 2.7438MW to 1.5533MW Therefore, pre-heating is recommended to improve the plant performance.

Keywords: Air Preheater Combustion chamber, Exergy destroyed, Efficiencies , Irreversibility, Turbine.

Energy consumption is one of the indices used for measuring the level of development of Nations. All over the world researchers are working on suitable means of improving the efficiency and performance of plants to meet the growing population. Nigeria should not be left behind, the epileptic power supply in Nigeria is no longer news. Power Engineers should brace up to the challenge to see how energy can be efficiently generated and utilized so as to meet the government's target of electricity for all. Electricity generation in Nigeria is basically from fuel fired and hydroelectric system, though recent research now looks at Solar, wind and Nuclear power systems. Because of the abundant supply of crude oil in Nigeria, over 70% of Nigeria power is generated from fuel. Hence this study which deals with the Effects of Incorporating Air Pre-Heater after the Compression Process to Exergy Destruction and Exergy Efficiency of a Gas Turbine Plant. The gas turbine plant of Warri Refining and Petrochemical Company was used in the analysis.

Exergy is generally defined as the maximum theoretical work that can be obtained from an amount of energy. A more comprehensive definition is the work that can be obtained from an amount of energy (converted in a well defined system) under ideal conditions (applying reversible processes) using the environment only as the reservoir of heat and matter [1]

Or in a simplier form, it is the useful work potential of energy.

To achieve this, two thermodynamic methods are used for analyzing energy conversion processes in plants: namely the conventional method which is first law (energy) analysis and the more recent and reliable method which is second law (exergy) analysis.

The performance of thermal power plants is evaluated through the energy analysis which is based on first law of thermodynamics, including electrical power and thermal efficiency [2]. Energy analysis is only able to quantify efficiency of plants without pin pointing components energy losses. To overcome this limitation, there is need of exergy analysis, which the analysis can not only determine magnitudes, location and causes of irreversibilities in the plants, but also provides more meaningful assessment of power plant components efficiency. Exergy analysis is a useful method to complement,

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not to replace the energy analysis [3]. 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 [4,5].

The application of exergy analysis in power plant such as gas turbine is very important to engineers, because it helps to quantify and locate plant components with major energy losses which will then help the plant engineer make decisions and possibly optimize plant performance and minimize fuel consumption. With second law analysis (exergy) the engineer is able to bring about improvement of plant performance and develop new components or processes with minimum energy losses.

Bejan [6] developed the analysis methodology for gas turbine plants while Kotas [7] developed the method to determine chemical and physical exergies for various components. The distribution of the exergy losses in several plant components during the real time plant running conditions has been assessed to locate process irreversibilities[8].

The main aim of exergy analysis is to identify meaningful (exergy) efficiencies, causes, true magnitudes of exergy losses, position and amount in the components and total plant [11, 12]. Some exergy analysis works done by [12, - 17] in gas turbine power plants showed that they is need to carryout this analysis from time to time in gas power plant because of its important in gas power plant. Gas turbines majors components are compressor, combustion chamber, gas turbine and generator that operates on a Brayton Cycle [12,18]. This make it necessary to carry out the exergetic performance of gas turbine power plant and its various components as mentioned to know its efficiencies and areas of improvement. Therefore, the aim of this paper is to carry out an exergy analysis on single shaft open cycle gas turbine plant when a pre-heater is introduced after the compression stage of Warri Refining and Petrochemical Company (WRPC) located in Ekpan, Delta state, Nigeria.

METHODOLOGY

The method of analysis involved getting data from the operators manual Log book from three years. Available readings were taken for the functioning gas turbines (Permission was sought from Department of Petroleum Resources Warri).

The operators in the power plant section take readings daily after every two hours, meaning that twelve readings are normally recorded per day. Recorded values for 12noon was collected, average computed using Microsoft Excel based on inlet temperatures varying from 24^oC to 36^oC .

These data were analysed by identifying the boundaries and using energy and material balance equation (2nd Law of thermodynamics) to calculate exergy efficiency and exergy destruction for the plant without air preheater and the values were used to analyse similar plant with air pre-heater incorporated after the compression stage.

Processed data was later analysed with the aid of graphs and charts.

The following assumptions were made in considering the 2nd law analysis:

1. Heat losses from all plant components are negligible including the combustion chamber.
2. Kinetic and potential energy components of exergy are negligible
3. The combustion process is treated as complete

The gas turbine section of the plant operates on an open Brayton cycle; the main components are compressor, combustion chamber, gas turbine and generator. The schematic and T – s diagrams are shown in Figures 1and 2 respectively.

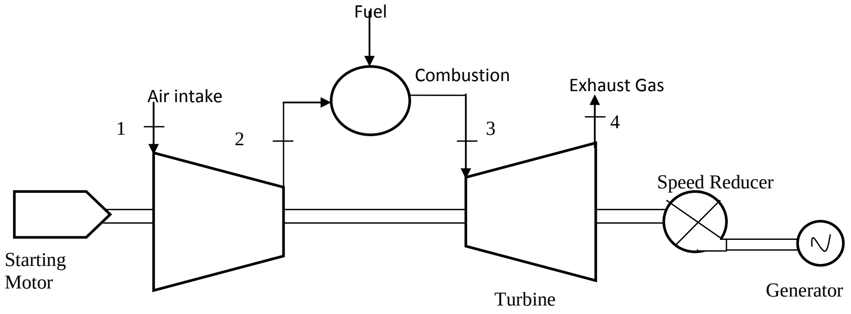

Fig1.*The Schematic Diagram of Warri Refining and Petrochemical Gas Turbine Plant*

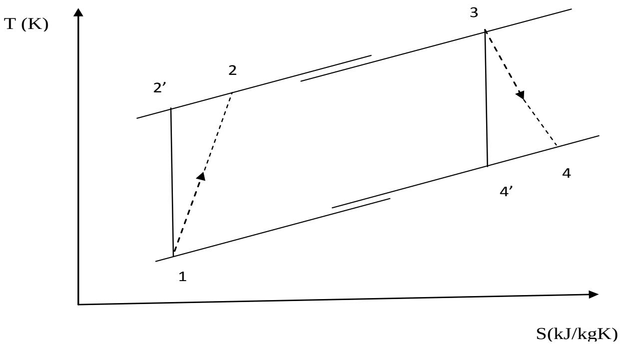

Fig2. *T- s Diagram of Warri Refining and Petrochemical(WRPC) Gas Turbine Power Plant Incorporating Air Pre-Heater after the Compression Stage*

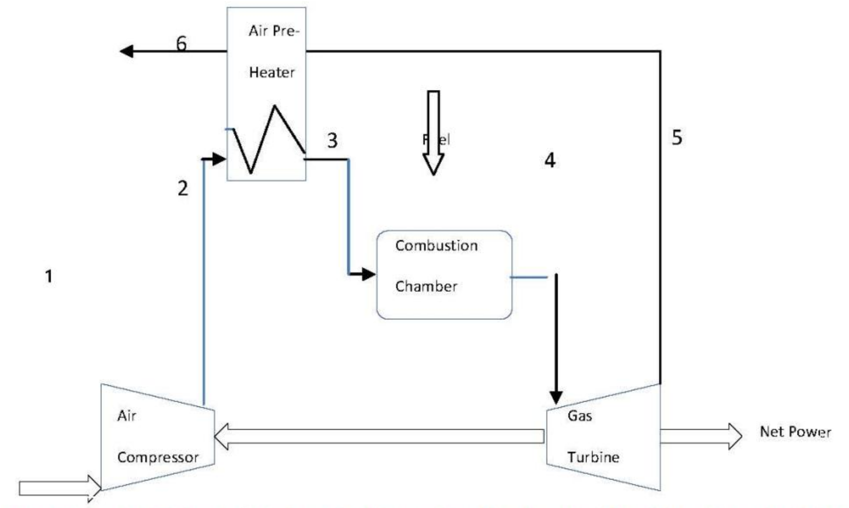

Fig3. *Schematic diagram of a Gas turbine Plant with Air pre-heater*

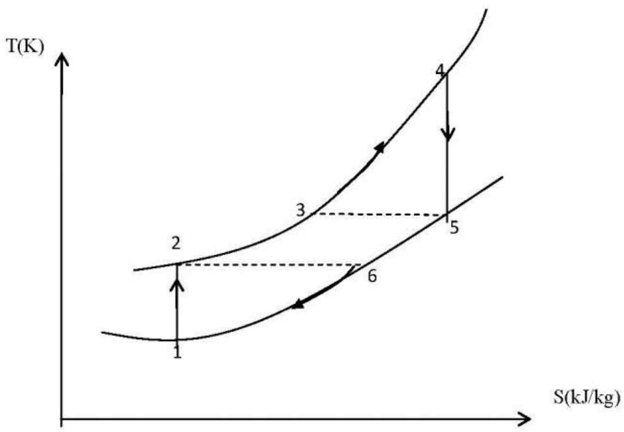

Fig4. *T-s Diagram for hypothetic Gas Turbine Plant with Air Pre-heater*

For the hypothetical Gas Turbine, $T_2 = T_6$ and $T_3 = T_5$ and there is a pressure drop of 4% across flow stream of the Air pre-heater.

Exergy Balance Equations

The following assumptions were made in considering the 2nd law analysis:

1. Heat losses from all plant components are negligible including the combustion chamber.
2. Kinetic and potential energy components of exergy are negligible
3. The combustion process is treated as complete
4. Pressure drops in the combustion chamber and exhaust assumed to be 3% and 4% across the air preheater stream.

The thermo-mechanical exergy stream equation used to analyse components of a thermal system derived from the 1st and 2nd Law of Thermodynamics is broken down into thermal, mechanical and chemical components expressed by [20, 29] as shown in equation (1)

$$E_i^M - E_o^M = (E_i^T - E_o^T) + (E_i^P - E_o^P) \tag{1}$$

Where, i and o denotes, respectively, exergy flow stream entering or leaving the plant component. M, T and P represent material components under study, thermal property and mechanical property respectively.

The thermal and mechanical components of the exergy stream for an ideal gas with constant specific heat expressed are presented in equations (2) - (4).

$$E^T = mc_p\,[\,(T - T_{ref}) - T_{ref}\ln T/T_{ref}] \tag{2}$$

$$E^P = mRT_{ref}\ln p/p_{ref} \tag{3}$$

$$\dot{S} = \dot{m}(c_p\ln T/T_{ref} - R\ln P/P_{ref} \tag{4}$$

With the decomposition defined by equation (1), the general exergy-balance equation is expressed in equation (5) as stated in [18]

$$E^{CHE} + \left(\sum E_i^T - \sum E_o^T\right) + \left(\sum E_i^P - \sum E_o^P\right) + T_{ref}\left(\sum \dot{S}_i - \sum \dot{S}_o + \frac{Q_{cv}}{T_{ref}}\right) = E^W \tag{5}$$

The term E^{CHE} in equation (5) represents the rate of exergy flow of fuel in the plant and Q_{cv} represents the heat transfer interaction between the component and environment and E^W represents work done by the material component under study.

Gas Turbine Components Exergy Balance Equations

The equations derived from the general exergy balance equation given in equation (5) for Gas Turbine components are shown in equations (6) – (9).

Air Compressor

$$(E_1^T - E_2^T) + (E_1^P - E_2^P) + T_{ref}(S_1 - S_2) = E^{WAC} \tag{6}$$

Combustion Chamber

$$E^{CHE} + (E_2^T + E_f^T - E_3^T) + (E_2^P + E_f^P - E_3^P) + T_{ref}(S_2 + S_f - S_3 + Q_{CC}/T_{ref}) = 0 \tag{7}$$

Equation (8) is used to calculate the chemical exergy of fuel (methane) which is obtained from [12, 21, 22]

Chemical exergy of fuel (Methane),

$$E^{CHE} = (1.0308 + m_f)\ LHV \tag{8}$$

Turbine

$$(E_3^T - E_4^T) + (E_3^P - E_4^P) + T_{ref}(S_3 - S_4) = E^{WGT} \tag{9}$$

Exergy Destruction

Exergy is not conserved but destroyed in irreversible systems. The irreversibilities are caused by internal irreversibilities such as friction, unrestrained expansion, mixing and chemical reaction, and external irreversibilities arised from heat transfer through a finite temperature difference. The energy associated with material or energy stream is rejected to the environment whenever there is exergy lost in the system [23]. The exergy destroyed in each of the components and for the total plant is shown in equations (10) – (13) as stated in [12].

Compressor, Exergy destroyed, E_{DAC}

$$E_{DAC} = T_{ref}\left(\dot{S}_2 - \dot{S}_1\right) \tag{10}$$

Combustion chamber, E_{DCC}

$$E_{DCC} = E^{CHE} + \left(E_2^T + E_f^T - E_3^T\right) + \left(E_2^P + E_f^P - E_3^P\right) \quad (11)$$

Gas Turbine, E_{DGT}

$$E_{DGT} = T_{ref}\left(\dot{S}_4 - \dot{S}_3\right) \quad (12)$$

Total exergy destroyed in the plant, E_{Dplant}

$$E_{Dplant} = E_{DAC} + E_{DCC} + E_{DGT} \quad (13)$$

Exergy Efficiency

Exergy efficiency also known as second law efficiency, it is mathematically represented in equation (14). The exergy efficiency of various components and overall plant of gas turbine are evaluated using equations (15) – (18).

$$\varepsilon = 1 - \frac{EXERGY\ DESTROYED}{EXERGY\ SUPPLIED} \quad (14)$$

Applying the equation above for various components

Air Compressor

$$\varepsilon_{AC} = 1 - \frac{E_{DAC}}{E^{WAC}} \quad (15)$$

Combustion Chamber

$$\varepsilon_{CC} = 1 - \frac{E_{DCC}}{E^{CHE}} \quad (16)$$

Gas Turbine

$$\varepsilon_{GT} = 1 - \frac{E_{DGT}}{E^{WGT}} \quad (17)$$

Overall Plant

$$\varepsilon_{Plant} = 1 - \frac{E_{Dplant}}{E^{CHE}} \quad (18)$$

Exergy Destruction Efficiency

The exergy destruction efficiency can be compared to the rate of exergy flow of fuel in plant as shown in equation (19). Equations (20) – (24) are use to evaluate the exergy destruction efficiency for the compressor, combustion chamber, turbine units and overall plant.

$$\mathcal{E}_D = \frac{E_D}{E^{CHE}} \quad (19)$$

$$\mathcal{E}_{DAC} = \frac{E_{DAC}}{E^{CHE}} \quad (20)$$

$$\mathcal{E}_{Dpreht} = \frac{E_{DPre\ ht}}{E^{CHE}} \quad (21)$$

$$\mathcal{E}_{DCC} = \frac{E_{DCC}}{E^{CHE}} \quad (22)$$

$$\mathcal{E}_{DGT} = \frac{E_{DGT}}{E^{CHE}} \quad (23)$$

$$\mathcal{E}_{Dplant} = \frac{E_{DPT}}{E^{CHE}} \quad (24)$$

RESULTS AND DISCUSSION

Results

The Data used in this analysis were values obtained from Operators Manual and log book of WRPC from January 2009 to December 2011 as shown in Table 1. The mass flow rates, temperatures, power output, pressures were obtained from the speedtronics control system [30]. Relevant working fluid parameters for air and fuel such specific heat capacity and gas constant were obtained from [31]. For the hypothetical Gas Turbine with air pre-heater, $T_2 = T_6$ and $T_3 = T_5$ [26] figure 4 and there is a pressure drop of 4% across flow stream of the Air pre-heater.

The exergy flow rates and exergy destruction at the inlet and outlet of each components of the plant were calculated using equations (2) – (23) based on the corresponding values from Table 1 at compressor inlet temperature of 24^0C. The results obtained for the gas turbine without pre-heater are shown in Tables 2, 3 and 4 while the result for incorporating air pre-heater is shown in Tables 5, 6 and 7.

Positive values indicate the exergy flow rate of products while negative values represent the exergy flow rate of resources or fuel as shown in Table 4. Here, the product of a component corresponds to the added exergy whereas the resource to the consumed exergy [26,32]. The sum of the exergy flow rates products, resources and destruction equals zero for each component and for the total plant; this zero sum indicates that exergy balances are satisfied.

The exergy calculation was done for all the values in Table 1 applying equations (2) – (23) with the aid of Excel spread sheet. The results obtained were presented graphically in Figures 5, 6 and 7.

Table1. *Operating Data for WRPC Gas Turbine Power Plant*

Power (MW)	t_1(^{0}C)	t_2(^{0}C)	P_1 (Bar)	P_2 (Bar)	t_3(^{0}C)	t_4(^{0}C)	m_1(kg/s)	m_f(kg/s)	m_{exh}(kg/s)
6.77	24	295	1.013	6.40	620	362	120.90	1.60	122.50
6.91	27	298	1.013	6.36	630	360	120.63	1.57	122.20
6.96	28	297	1.013	6.46	636	362	120.23	1.58	121.88
5.48	29	298	1.013	6.20	616	353	119.83	1.25	121.08
5.78	30	299	1.013	6.16	620	357	119.45	1.31	120.76
6.05	31	302	1.013	6.30	631	362	119.04	1.37	120.41
6.43	32	304	1.013	6.27	634	365	118.65	1.46	120.11
6.76	33	306	1.013	6.22	637	368	118.27	1.54	119.81
7.29	34	310	1.013	6.46	648	371	117.88	1.66	119.54

Table2. *Property values and chemical, thermal and mechanical exergy flows and entropy production rates for various States in WRPC Gas Turbine One at inlet temperature of 24^0C*

State	m (kg/s)	T(K)	P (Bar)	E^{CHE}(MW)	E^T(MW)	E^M(MW)	S (MW/K)
1	120.90	297	1.013	0.0000	0.000	0.0000	0.00000
2	120.90	568	6.400	0.0000	9.529	18.9960	0.01482
Fuel	1.60	297	20.000	124.019	0.000	0.63784	-0.00215
3	122.50	893	6.208	0.0000	37.837	19.1280	0.09040
4	122.50	635	1.076	0.0000	15.794	0.6366	0.09947

Table3. *Exergy values of WRPC Gas Turbine Power Plant at 24^0C compressor inlet temperature*

Component	E^W(MW)	E^{CHE}(MW)	E^T(MW)	E^M(MW)	E_D(MW)
Compressor	-32.927	0.000	9.529	18.99600	4.4020
Combustion Chamber	0.00000	-124.019	28.308	-0.51384	96.2248
Turbine	37.8406	0.000	-22.093	-18.49140	2.7438
Total Plant	4.9136	-124.019	15.744	-0.99076	103.3706

Table4. *The Exergy Efficiency and Exergy Destruction Efficiency of components at 24^0C*

Components	$\mathcal{E}$ (%)	$\mathcal{E}_D$(%)
Air Compressor	86.63	3.55
Combustion Chamber	22.41	77.59
Gas Turbine	92.75	2.21
Total Plant	16.65	83.35

Incorporating Air Pre-Heater after the Compression Stage the following data were obtained also at 24^0C

Table5. *Property values and chemical, thermal and mechanical exergy flows and entropy production rates for various States in WRPC Gas Turbine at inlet temperature of 24⁰C with Air pre-heater*

State	m (kg/s)	T(K)	P (Bar)	E^{CHE}(MW)	E^{T}(MW)	E^{M}(MW)	S (MW/K)
1	120.90	297	1.013	0.0000	0.0000	0.0000	0.00000
2	120.90	568	6.400	0.0000	9.5290	18.9960	0.01482
3	120.90	635	6.144	0.0000	13.6460	18.5760	0.02980
Fuel	1.20	297	20	105.162	0.0000	0.4794	-0.00161
4	122.50	893	5.690	0.0000	37.8370	18.6980	0.09947
5	122.50	635	1.076	0.0000	15.7940	0.4300	0.10470
6	122.50	568	1.033	0.0000	11.0290	0.2060	0.09050

Table6. *Exergy values of WRPC Gas Turbine Power Plant at 24⁰C compressor inlet temperature with air pre-heater*

Component	E^{W}(MW)	E^{CHE}(MW)	E^{T}(MW)	E^{M}(MW)	E_{D}(MW)
Compressor	-32.927	0.000	9.529	18.996	4.4020
Air Pre-heater	0.000	0.000	-0.648	-0.644	1.2920
Combustion Chamber	0.000	-105.162	24.191	-0.517	81.3224
Turbine	38.7577	0.000	-22.043	-18.268	1.5533
Total	5.8307	-105.162	11.029	-0.433	88.5697

Table7. *The Exergy Efficiency and Exergy Destruction Efficiency of components at 24⁰C with air pre-heater*

Components	Ɛ (%)	$Ɛ_{D}$(%)
Air Compressor	86.63	4.19
Air Pre-heater	95.61	1.23
Combustion Chamber	22.67	77.33
Turbine	95.99	1.48
Total	15.78	84.22

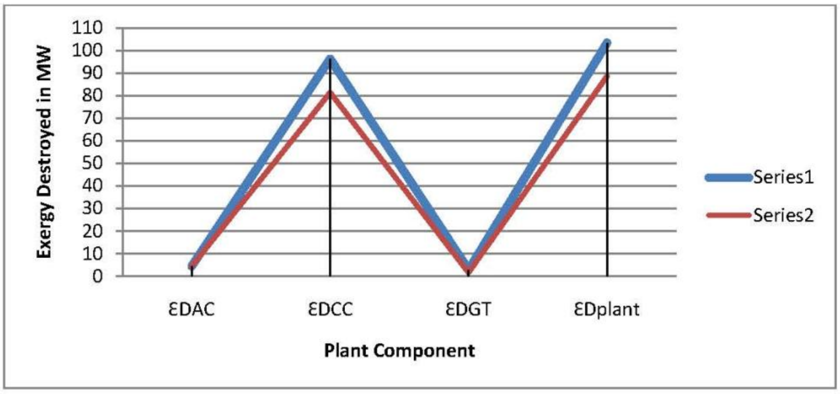

Fig5. *Exergy Destroyed in GT without pre-heater (series 1) and with pre-heater (series2)*

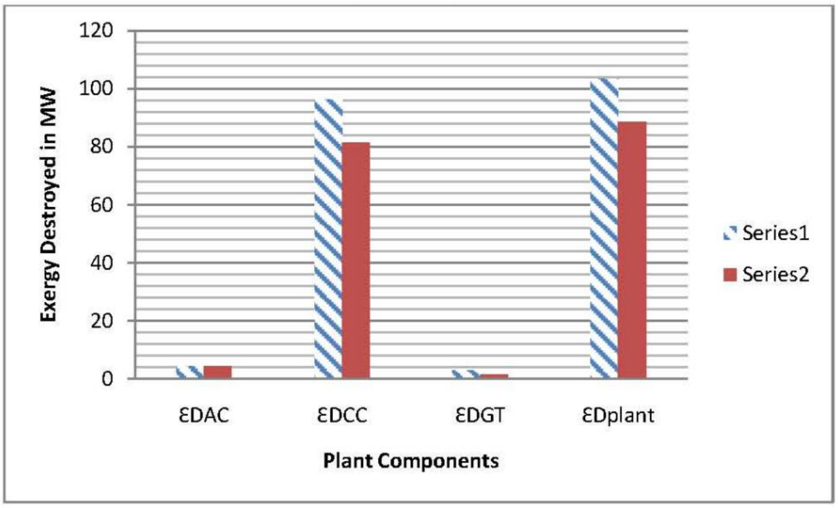

Fig6. *Bar Chart showing Exergy Destroyed in GT without pre-heater (series 1) and with pre-heater (series2)*

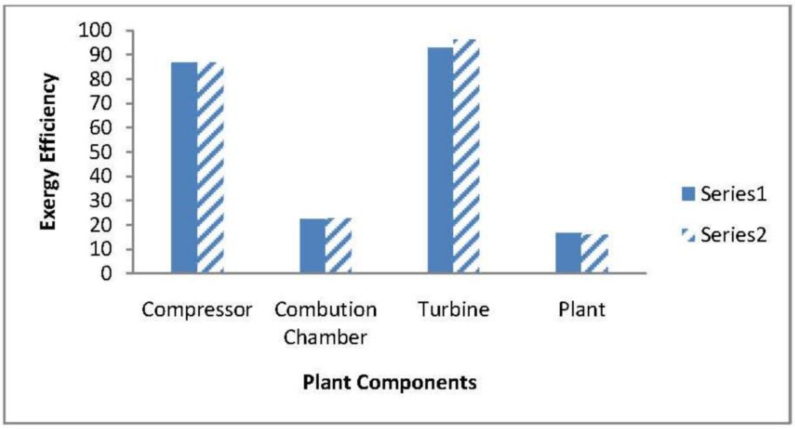

Fig6. *Bar Chart showing Exergy Efficiency in GT without pre-heater (series 1) and with pre-heater (series2)*

DISCUSSION

The net flow rates of the various exergies crossing the boundary of each component in the gas turbine plant are shown in table 3 and 6 for the plant without pre heater and with pre heater respectively. The exergy destruction efficiencies are also shown in table 4 and 7. With the incorporation of air pre-heater to the plant, exergy destruction in the combustion chamber drops from 96.224MW to 81.3224MW while that of the turbine decreased from 2.7438MW to 1.5533MW . The combustion chamber has the highest exergy destroyed and low second law efficiency due to loses. These irreversibilties can be reduced by incorporating air pre heater as shown. When this is done energy will be saved and profit maximised.

CONCLUSION

The effect of incorporating a pre-heater revealed that there is reduction in irreversibility and degradation that takes place in the combustion chamber. To minimize this loss; there is need to incorporate a heat recovery device like the pre –heater to utilize the energy available in the exhaust gases from the turbine. In the analysis the exergetic efficiency of the combustion improved from 22.41% to 22.67% while the exergy destroyed dropped. In conclusion, pre-heating is recommended to improve the plant performance and save cost .

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