Exergetic Analysis of South Tripoli Gas Turbine Power Plant (Unit Four)

Naji Sassi. Younis[1], Bahlul O. Abbani[2], Othman A. Alnayed[3]
[1] *Power Generation Technologies, Atomic Energy Establishment, Libya*
[2] *Nuclear Regulatory Office, Atomic Energy Establishment, Libya*
[3] *General Electricity Company of Libya (GECOL)*

Abstract

This work is aimed to carry out the exergy analysis of 47 MW gas turbine power plant (unit four in south Tripoli gas turbine power plant). Exergy analysis based on the second law of thermodynamics for each component and for the whole plant at 20 MW and 30 MW was done. Exergy balance model was developed and a visual basic application program is used to investigate the exergy destruction and the performance of the power plant at variant ambient temperature conditions. The obtained results show that the largest exergy destruction occurs in the combustion chamber followed by the gas turbine. The lowest amount occurs in the compressor. In addition, the exergetic efficiency of various components were evaluated.

Keywords— *Gas Turbine, Exergy, Exergy Destruction, Exergetic Efficiency*

I. INTRODUCTION

In this work the exergy analysis of gas Turbine Power plant was applied based on the second law of thermodynamics. A mathematical model was developed based on both first and second law of thermodynamics. This is a very useful approach for evaluation and improvement of power plants. The Exergy analysis was carried out to determine the magnitude and location of exergy destruction in different components in the plant, and to evaluate its exergetic efficiency.

Exergy can be defined as the maximum work, which can be produced by the system or by, flow of matter and comes to equilibrium state with a specific environmental state.

In recent years, the exergy analysis become the most dominant tool for studying the energy systems. The first law of thermodynamics does not differentiate between the quantity and the quality of energy and it does not provide the details of energy losses in various components in the plant. Bejan et al [1] developed analysis method for gas turbine cogeneration system. Kotas [2] developed a method to determine physical and chemical exergy for various components in power plants.

Several authors were considered and discussed the exergy analysis on power plants [1],[3]-[6]. The effect of gas turbine load and performance variations with ambient temperature and pressure ratio were investigated to analyze the change in system behavior by Lalatendu P.[7]. Exergy analysis of a Power plant in Abu Dhabi to determine the main source of it irreversibilities was presented by Omar M.et al[8]. Martin A.et described the performance of a 20 MW gas turbine power plant in Pekanbaru-Indonesia. al.[9]. Villela I. A., conducted an energetic and exergetic analysis of a Gas Turbine combines cycle power plant [10]. Mehta p. N. et al [11] presented an exergy analysis of a gas Turbine power plant, they determined the effect of operating thermodynamic variables on the performance of gas turbine power plant. A similar study was conducted by Chand V.,et al[12]. Exergy analysis and second law efficiency of a regenerative Brayton cycle with isothermal heat addition was presented by Jubeh N. M. [13], the effect of pressure ratio, turbine inlet temperature on exergy destroyed and exergetic efficiency was investigated and compared for all models. Tsatsaronis G. and Cziesla F. [14] analyze the different types of system components in the power plant from the thermodynamic viewpoint.

II. PLANT DESCRIPTION

The simplified schematic diagram of the plant is shown in Figure 1. Unit four of south Tripoli gas turbine power plant of (47 MW) which was used in this study is an open single shaft system a new unit installed in the plant). The plant consists of Air Compressor, Combustion Chamber and Gas Turbine. The fuel used in this plant is natural gas. The physical parameters of the working fluid at different states are marketed as numbers as shown in Figure 1.

The model of Gas turbine power plant are developed on the following assumptions:

- All the processes in the system under study are in steady state.

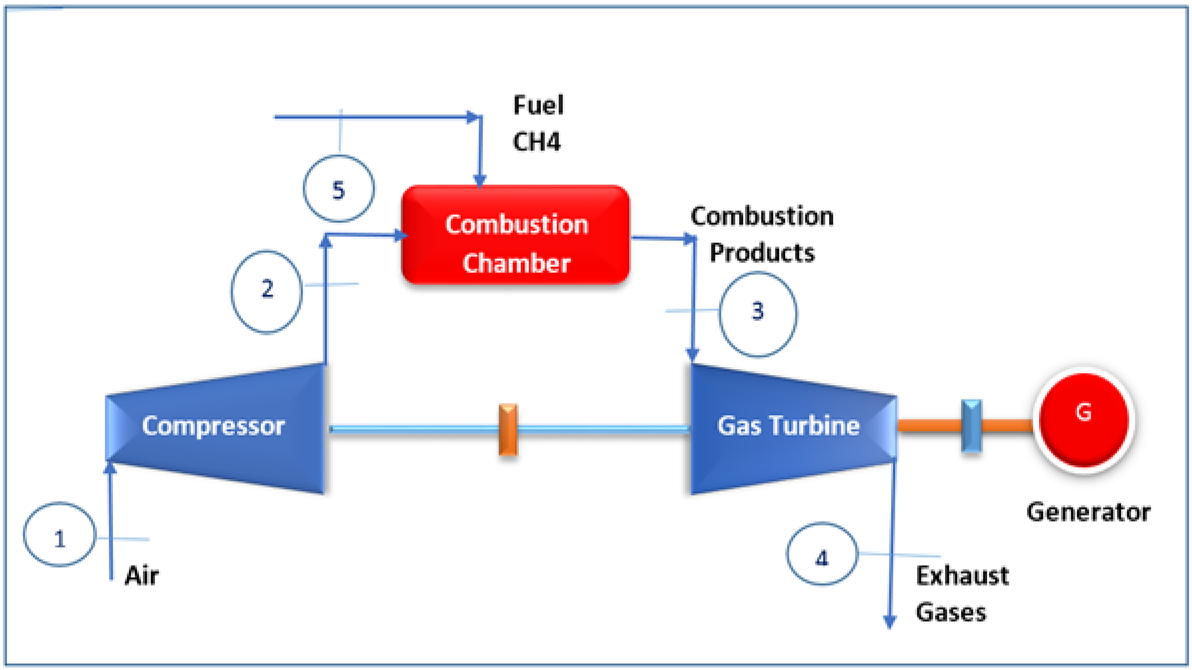

Figure 1. Schematic Diagram of Gas Turbine Power plant

- All the components in the plant have adiabatic boundaries.
- The air and combustion products are assumed ideal gases.
- Kinetic and potential exergies are neglected
- The natural gas (Fuel) is taken as methane and is modeled as an ideal gas.
- No heat losses from the plant components.
- The temperature and pressure at ambient conditions are 25 oC and 1.01013 bar respectively.

III. EXERGY ANALYSIS

For each system component, the exergy destruction and exergetic efficiency are calculated for each component in the plant.

The exergy analysis is applied for all the components in the plant and for the whole plant. The total exergy of the system can be divided into physical exergy, chemical exergy, kinetic exergy and potential exergy. The kinetic and potential exergies are assumed to be negligible. The physical exergy is defined as the maximum work obtained by the system from its initial state to the dead state through reversible process while interacting with an equilibrium state [2]. The chemical exergy is the maximum work that can be obtained with the departure of chemical composition of the system from its chemical equilibrium [8].

The exergy analysis is a method used for analyzing the energy systems by implements the mass and energy conservation together with the second law of thermodynamics.

In this paper, an exergy analysis was performed for 47 MW gas turbine power plant, which is an existing plant located in South Tripoli, Libya. The exergy analysis has been done by treating each component in the plant as a separate control volume at steady state. Applying the steady state exergy balance equation for a control volume [2] is:

$$\sum\left(1-\frac{T_0}{T}\right)Q+\sum_{in}\dot{m}_{in}.\psi_{in} = \dot{W}+\sum_{out}\dot{m}_{ex}.\psi_{ex}+\dot{\Psi}_D \quad \text{.. (1)}$$

The subscript *i* and *e* denotes inlets and outlets respectively. The first term $\sum\left(1-\frac{T_0}{T}\right)Q$ is the rate of exergy transfer at temperature T. The exergy transfer rates at inlets and outlets are represented as, $\dot{\Psi}_{in}=\dot{m}_{in}\psi_{in}$ and $\dot{\Psi}_{ex}=\dot{m}_{ex}\psi_{ex}$, $\dot{\Psi}_D$ is the exergy destruction rate, and $\dot{W}$ is the work rate.

The total exergy of the system is given by:

$$\dot{\Psi}=\dot{\Psi}_{ph}+\dot{\Psi}_{ch} \quad \text{..........................(2)}$$

$$\dot{\Psi}_{ph}=\dot{m}\psi_{ph}=\dot{m}[h-h_0-T_0(s-s_0)] \quad \text{... ......(3)}$$

Where $\dot{\Psi}_{ph}$ the specific physical exergy, *h* and *s* are the specific enthalpy and specific entropy respectively.

$$\dot{\Psi}_{ch} = \dot{m}\psi_{ch} \quad \text{.................. ....(4)}$$

Where $\dot{\Psi}_{ch}$ is specific chemical exergy of mixture [2], and can be found using the following equation:

$$\psi_{ch} = \sum_{i=1}^{n} x_i \psi_{chi} + RT_0 \sum_{i=1}^{n} x_i \ln x_i \quad \text{...(5)}$$

Where, *i* is the components in the mixture. As shown in Figure 1, the main components in the plant are: Air compressor, combustion chamber, turbine, and electricity generator. The gas turbine and compressor are connected with a single shaft aligned to an electricity generator. The exergy analysis of various component in the plant are presented as follows:

A. Air Compressor

$$s_1 - s_0 = c_p \ln\left(\frac{T_1}{T_0}\right) - R \ln\left(\frac{p_1}{p_0}\right)$$

$$\psi_{c1} = \dot{m}_{air} c_p (T_1 - T_0) - \dot{m}_{air} T_0 (s_1 - s_0) \quad \text{..(6)}$$

$$s_1 - s_0 = c_p \ln\left(\frac{T_1}{T_0}\right) - R \ln\left(\frac{p_1}{p_0}\right) \quad \text{.........(7)}$$

ψ_{c1} is the exergy rate of the air entering to the compressor.

$$\psi_{c2} = \dot{m}_{air} c_p (T_2 - T_0) - \dot{m}_{air} T_0 (s_2 - s_0) \quad \text{..(8)}$$

$$s_2 - s_0 = c_p \ln\left(\frac{T_2}{T_0}\right) - R \ln\left(\frac{p_2}{p_0}\right) \quad \text{..........(9)}$$

ψ_{c2} is the exergy rate of the air leaving the compressor.

T_1 and T_2 are the compressor inlet and outlet temperatures respectively; p_1 and p_2 are the compressor inlet and exit pressures respectively.

The input power rate to the compressor is given by:

$$\dot{W}_c = \dot{m}_{air} c_p (T_2 - T_1) \quad \text{................(10)}$$

The exergy destruction rate in the air compressor:

$$\dot{\Psi}_D = \dot{W}_C + \dot{\Psi}_{c1} - \dot{\Psi}_{c2} \quad \text{....................(11)}$$

The specific heat capacity is obtained by polynomial form as a function of temperature given by [3] [4]:

$$\bar{C}_p = \alpha + \beta T + \gamma T^2 + \delta T^3 \quad \text{..............(12)}$$

The values of *α, β, γ*, and *δ* are constant characteristics of considered gas obtained from standard tables.

B. Combustion Chamber

The exergy flow rate in the combustion chamber is obtained from equation (1), which reduces to:

$$\sum_i \dot{\Psi}_F + \sum_{in} \dot{\Psi}_2 = \sum_{out} \dot{\Psi}_3 + \dot{\Psi}_D \quad \text{.......(13)}$$

The specific chemical exergy of hydrocarbons fuel can be calculated using the following formula which is the ratio of fuel exergy to the lower heating value of fuel [2][8]

$$\varphi = \frac{\psi_F}{LHV} \quad \text{....................................(14)}$$

Where ψ_F is the fuel exergy, for the gaseous fuel with composition C_aH_b, the ratio φ is given by the relation [2][4][8][15]:

$$\varphi = 1.033 + 0.0169\frac{b}{a} - \frac{0.0698}{a} \quad \text{......(15)}$$

LHV is the lower heating value fuel (for methane, LHV = 50.0 MJ/kg).

The exergy of combustion products exit the combustion chamber can be expressed as:

$$\dot{\Psi}_3 = \dot{\Psi}_{ph} + \dot{\Psi}_{ch} \quad \text{...........................(16)}$$

$$\dot{\Psi}_3 = \dot{m}_{air+fuel}(c_p(T_3 - T_0) - T_0\left[c_p ln\left(\frac{T_3}{T_0}\right) - Rln\left(\frac{p_3}{p_0}\right)\right] + \sum_i x_i \psi_{i0} + \bar{R}T_0 \sum_i x_i \ln(x_i)) . \quad \text{...(17)}$$

Where $\dot{\Psi}_{ch}$is chemical exergy rate of combustion products, x_i is mole fraction of constituent's elements and ψ_{i0} is standard molar exergy [1].

C. Turbine

The exergy balance of the expansion process 3-4 and the exergy destruction rate in the turbine can be written as [2]:

The power out rate from turbine is:

$$\dot{W}_T = (\dot{m}_{air} + \dot{m}_{fuel}) c_p (T_3 - T_4) \quad \text{....(18)}$$

And the exergy destruction in the turbine is obtained as:

$$\dot{\Psi}_D = \dot{\Psi}_4 - \dot{\Psi}_3 - \dot{W}_T \quad \text{....................(19)}$$

Where $\dot{\Psi}_3$, and $\dot{\Psi}_4$ are the exergy rate of combustion products entering and leaving the turbine.

D. Exergetic Efficiency of the Gas Turbine Power Plant:

The general definition of the exergetic efficiency (ε) for a system may be written as:

$$\varepsilon = 1 - \frac{Exergy\ destroyed}{Exergy\ supplied} \quad \text{................(20)}$$

The exergetic efficiency of various components in the gas turbine power plant and for the overall plant is calculated from the following equations:

Gas Turbine:

$$\varepsilon = 1 - \frac{\dot{\Psi}_{DGT}}{W_T} \quad \text{.......................................(21)}$$

Compressor:

$$\varepsilon = 1 - \frac{\dot{\Psi}_{DC}}{W_C} \quad \text{.......................................(22)}$$

Combustion chamber:

$$\varepsilon = 1 - \frac{\dot{\Psi}_{DCC}}{\dot{\Psi}_{ch}} \quad \text{.......................................(23)}$$

Overall plant:

$$\varepsilon = \frac{\dot{W}_{Plant}}{\dot{\Psi}_{ch}} \quad \text{.......................................(24)}$$

Where: $\dot{\Psi}_{DGT}, \dot{\Psi}_{DC}, \dot{\Psi}_{DCC}$ are the exergy destroyed in the gas turbine, air compressor, and combustion chamber respectively, $\dot{\Psi}_{ch}$ is the exergy flow rate of fuel in the combustion chamber; and W_T, W_C, represent the exergy flow rate of the power output from gas turbine and air compressor. $\dot{W}_{Plant}$, is the net power output from the plant.

Table 1, presents the operating data collected for the gas turbine power plant which utilized for numerical application of the exergy modeling. The state numbers refer to Figure 1.

TABLE 1 : OPERATING DATA FOR THE 20 MW AT VARIOUS STATE POINTS IN THE GAS TURBINE POWER PLANT

	Power (20 MW)			
	Fluid Type	**$\dot{m}$ (kg/s)**	**T(K)**	**P (MPa)**
1	Air	78.51	299.15	0.1013
2	Air	78.51	681.15	1.8045
3	Combus. Gases	80.1	1429.15	1.8045
4	Combus. Gases	80.1	873.15	1.008
5	Fuel	1.59	305.15	2.82

Table 2 : Operating Data for the 20 Mw at Various State Points in the Gas Turbine Power Plant

	Power (30 MW)			
	Fluid Type	**$\dot{m}$ (kg/s)**	**T(K)**	**P (MPa)**
1	Air	93.49	301.15	0.1004
2	Air	93.49	684.15	1.3600
3	Combus. Gases	95.5	1467.15	1.3500
4	Combus. Gases	95.5	860.15	0.1016
5	Fuel	2.01	305.15	2.79

Results and Discussion

The results obtained from the exergy analysis of the gas turbine power plant components are presented in table (3) for 20 MW load and table (4) for 30 MW load, also the results are shown in Figures (2-7).

The largest exergy destruction for 20 MW and 30 MW occurs in the combustion chamber and it is equal to (19.134 MW) with the percentage of (68.174 %) and (24.174 MW) (62.21 %) respectively, followed by gas turbine for both loads with (5.145 MW) (18.34 %) and (12.04 MW (30.98 %) respectively. The smallest value of exergy destruction occurs in the compressor for both loads (3.78 MW) (13.48 %) and (2.646 MW) (6.81 %) respectively.

The percentage of exergy destruction and the second law efficiency, which is referred to in this work as the exergetic efficiency are presented in Figure 2 and Figure 3 for various components in the plant. The reason of the largest exergy destruction rate and lowest exergetic efficiency occur in the combustion chamber are due to unburnt fuels, heat losses to the surrounding through the combustion process and incomplete combustion.

The exergetic efficiency of the gas turbine power plant is increased as the power load increases from 57.15 % to 58.76 % as shown in table 2 and 3.

Table 3: Results Obtained from the Exergy Analysis of South Tripoli Gas Turbine Power Plant at Load 20 MW

1)	**Power = 20 MW**				
components	Ψ_{in} (MW)	Ψ_{out} (MW)	Ψ_D (MW)	ε(%)	Ψ_D (%)
compressor	29.95969	26.17613	3.783564	87.37115	13.48067
Combustion Chamber	108.2067	89.07256	19.13412	82.31706	68.174
Gas Turbine	89.07256	83.92365	5.148912	94.21942	18.34534
Exergetic Efficiency of the plant	ε (Plant) = 57.15 %				

Table 4: Results Obtained from the Exergy Analysis of South Tripoli Gas Turbine Power Plant at Load 30 MW

	Power = 30 MW				
components	$\dot{\Psi}_{in}$ (MW)	$\dot{\Psi}_{out}$ (MW)	$\dot{\Psi}_{D}$ (MW)	ε(%)	$\dot{\Psi}_{D}$ (%)
compressor	35.88644	33.23992	2.646523	92.62529	6.810278
Combustion Chamber	136.9389	112.7644	24.17451	82.3465	62.20809
Gas Turbine	112.7644	100.7247	12.03968	89.32315	30.98163
Exergetic Efficiency of the plant:	ε (Plant) = 58.76 %				

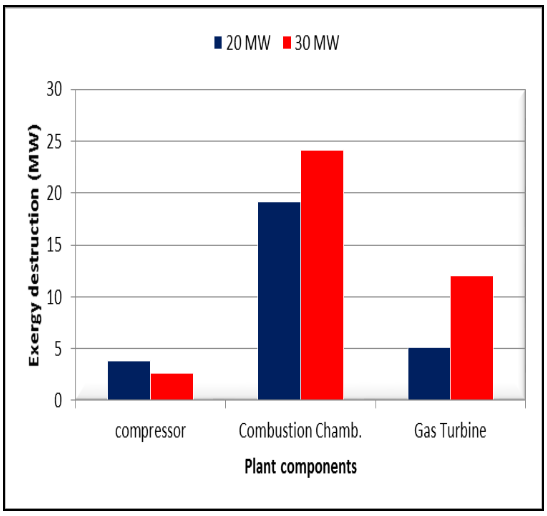

Figure 2, Exergy Destruction in Various Components in the Plant at loads 20 MW and 30 MW

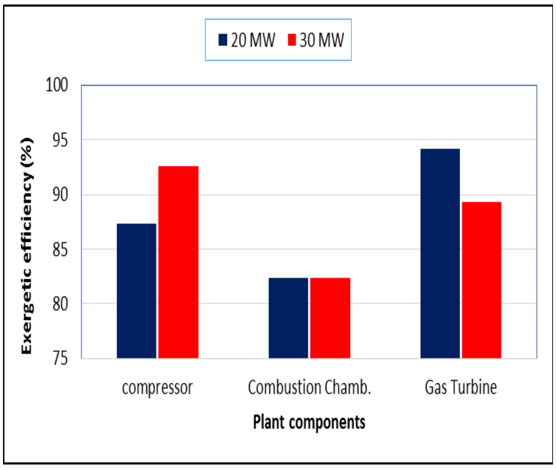

Figure 3, Exergetic Efficiency in (%) of Different Components in the Plant at Loads 20 and 30 MW

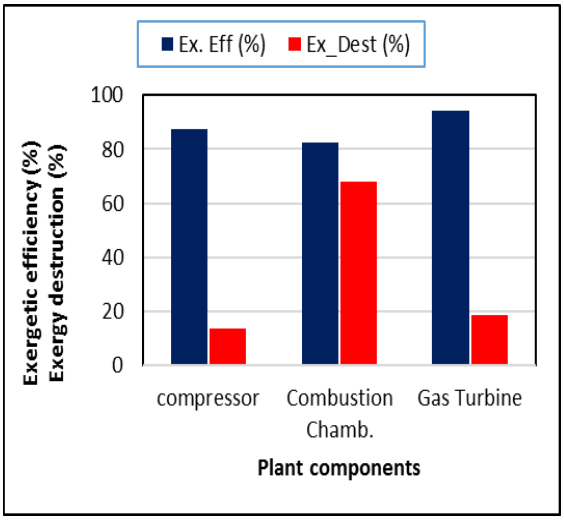

Figure 4, Exergetic Efficiency (%), and Exergy Destruction (%) of Various Components in the plant (Power 20 MW)

Chemical reaction is one of the most significant source of exergy destruction in the combustion chamber, the irreversibilities associated with the heat transfer, mixing, and friction decreases the thermodynamic performance such as exergetic efficiency. Compared with the exergy destruction due to chemical reactions, friction and mixing effects are of insignificant importance.

Figure 6 and Figure 7showthat the variation of exergy destruction and its percentage of gas turbine power plant with the inlet compressor temperature. It can be observed that the change of compressor inlet temperature has insignificant effect on exergy destruction of plant components.

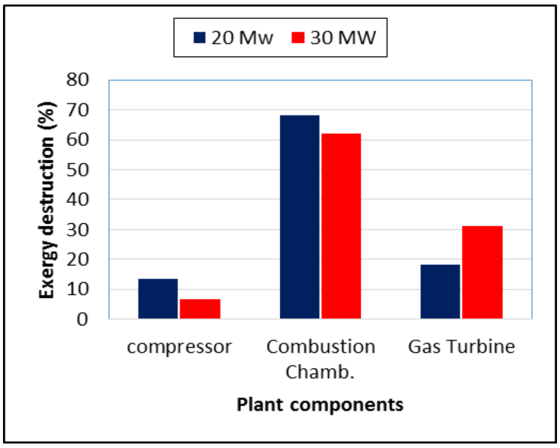

Figure 5, The Percentage of Exergy Destruction in Various Components in the Plant at Load 20 MW and 30 MW

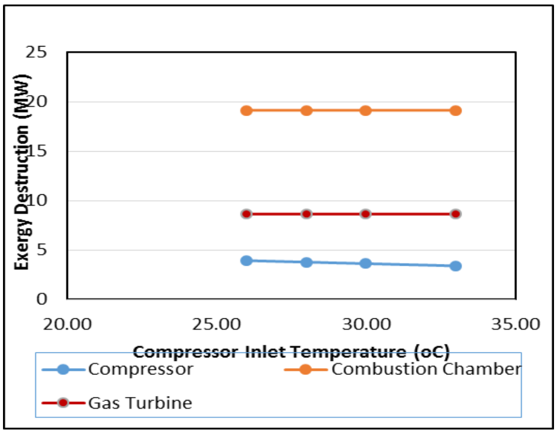

Figure 6, The Relation Between Exergy Destruction And Compressor Inlet Temperature

Figure 8 shows that the exergetic efficiency for various plant components with the compressor inlet temperature. From the figure, it is observed that the change of inlet compressor temperature has insignificant effect on exergetic efficiency of combustion chamber and gas turbine while the exergetic efficiency of compressor increases with inlet temperature increases.

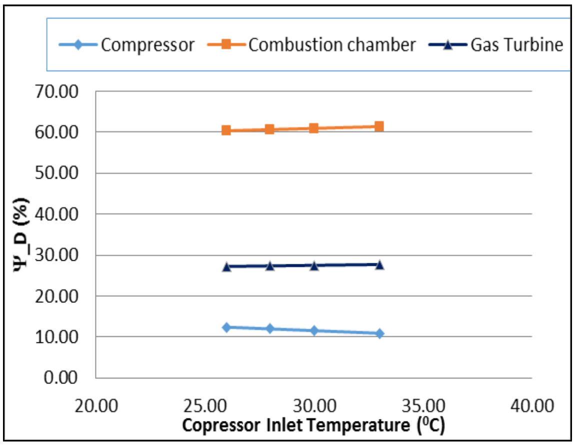

Figure 7, Exergy Destruction (%) vs Compressor Inlet Temperature for Various Plant Components (Load 20 MW)

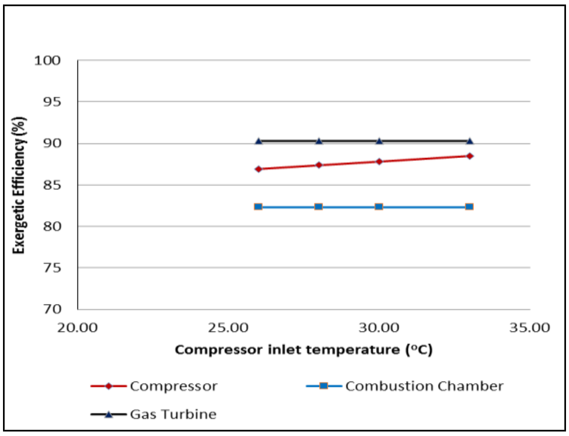

Figure 8, Exergetic Efficiency (%) Vs Compressor Inlet Temperature For Various Plant Components (Load 20 MW)

Figure 9 shows the Grassmann diagram of the gas turbine power. It shows the exergy destruction and its percentages in each components in the plant based on the results obtained. It is also shown that about 35.3% of the total turbine inlet exergy destroyed and rejected in the exhaust to the surroundings

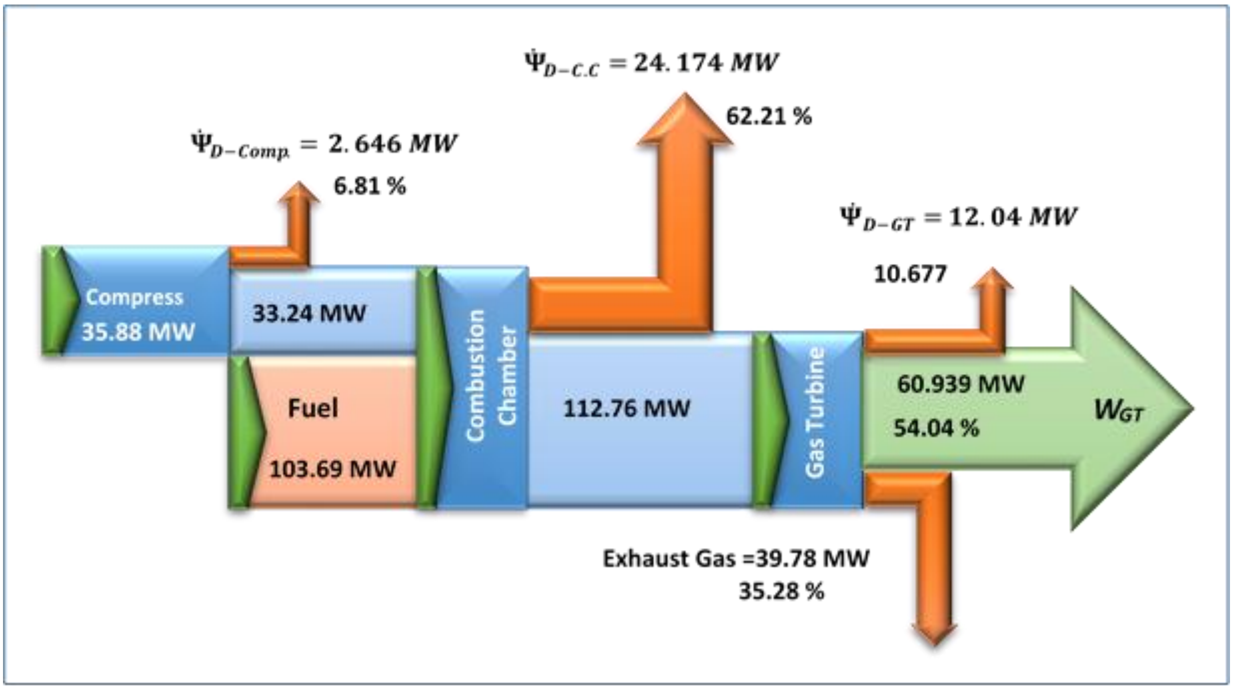

Figure 9 Shows the Grassmann Diagram of the Gas Turbine Power

IV. CONCLUSIONS

From this work, it can be concluded that the exergy method contrary to the first law analysis quantifies and localize the thermodynamic losses of various plant components (exergy destruction).

The highest exergy destruction occurs in the combustion chamber followed by the gas turbine and the smallest value occurs in the air compressor.

The inlet temperature of compressor has insignificant effect on the components of gas power plant.

REFERENCES

[1] Bejan, g. Tsatsaronis, m. j. Moran, Optimization and thermal design, Willey, 1996.
[2] Kota, T.J., The Exergy Method of Thermal Plant Analysis, Butterworths, U.K., 1985.
[3] Cenggel, A.Y., Boles, M.A., Thermodynamics Engineering Approach,Fifth Edition,McGraw Hill Companies, New York,USA, 2006.
[4] Moran M.J., Shapiro, H.N., Fundamental of Engineering Thermodynamics, Third edition, John Wiley and Sons, New Jersy, USA, 2006.
[5] Aljundi, I.H., Energy and exergy analysis of a steam poer plant in Jordan. Applied thermal engineering, vol. 29, 2009.
[6] Naji S. Y. Thermoeconomic Optimization of Steam power plants, MSc Thesis, University of Tripoli, 1998.
[7] Lalatendu P., Thermodynamic modeling and exergy analysis of Gas turbine Cycle for Different Boundary conditions, international Journal of Power electronics and Drive System, Vol.6, No. 2, June 2015.
[8] Alhosani O. M., Alhosani A. A. and Dadach Z. E., Exergy Analysis of a power Plant in Abu Dhabi (UAE), International Journal of Energy Engineering, Vol.5., Iss. 3, June 2015.
[9] Martin A., Miswandi, Prayitino A., Kurniawan I., and Romy, Exergy Analysis of Gas Turbine Power Plant 20 MW in Pekaanbaru-Indonesia, international Journal of Technology, Vol.5,June 2016.
[10] Iraides Aparecida de Castro Villela, Energetic and exergetic analysis of a Gas-Turbine Combined cycle power plant, 19th international Congress of Mechanical Engineering, November 5-9, 2007, Barasilia.
[11] Mehta Parth N., Meta N. S., Panchal C. P., Exergy Analysis of gas turbine power Plant, international journal of Science and engineering Research, Vol. 5,Iss. 2, Feb. 2014.
[12] Chand V.T T., B. Ravi Sankar, and Chwdary J., R., Exergy analysis of gas Turbine power Plant, International Journal of engineering and Technology, Vol. 4, Iss.9, September 2013.
[13] Naser M. Jubeh, Exergy analysis and second law efficiency of a regenerative Brayton Cycle with isothermal Heat addition, Entropy,7[3],2005.
[14] G. Tsatsaronis and F. Cziesla, exergy Analysis of simple process, Energy, energy Steam analysis and Optimization, vol. 1.(year N/A).
[15] S.Kaushika, V. Reddya and S.K.Taygi, Energy and Exergy analysis of Thermal power plant: A review, Renewable and sustainable energy review, vol.5, 2011.

Nomenclature

$\dot{Q}$	*Heat transfer rate (MW)*
$\dot{W}$	*Power (MW)*
$\dot{m}$	*Mass flow rate (kg/s)*
h	*Specific enthalpy (kJ/kg)*
s	*Specific entropy (kJ/kg.K)*
x	*No. of moles*
T	*Temperature (K)*
R	*gas constant (kJ/kg.K)*
c	*Specific heat (kJ/kg.K)*
P	*Pressure (MPa)*
LHV	*Lower Heating value(kJ/kg)*

Greek Symbols

$\dot{\Psi}$	*Exergy (MW)*
ε	*Exergetic efficiency*
ψ	*Specific exergy (kJ/kg)*
φ	*Ratio of fuel exergy to LHV*

Subscripts

D	*Destruction*
in	*inlet*
ex	*exit*
F	*Fuel*
i	*No of constituents*
ch, ph	*Chemical, Physical*