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Thermodynamic modeling and Exergy Analysis of Gas Turbine Cycle for Different Boundary conditions

Lalatendu Pattanayak
Steag Energy Services India Pvt. Ltd, A-29, Sector-16, Noida, UP, India

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ABSTRACT

In this study an exergy analysis of 88.71 MW 13D2 gas turbine (GT) topping cycle is carried out. Exergy analysis based on second law was applied to the gas cycle and individual components through a modeling approach. The analysis shows that the highest exergy destruction occurs in the combustion chamber (CC). In addition, the effects of the gas turbine load and performance variations with ambient temperature, compression ratio and turbine inlet temperature (TIT) are investigated to analyse the change in system behavior. The analysis shows that the gas turbine is significantly affected by the ambient temperature and with increase there is decrease in GT power output. The results of the load variation of the gas turbine show that a reduction in gas turbine load results in a decrease in the exergy efficiency of the cycle as well as all the components. The compressor has the largest exergy efficiency of 92.84% compared to the other component of the GT and combustion chamber is the highest source of exergy destruction of 109.89 MW at 100 % load condition. With increase in ambient temperature both exergy destruction rate and exergy efficiency decreases.

Corresponding Author:

Lalatendu Pattanayak,
Departement of System Technologies,
Steag Energy Services India Pvt. Ltd,
A-29, Sector-16, Noida, UP, 201301, India.
Email: lala_tendu@rediffmail.com

1. INTRODUCTION

Concept of exergy analysis involves both laws of thermodynamics (first and second laws) is an analysis technique applied on energy systems to identify and quantify the amount of thermodynamic adversity involved in the processes and or energy systems. This technique is used as a potential tool to evaluate the thermal performance and efficiency of system and components involve in energy process during design as well as in operation phase. By definition exergy is the amount of maximum work potential for an energy system in relation to its environment through reversible processes [1]. Exergy analysis quantitatively detects and evaluates the thermodynamic inefficiencies of the process under consideration [2], [3].

In recent years many studies have been performed by researchers to evaluate the performance of combined cycle power plants (CCPPs) and its subsystems based on concept of energy and exergy [4]-[14]. Boksteen et al. [15] performed the second law based analysis with steady state thermodynamic model for KA26 gas turbine combined cycle plant to improve its operational efficiency. A concept of exergy was used by I.S. Ertesvag et al. [16] to investigate the CO_2 capture in a gas turbine plant. Also the study investigates the effects of change in natural gas composition and ambient temperature. Akbari et al. [17] conducted a parametric study with design parameters to evaluate the performance of CCPP using energy and exergy concept. Ali and Ameri [18] evaluate the system performance of gas turbine power plant for different load and ambient temperature based on energy, exergy and exergoeconomic analysis. Ebadi and Gorji-Bandpy [19] performed the exergy analysis of a 116 MW gas turbine power plant based on varying TIT. The application of exergy analysis to determine the irreversibility of CCPP was presented by Ameri et al. [20]. Ghazikhani et al. [21] investigate the performance of gas turbine air bottoming combined cycle based on exergy analysis. The result shows that the second law efficiency of gas turbine with air bottoming cycle is 6 % more that the second law efficiency of simple gas turbine keeping same intake air temperature for both the cycle. An advanced exergy analysis is performed by Soltani et al. [22] for a CCPP configuration of an externally fired system, integrated with biomass gasification. They concluded that the performance of the cycle can be improved by improving the performance of heat exchanger though the maximum rate of exergy destruction occurs at the combustion chamber. Wang and Lv [23] investigate the M701F gas turbine based combined cycle plant to improve the service life of hot end components using equivalent operation time analysis method. Al-Doori [24] performed an exergetic analysis for a Baiji plant gas turbine of capacity 159 MW with effect of cycle temperature. The result shows that the TIT has an impact on both exergetic efficiency and exergy destruction of the plant. Egware and Obanor [25] presented the use of exergy analysis for evaluating the performance of Omotosho Phase I gas thermal power plant. Results obtained show that the gas turbine had the largest exergy efficiency of 96.17%, while that of the total plant was 41.83%, the combustion chamber had the largest exergy destruction of 54.15% while that of the total plant was 58.17%.

In this study the exergetic analysis is performed for a 88.71 MW GT cycle through a modeling approach. Exergy analysis for the gas cycle is carried out to assess the performance of different component and find out areas of exergy destruction at design and off design condition. Exergy destruction of the combined cycle plant component is quantified and the effect of boundary conditions like ambient temperature, compression ratio and TIT on the performance of gas turbine cycle is investigated.

2. DESCRIPTION OF GAS TURBINE CYCLE

Figure 1 shows a schematic diagram of GT 13D2 machine with 100% output (88.71 MW) at ambient temperature of 27 ^{o}C and air pressure at compressor inlet 1.003 ata. The conversion of heat released by burning fuel into mechanical energy in a gas turbine is achieved by first compressing air in an air compressor, then injecting and burning fuel at (ideally) constant pressure, and then expanding the hot gas in the gas turbine. Combustion product enters the GT at temperature of 1005 ^{o}C and pressure of 11.66 ata. At full load the GT produce 88.71 MW. The waste heat in flue gas exit from GT at temperature of 507.8^{o}C.The turbine provides the necessary power to operate the compressor. Whatever power is left is used as the mechanical output of the engine. This thermodynamic cycle is called as topping cycle. To represent the physical parameters of working fluid at different state is marked as 1, 2, 3…7 as shown in Figure 1. Basic assumption is that the system under study is in steady state and the mechanical efficiency of the GT and compressor is 99%.

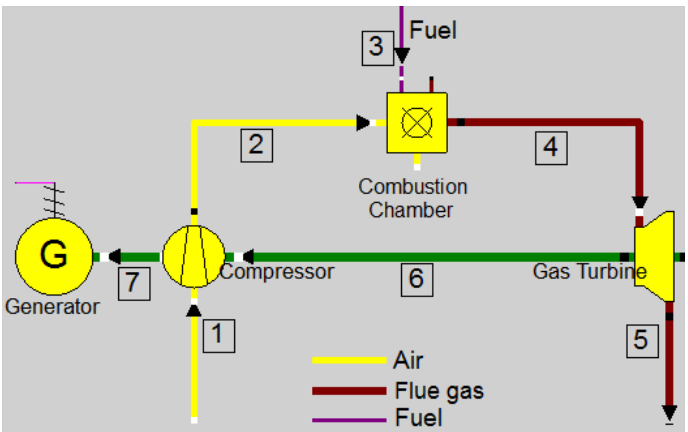


Figure 1. Schematic diagram of Gas turbine cycle

3. EXERGY ANALYSIS

Exergy analysis is a method that is used for analysis, design and performance improvement of energy and other systems. Furthermore it can be used as a tool for analyzing the efficient use of energy resource and also to determine the types and magnitude of wastes and losses occurring in the systems [26], [27]. According to the literature, total exergy of a system can be divided into four components. The two important are the physical exergy and chemical exergy. The physical exergy is the maximum work obtainable by a system from its initial state through reversible process while interacting with an equilibrium state. The chemical exergy is the maximum work that can be obtainable with the departure of chemical composition of the system from its chemical equilibrium. The chemical exergy plays an important role of exergy analysis in the combustion process. In this study, the two other components i,e kinetic exergy and potential exergy are assumed to be negligible.

Applying the first and second laws of thermodynamics, the exergy balance equation for steady state flow of stream [28]-[31] is given in (1).

$$\sum(1-\frac{T_0}{T})\dot{Q}+\sum_{in}\dot{m}_i e_i=\dot{W}+\sum_{out}\dot{m}_e e_e+\dot{E}_D \quad (1)$$

where $\sum(1-\frac{T_0}{T})\dot{Q}$ is the rate of exergy transfer at temperature T, and the subscripts i and e denote inlets and outlets, respectively. $\dot{W}$ is the work rate excluding the flow work. The exergy transfer rates at inlets and outlets are denoted respectively as, $\dot{E}_i=\dot{m}_i e_i$ and $\dot{E}_e=\dot{m}_e e_e$.
The total exergy, physical exergy, specific exergy and chemical exergy are evaluated using (2), (3), (4) and (5) respectively.

$$\dot{E}=\dot{E}_{ph}+\dot{E}_{ch} \quad (2)$$

$$\dot{E}_{ph}=\dot{m}\,e_{ph}=\dot{m}\,[h-h_0-T_0(s-s_0)] \quad (3)$$

$$e_{ph}=\text{specific exergy}=h-h_0-T_0(s-s_0) \quad (4)$$

where h and s denote the specific enthalpy and specific entropy respectively. The subscript '0' denotes the refernce state. Reference pressure (Pref) and temperature (Tref) are taken respectively as 1.003 ata and 27 ^{o}C.

$$\dot{E}_{ch}=\dot{m}\,e_{ch} \quad (5)$$

where e_{ch} is specific chemical exergy (mixture) [4] and can be evaluated using (6),

$$e_{ch}=\sum_{i=1}^{n}X_i e_{chi}+RT_0\sum_{i=1}^{n}X_i\ln X_i+G_E \quad (6)$$

where G_E is Gibbs free energy which is a negligible quantity in a gas mixture operated at low pressure. So for the calculation of fuel exergy, the expression in (6) does not hold good. Thus, the fule exergy can be calculated using (7) as the ratio of fuel exergy to lower heating value of fuel (LHV) [4], [20], [32].

$$\varphi=\frac{e_F}{LHV} \quad (7)$$

where e_F is fuel exergy. For the majority of gaseous fuel, the value of φ is normally close to 1. For the fuel like methane, fallowing relationship can be used as given by Kotas [4]:

$\varphi_{CH4}=1.06$
$\varphi_{H2}=0.985$

For gaseous fuel with composition C_xH_y, the ratio φ can be calculated using (8) [4], [13].

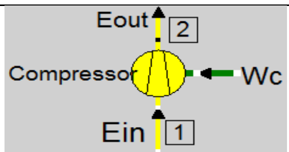
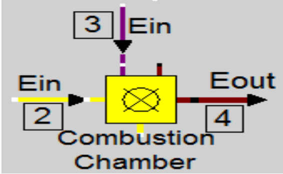
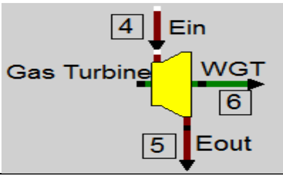
$$\varphi=1.033+0.0169\frac{y}{x}-\frac{0.0698}{x} \quad (8)$$

The exergetic efficiency can be evaluated using the relationship of both product and fuel for the system. The product exergy represents the desired result produced by the system and the fuel exergy represents the resources expended to generate the product. Thus the exergetic efficiency is the ratio between product exergy and fuel exergy [28], [33], [34] as given in (9). The exergy efficiency and exergy destruction of all other individual components of gas cycle are shown in Table 1.

$$\varepsilon_{ex}=\frac{\dot{E}_P}{\dot{E}_F} \quad (9)$$

where $\dot{E}_F$ is the rate at which fuel is supplied and $\dot{E}_P$ is the product generated.

Table 1. The exergy destruction rate and exergy efficiency equations for GT components

Component	Exergy destruction ($\dot{E}_D$)	Exergy efficiency ($\mathcal{E}_{ex}$)
	$\dot{E}_1 - \dot{E}_2 - W_C$	$\frac{\dot{E}_2 - \dot{E}_1}{W_C}$
	$\dot{E}_2 + \dot{E}_3 - \dot{E}_4$	$\frac{\dot{E}_4}{\dot{E}_2 + \dot{E}_3}$
	$\dot{E}_4 - \dot{E}_5 - W_{GT}$	$\frac{W_{GT}}{\dot{E}_4 - \dot{E}_5}$

4. RESULTS AND DISCUSSION

Exergy analysis of a GT topping cycle is presented in this section. The effects of ambient temperature, compression ratio and TIT on power output, exergy destruction rate and exergy efficiency are obtained from the exergy (second law) analysis. Figure 2 shows the effect of ambient temperature on exergy destruction rate of gas cycle component at 100 % load condition of GT. With increase in ambient temperature from 0 °C to 50 °C the exergy destruction rate of compressor, combustion chamber and gas turbine decreases. The maximum exergy destruction takes place in combustion chamber followed by gas turbine.

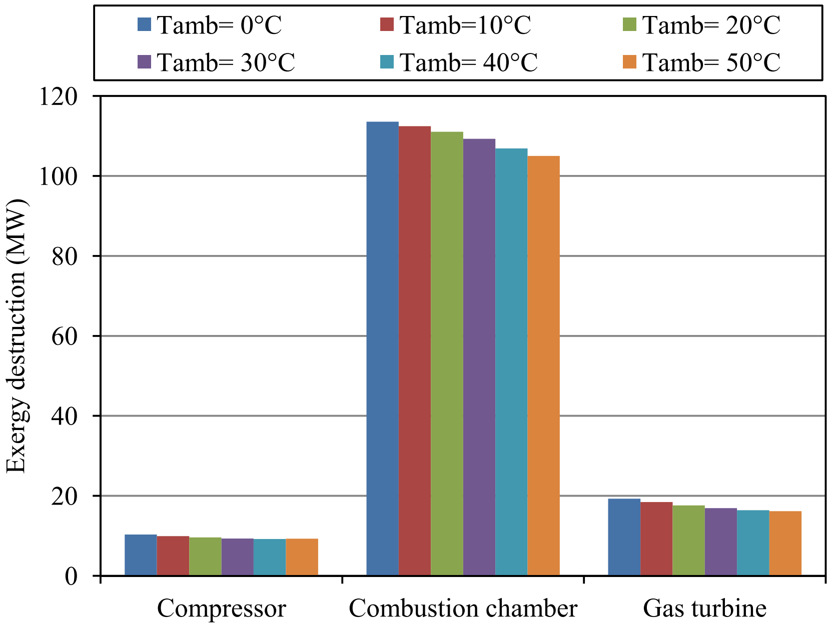


Figure 2. Variation of exergy destruction rate of components at different ambient temperature for 100 % load.

Figure 3 presents the variation of exergy efficiency of components with change in ambient temperature at 100 % load. There is a significant change in exergy efficiency of combustion chamber with temperature. As the ambient temperature increases the exergy efficiency decreases. This is due to with rise in temperature the fuel flow rate decreases and thus the total fuel exergy also reduces. Thus the overall exergy destruction and exergy efficiency of combustion chamber reduces with rise in temperature. At the same time the exergy efficiency of gas turbine increase with rise in ambient temperature from 0 ^oC to 30 ^oC from 92.76 % to 92.92 % and thereafter by further increase in temperature efficiency reduces as the gas turbine load reduce with rise in temperature from the rated capacity. The exergy destruction rate of the gas turbine reduces with rise in ambient temperature. As the temperature rise the gas turbine load reduces and the turbine exit temperature increases. Total exergy at gas turbine inlet and outlet reduces, resulting reduce in gas turbine exergy destruction rate.

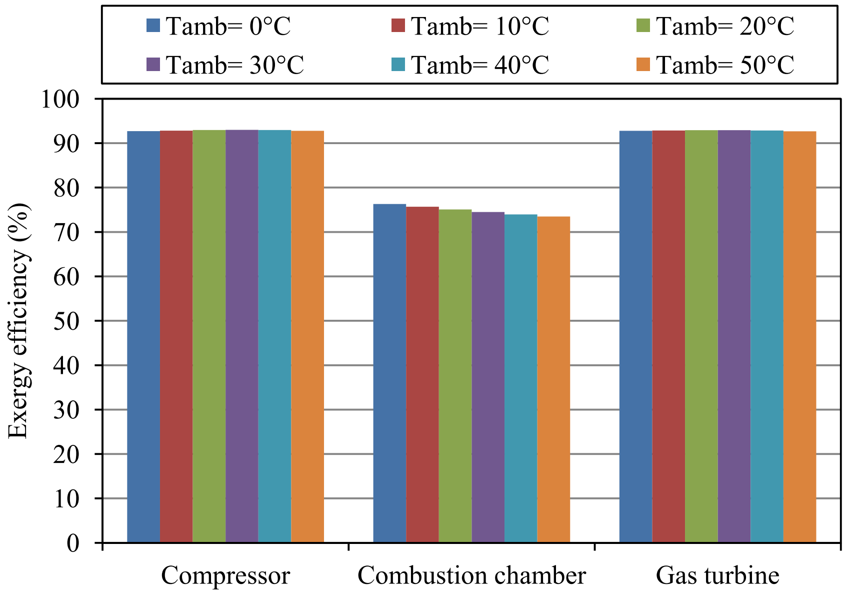


Figure 3. Variation of exergy efficiency of components at different ambient temperature for GT load 100 %.

Figure 4 depicts the effect of ambient temperature on exergy destruction rate and exergy efficiency of GT cycle. With increase in ambient temperature both exergy destruction rate and exergy efficiency of GT cycle decreases. Exergy efficiency decreases continuously up to ambient temperature of 27 ^oC and from 27 ^oC to 30 ^oC it increases by maintaining the rated load of 88. 71MW and further decreases with increase in temperature. This indicates that the best performance of the gas cycle can be achieved in between the temperature range of 27 ^oC to 30 ^oC.

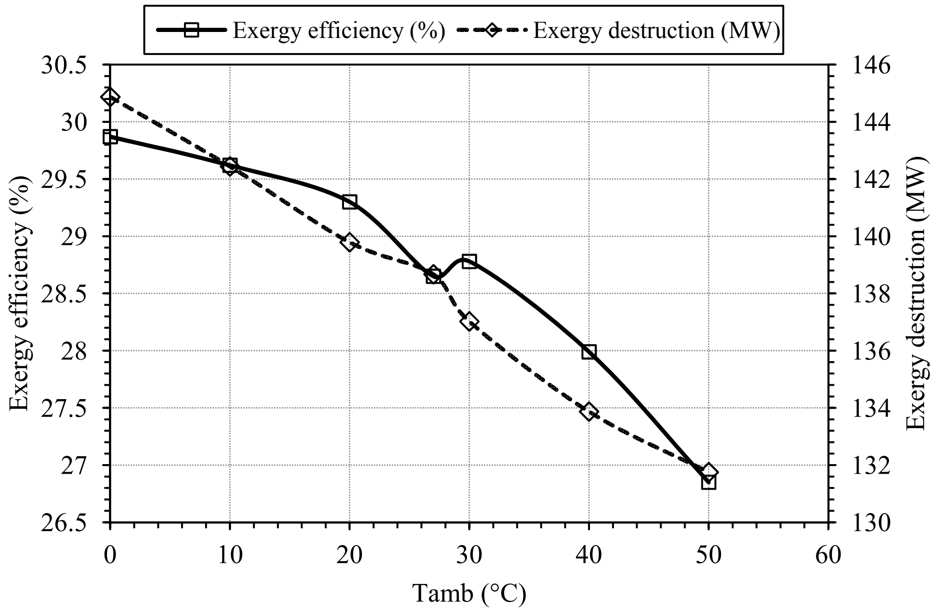


Figure 4. Variation of exergy efficiency and exergy destruction of gas cycle with ambient temperature

Though the gas turbine produces maximum power at low ambient temperature but at the same time the rate of exergy destruction is high at lower ambient temperature. The high temperature air leaving from compressor becomes hotter with the high ambient temperature entering into the combustion chamber while gases leaving from combustion chamber are also at higher temperature thereby reducing the irreversibility. Figure 5 shows the corresponding temperature-entropy(t-s) diagram of the gas turbine cycle at different ambient temperature. With rise in ambient temperature the compression outlet temperature rises this is due to reduction in air flow.

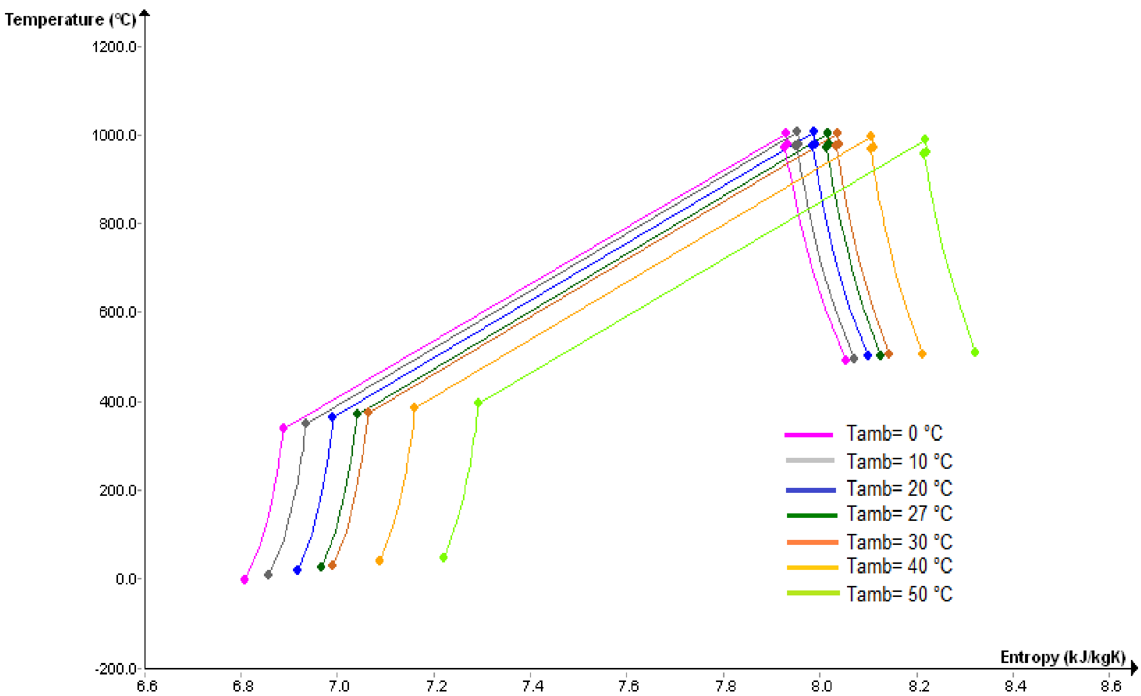


Figure 5. T-S diagram of gas turbine cycle at different ambient temperature

The exergy destruction and exergy efficiency of various plant components are shown in Figure 6 and Figure 7 for various gas turbine load at refernce temperature (Tref) of 27^{o}C and pressure (Pref) of 1.003 ata. The result shows that the compressor has the largest exergy efficiency of 92.84% compared to the other component of the GT and combustion chamber is the highest source of exergy destruction of 109.89 MW at 100 % load condition. It is also shown that the exergy destruction rate increases with increase in load form 50 % to 100 %.

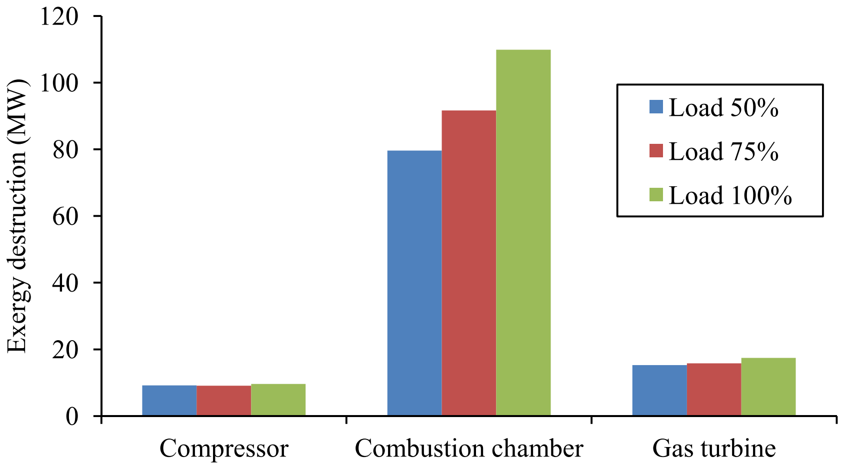


Figure 6. Exergy destruction of components at various load

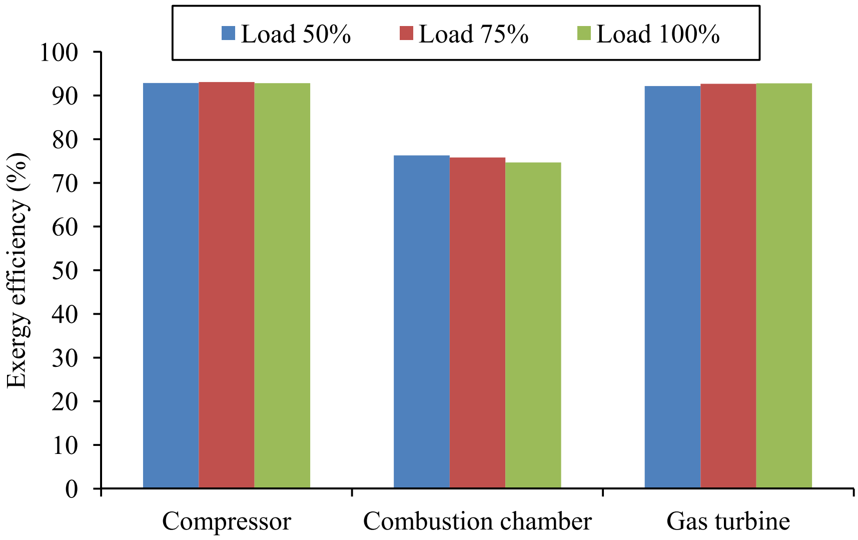


Figure 7. Exergy efficiency of components at various load

Figure 8 shows the effect of ambient temperature on gas cycle power output and exergy efficiency at various load. The efficiency of gas turbine cycle decreases with increase in ambient temperature as the power output of the gas turbine cycle decreases with increase in ambient temperature. This may be due to increase in compressor work at high temperature and the mass flow rate reduces.

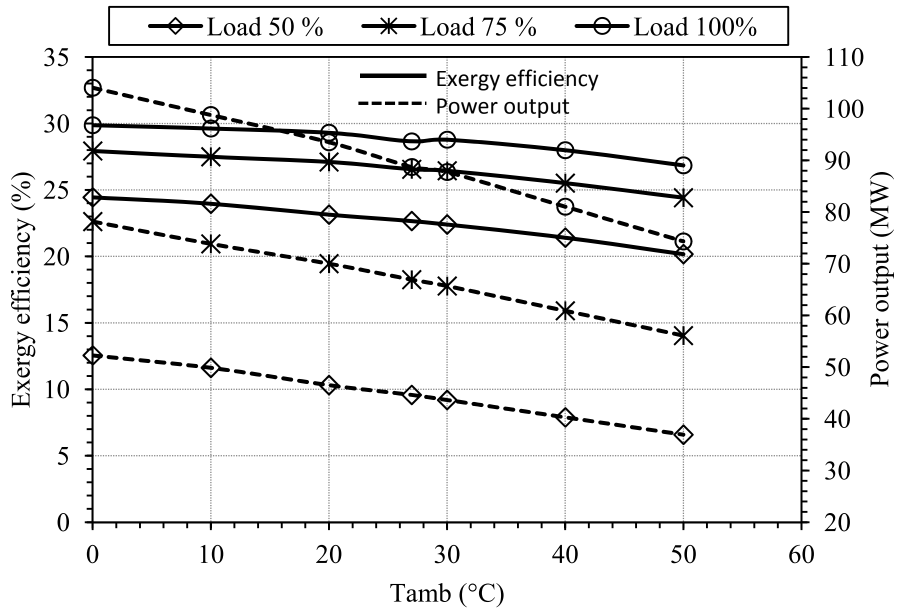


Figure 8. Variation of gas cycle exergy efficiency with ambient temperature and load

The effect of TIT and compression ratio on power output and over all exergy efficiency of gas cycle is depicts in Figure 9 at reference temperature of 27 ^{o}C. Exergy efficiency and power output of gas cycle increases with increase in TIT and decreases with decrease in compression ratio. An increase in the TIT leads to an increase in the GT exergy efficiency due to the fact that the GT turbine work output increases. As the load increases thus leads to reduction in exergy destruction. Therefore, it can be concluded that TIT is the most important parameter in designing the gas turbine cycle due to the decrease in exergy destruction and increase in cycle exergy efficiency.

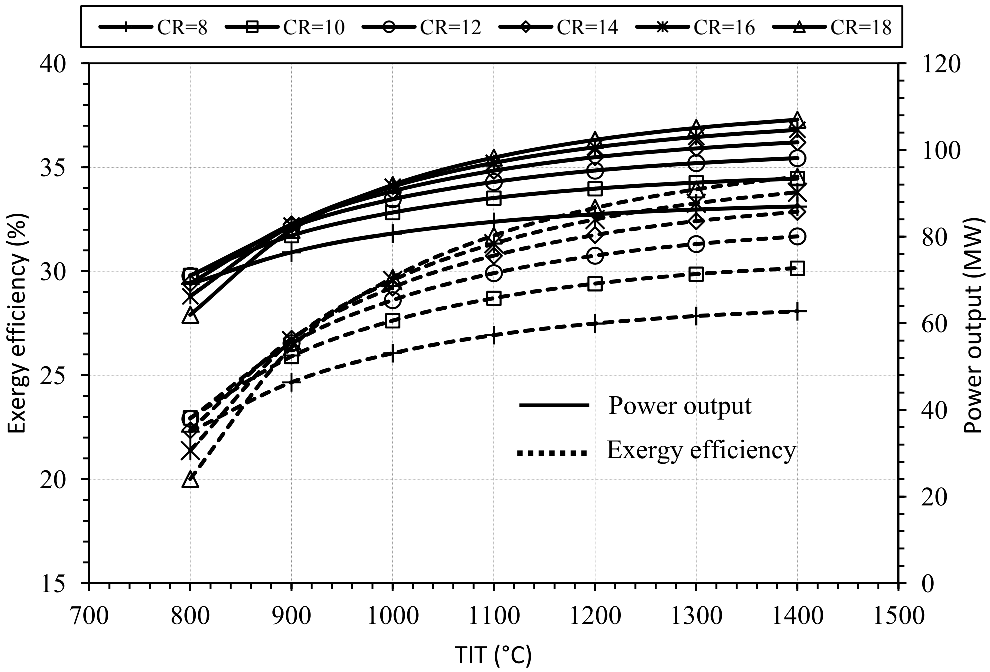


Figure 9. Effect of TIT and compression ratio on gas turbine power out and gas cycle exergy efficiency

5. CONCLUSION

An exergy analysis applied to a process or to total plant gives quantitative information that how much work potential, or exergy input to the system under study has been consumed by the process or plant components. The exergy analysis (loss of exergy, or irreversibility) provides quantitative information of the system and process inefficiency. In this study the exergetic analysis is performed for a 13D2 GT machine. The effect of ambient temperature, compression ratio and TIT on the exergy efficiency and exergy destruction of gas turbine cycle and on individual component is analyzed. The results evident that considerable amount of exergy destruction occur in the combustion chamber. This may be due to higher fuel exergy and chemical reactions of fuel with air, and heat transfer takes place inside the combustion chamber. The exergy efficiency of gas turbine increase with rise in ambient temperature from 0 ^{o}C to 30 ^{o}C from 92.76 % to 92.92 % and thereafter by further increase in temperature efficiency reduces as the gas turbine load reduce with rise in temperature from the rated capacity. The best performance of the gas cycle can be achieved in between the temperature range of 27 to 30 ^{o}C.

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Nomenclature

e	specific exergy (kJ/kg)
$\dot{E}$	total exergy (kJ/kg)
h	enthalpy (kJ/kg)
LHV	lower heating value (kJ/kg)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (ata)
$\dot{Q}$	heat transfer rate (MW)
s	entropy (kJ/kgK)
T	temperature (^{o}C)
$\dot{W}$	rate of work (MW)

Greek Symbol

φ	ratio of fuel exergy to lower heating value
ε_{ex}	exergy efficiency (%)

Subscripts and superscripts

a	air
amb	ambient
c	compressor
ch	chemical
D	destruction
e	outlet
F	fuel
i	inlet
ph	physical
P	product
0	reference state
1-7	state points on the schematic flow sheet

Abbreviation

CC	combustion chamber
GT	gas turbine
TIT	turbine inlet temperature

BIOGRAPHY OF AUTHOR

Lalatendu Pattanayak received his B.E degree in Mechanical Engineering from Berahmpur University, MTech in Environmental Science and Engineering from Jamia Millia Islamia (New Delhi, India) and PGDip in Thermal power plant Engineering from NPTI (Badarpur) India. He is currently working as DGM (System Technology dept.) at Steag Energy Services India Pvt. Ltd. and his research interest covers topics in energy engineering including energy efficiency, energy auditing, energy conservation, life cycle assessment, exergy analysis and modeling & simulation.