Published in the Russian Federation
European Journal of Technology and Design
Has been issued since 2013.
ISSN: 2308-6505
E-ISSN: 2310-3450
Vol. 12, Is. 2, pp. 72-78, 2016

DOI: 10.13187/ejtd.2016.12.72
www.ejournal4.com

UDC 62

Energy and Exergy Analysis on 350MW Combined Cycle Power Plant

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Abstract

The energy of exhaust gases from gas turbines are recovered by an unfired HRSG to supply steam to the steam cycle. The first law of thermodynamics deals with quantity of energy and asserts that energy cannot be created nor be destroyed. But, the second law deals with quality of energy. It is concerned with degradation of energy during a process. It gives an insight to the lost opportunities to do work. Thus it gives lot of scope for improvement. This makes second law analysis a powerful tool in optimization of complex thermal systems. Exergy also known as availability is the maximum useful work that could be obtained from the system at a given state in a specified environment. In this paper the variation of exergetic efficiency of gas turbines and their impact on thermal efficiency of combined cycle with variation of gas turbine parameters is demonstrated.

Keywords: combined cycle, energy, exergy, EES.

Introduction

The properties of a system at the dead state are denoted by subscript zero such as P_0, T_0, h_0, u_0, and s_0. Usually the dead-state temperature and pressure are taken to be T_0 = 25°C (298.15K) and P_0 = 1 atm (101.325 kPa). A system has zero exergy at the dead state.

Exergy balance for any system is given by

$$X_{in} - X_{out} - X_{destroyed} = \Delta X_{system}$$

$$X_{destroyed} = T_0 S_{gen}$$

Soupayan Mitra and Subhankar Sarkar conducted an exergy analysis on thermal power plant. They utilized Taguchi's method and used regression analysis to correlate exergy efficiencies and operating parameters and procured a result with less than 1 % variation from actual data [1]. Reddy et al. conducted an energy and exergy analysis on 210MW thermal power plant and found that boiler has got the highest exergy destruction followed by HPT [2]. Boyaghchi and Molaie conducted and advanced exergy analysis on a combined cycle power plant and found out avoidable exergy destruction is greater for HPST. They also studied the effect of variation of mass flow rate of duct burner fuel [3]. Vandani et al. optimized heat recovery from boiler blow down using Genetic Algorithm and Particle Swarm Optimisation methods [4]. Taillon and Blanchard developed to novel graphs for exergy efficiency analysis. First cone combines total, electrical and thermal efficiencies whereas second one splits thermal exergy efficiency to plant thermal losses and useful heat output quality [5]. Boyaghchi and Molaieh has presented a parametric study discussing sensitivity of various performance indicators to turbine inlet temperature (TIT) and pressure ratio. They also concluded that most exergy destruction is accounted in combustion chamber [6]. Geete and Khandwawala investigated exergy efficiencies for various components of a 120MW thermal power plant for various inlet temperatures [7]. Ghazikhani et al. suggested the use of a gas turbine with air bottoming cycle instead of conventional gas turbine. The modified arrangement gave lower specific fuel consumption and increased work output[8].Mahmud et al. found that most of exergy destruction is in a boiler for a coal fired thermal power plant [9]. Maghsaudi et al. investigated energy and exergy efficiencies in a coal fired power plant and found that energy loss is critical in condenser and exergy loss is mostly in boiler [10]. Kaviri et al. modeled a combined cycle thermodynamically and optimized the cycle with multiple objectives. First set of objectives include factors such as cost while second set concentrated on cycle exergy [11].A detailed review of power plants fired by coal and gas has been presented by Kaushik et al. Component wise formulations for energy and exergy calculations are detailed by them [12]. Ahmadi et al. used evolutionary algorithm for a multi objective optimization of combined cycle power plant. Three objectives were considered for optimization namely exergy efficiency, cost rate of system product and cost rate of environmental impact. Effect of supplementary firing oncycle efficiency was also studied [13]. Gulen and Smith proposed a simple relation for finding out maximum achievable output of Rankine Bottoming cycle from exhaust exergy [14]. Regulagadda et al. conducted a parametric study on a coal fired power plant and found out that turbine and boiler irreversibilities yield highest exergy losses [15]. Aljundi conducted a component wise modeling and detailed break-up of energy and exergy losses were considered for a steam power plant. The effect of variation of reference environment on this analysis was also presented [16]. Sanjay et al. conducted a parametric study on exergy losses on a closed-loop-steam-cooled gas turbine. Effect of re-heat pressure on maximum plant efficiency was also studied [17].

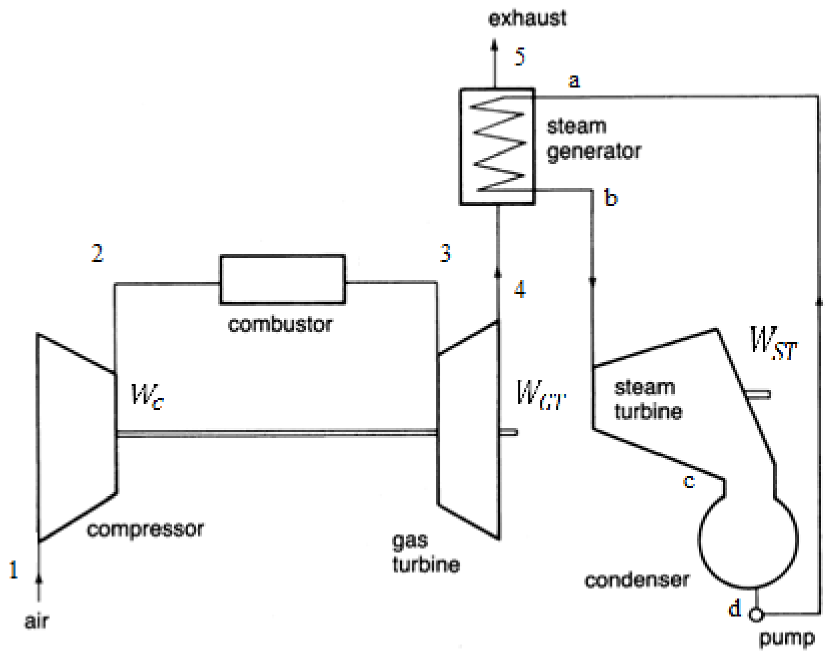

Fig 1. Combined Cycle Power Plant

Thermodynamic Modelling

Thermodynamic modelling of various components was done as below.

The Gas cycle or Brayton cycle consists of multi-stage axial compressor, combustion chamber and Gas Turbine which drives the compressor.

1. Compressor:

$$T_2 = T_1 \times (r_p)^{\frac{\gamma-1}{\gamma}}$$
$$P_2 = P_1 \times r_p$$
$$W_c = \dot{m_{air}} \times (h_2 - h_1)$$

Energy Analysis:

$$-W_c = \dot{m}_a(h_1 - h_2) - Energy\ Losses$$
$$Energy\ Losses = \dot{m}_a(h_2 - h_1) + W_c$$
$$\eta_{1,COMP} = 1 - \frac{Energy\ loss}{W_c} = \frac{\dot{m}_a(h_2 - h_1)}{W_c}$$

Exergy Analysis:

$$\psi_1 = (h_1 - h_0) - T_0(s_1 - s_0)$$
$$\psi_2 = (h_2 - h_0) - T_0(s_2 - s_0)$$
$$-W_c = \dot{m_{air}}(\psi_2 - \psi_1) - T_o\dot{S}_{gen}$$
$$T_o\dot{S}_{gen} = \dot{m_{air}}(\psi_2 - \psi_1) + W_c$$
$$\dot{S}_{gen} = \dot{m_{air}}(S_2 - S_1)$$
$$\dot{I}_{destroyed} = T_0\dot{S}_{gen} = T_0[\dot{m_{air}}(S_2 - S_1)]$$
$$\eta_{II,COMP} = 1 - \frac{\dot{I}_{destroyed}}{W_c} = \frac{T_0[\dot{m_{air}}(S_2 - S_1)]}{W_c}$$

2. Combustion Chamber

Energy Analysis:

$$0 = \sum_{k=1}^{r}\left[(\dot{m}h)_{fuel+air} - (\dot{m}h)_{products}\right]_k$$
$$\eta_{1,CC} = 1 - \frac{Energy\ loss}{Energy\ Input} = 1 - \frac{Energy\ loss}{(\dot{m}h)_{fuel+air}} = \frac{(\dot{m}h)_{products}}{(\dot{m}h)_{fuel+air}}$$

Exergy Analysis:

$$0 = \sum_{k=1}^{r}\left[(\dot{m}\psi)_{fuel+air} - (\dot{m}\psi)_{products}\right] - T_0\dot{S}_{gen}$$
$$T_0\dot{S}_{gen} = \left[(\dot{m}\psi)_{fuel+air} - (\dot{m}\psi)_{products}\right]$$
$$\eta_{II,CC} = \frac{Exergy\ output}{Exergy\ input} = 1 - \frac{Exergy\ loss}{Exergy\ input} = 1 - \frac{T_0[\dot{S}_{gen}]}{(\dot{m}\psi)_{fuel+air}} = \frac{(\dot{m}\psi)_{products}}{(\dot{m}\psi)_{fuel+air}}$$

3. Gas Turbine

Energy Analysis:

$$W_{GT} = \dot{m_{products}}(h_4 - h_3) - Energy\ loss$$
$$Energy\ loss = \dot{m_{products}}(h_4 - h_3) - W_{GT}$$
$$\eta_{1,GT} = 1 - \frac{Energy\ loss}{Energy\ Input} = 1 - \frac{Energy\ loss}{\dot{m_{products}}(h_4 - h_3)} = \frac{W_{GT}}{(\dot{m}h)_{fuel+air}}$$

Exergy Analysis:

$$W_{GT} = \dot{m_{products}}(\psi_4 - \psi_3) - T_0\dot{S}_{gen}$$
$$T_0\dot{S}_{gen} = \dot{m_{products}}(\psi_4 - \psi_3) - W_{GT}$$
$$\dot{S}_{gen} = \dot{m_{products}}(S_4 - S_3)$$
$$I_{destroyed} = T_0\dot{S}_{gen} = T_0\dot{m_{products}}(S_4 - S_3)$$
$$\eta_{II,GT} = 1 - \frac{\dot{I}_{destroyed}}{\dot{m_{products}}(\psi_4 - \psi_3)} = \frac{W_{GT}}{\dot{m_{products}}(\psi_4 - \psi_3)}$$

4. Heat Recovery Steam Generator

Energy Analysis:

$$0 = \dot{m_{products}}(h_4 - h_5) - \dot{m_{water}}(h_b - h_a) - Energy\ loss$$

$$\eta_{1,BOILER} = 1 - \frac{Energy\ loss}{Energy\ Input} = 1 - \frac{Energy\ loss}{\dot{m}_{products}(h_4 - h_5)} = \frac{\dot{m}_{water}(h_b - h_a)}{\dot{m}_{products}(h_4 - h_5)}$$

Exergy Analysis:

$$0 = \dot{m}_{products}(\psi_4 - \psi_5) - \dot{m}_{steam}(\psi_b - \psi_a) - T_0\dot{S}_{gen}$$

$$\dot{S}_{gen} = \dot{m}_{steam}\ (S_b - S_a)$$

$$T_0\dot{m}_{steam}\ (S_b - S_a) = \dot{m}_{products}(\psi_4 - \psi_5) - \dot{m}_{steam}(\psi_b - \psi_a)$$

$$\eta_{II,HRSG} = 1 - \frac{\dot{I}_{destroyed}}{\dot{m}_{products}(\psi_4 - \psi_5)} = \frac{\dot{m}_{steam}(\psi_b - \psi_a)}{\dot{m}_{products}(\psi_4 - \psi_3)}$$

5. Steam turbine:

Energy Analysis:

$$W_{ST} = \dot{m}_{steam}(h_b - h_c) - Energy\ loss$$

$$Energy\ loss = \dot{m}_{steam}(h_b - h_c) - W_{ST}$$

$$\eta_{1,ST} = 1 - \frac{Energy\ loss}{Energy\ Input} = 1 - \frac{Energy\ loss}{\dot{m}_{steam}(h_b - h_c)} = \frac{W_{ST}}{\dot{m}_{steam}(h_b - h_c)}$$

Exergy Analysis:

$$W_{ST} = \dot{m}_{steam}(\psi_d - \psi_c) - T_0\dot{S}_{gen}$$

$$T_0\dot{S}_{gen} = T_0\dot{m}_{steam}\ (S_d - S_c)$$

$$\dot{I}_{destroyed} = T_0\dot{S}_{gen} = T_0\dot{m}_{steam}\ (S_d - S_c)$$

$$\eta_{II,ST} = 1 - \frac{\dot{I}_{destroyed}}{\dot{m}_{steam}(\psi_d - \psi_c)} = \frac{W_{ST}}{\dot{m}_{steam}(\psi_d - \psi_c)}$$

6. Condenser

Energy Analysis:

$$0 = \dot{m}_{steam}(h_c - h_d) - Q_{rejected} - Energy\ loss$$

$$Energy\ loss = \dot{m}_{steam}(h_c - h_d) - Q_{rejected}$$

$$\eta_{1,COND} = 1 - \frac{Energy\ loss}{Energy\ Input} = 1 - \frac{Energy\ loss}{\dot{m}_{steam}(h_c - h_d)} = \frac{Q_{rejected}}{\dot{m}_{steam}(h_b - h_c)}$$

Exergy Analysis:

$$0 = \dot{m}_{steam}(\psi_a - \psi_d) - T_o\dot{S}_{gen} - \sum_{k=1}^{n}\left(1 - \frac{T_0}{T_k}\right)Q_k$$

$$T_0\dot{S}_{gen} = \dot{m}_{steam}(\psi_a - \psi_d) - \sum_{k=1}^{n}\left(1 - \frac{T_0}{T_k}\right)Q_k$$

$$\dot{I}_{destroyed} = T_0\dot{S}_{gen} = [\dot{m}_s(h_a - h_d) - T_0\{\dot{m}_s(s_a - s_d)\}] - \sum_{k=1}^{n}\left(1 - \frac{T_0}{T_k}\right)Q_k$$

$$\eta_{II,COND} = 1 - \frac{\dot{I}_{destroyed}}{\dot{m}_s(\psi_a - \psi_d)}$$

7. Pump

Energy Analysis:

$$-W_{PUMP} = \dot{m}_{steam}(h_a - h_d) - Energy\ loss$$

$$Energy\ loss = \dot{m}_{steam}(h_a - h_d) + W_{PUMP}$$

$$\eta_{1,PUMP} = 1 - \frac{Energy\ loss}{Energy\ Input} = 1 - \frac{Energy\ loss}{W_{PUMP}} = \frac{\dot{m}_{steam}(h_a - h_d)}{W_{PUMP}}$$

Exergy Analysis:

$$-W_{PUMP} = \dot{m}_{steam}(\psi_b - \psi_a) - T_0\dot{S}_{gen}$$

$$\dot{I}_{destroyed} = T_0\dot{S}_{gen} = \dot{m}_{steam}(\psi_b - \psi_a) + W_{PUMP}$$

$$\eta_{II,PUMP} = 1 - \frac{\dot{I}_{destroyed}}{W_{PUMP}} = \frac{\dot{m}_{steam}(\psi_b - \psi_a)}{W_{PUMP}}$$

Parametric Study on Gas Turbine cycle using EES

The thermodynamic modelling of combined cycle was done in Engineering Equation Solver (EES).

Net work done by Gas Turbine Cycle

$W_{Net,GT} = W_{GT} - W_C$

Heat added, Q = $m_f \times LHV = (m_{air} + m_{fuel})(h_3) - (m_{air}.h_2)$

$$\eta_{cycle} = \frac{W_{Net,GT}}{Q}$$

Effect of Mass Flow of Air to Compressor on Exergetic Efficiency of Gas Turbine and overall cycle thermal efficiency

The model simulated in EES was run for different air flow rates and different TITs. The variation is demonstrated below. The exergetic efficiency as well as thermal efficiency of combined cycle increases with TIT and mass flow rate.

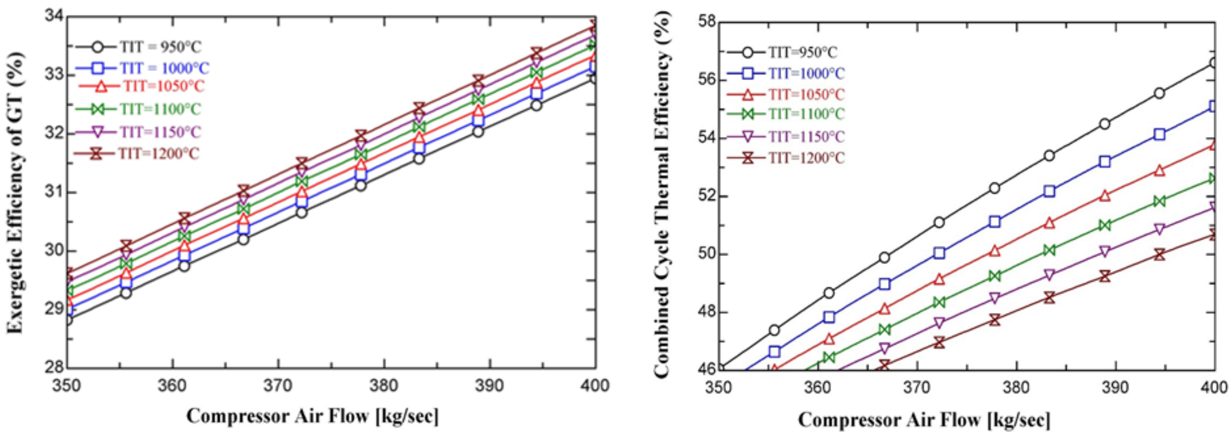

Figure 2. Exergetic Efficiency and Combined cycle thermal efficiency vs Air Flow

Effect of Temperature of Inlet Air to Compressor on Exergetic Efficiency of Gas Turbine and overall cycle thermal efficiency

The variation of exergetic efficiency with inlet air temperature for various gas flows is given below. The exergetic efficiency of gas turbine increases with increase in inlet temperature and increase in gas flow rate through the turbine. But on the other hand the thermal efficiency of cycle decreases with inlet air temperature and increases as gas flow rate increases.

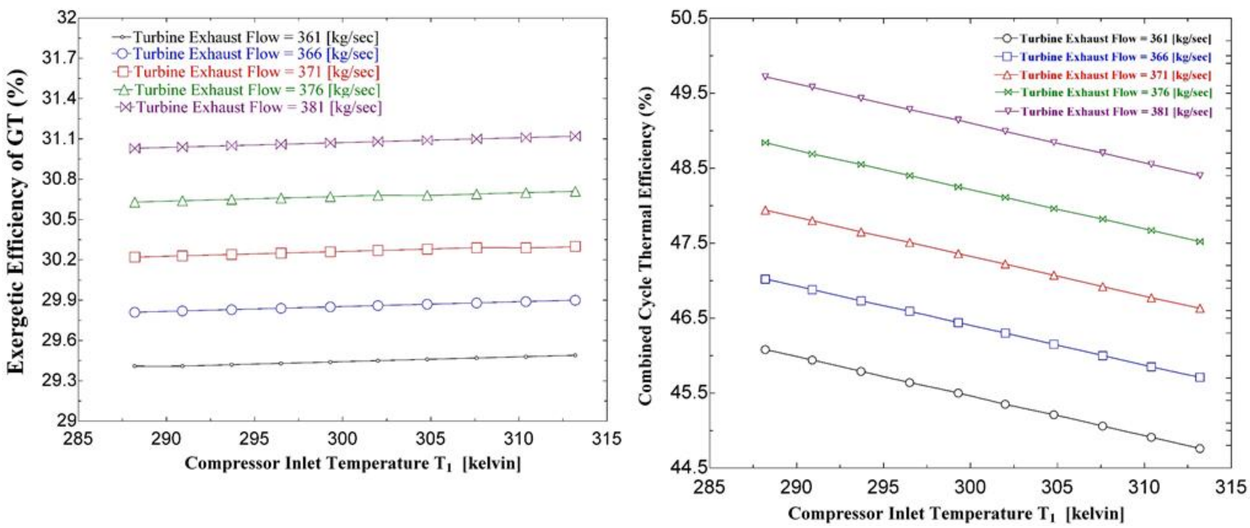

Figure 3. Exergetic Efficiency and Combined cycle thermal efficiency vs Inlet Temperature

Effect of Air Fuel Ratio on Exergetic Efficiency of Gas Turbine and overall cycle thermal efficiency

As air-fuel ratio increases the exergetic efficiency decreases. The exergetic efficiency also decreases with decrease in gas flow rate. On the other hand the thermal efficiency of cycle increases with increase in air fuel ratio and gas flow rates.

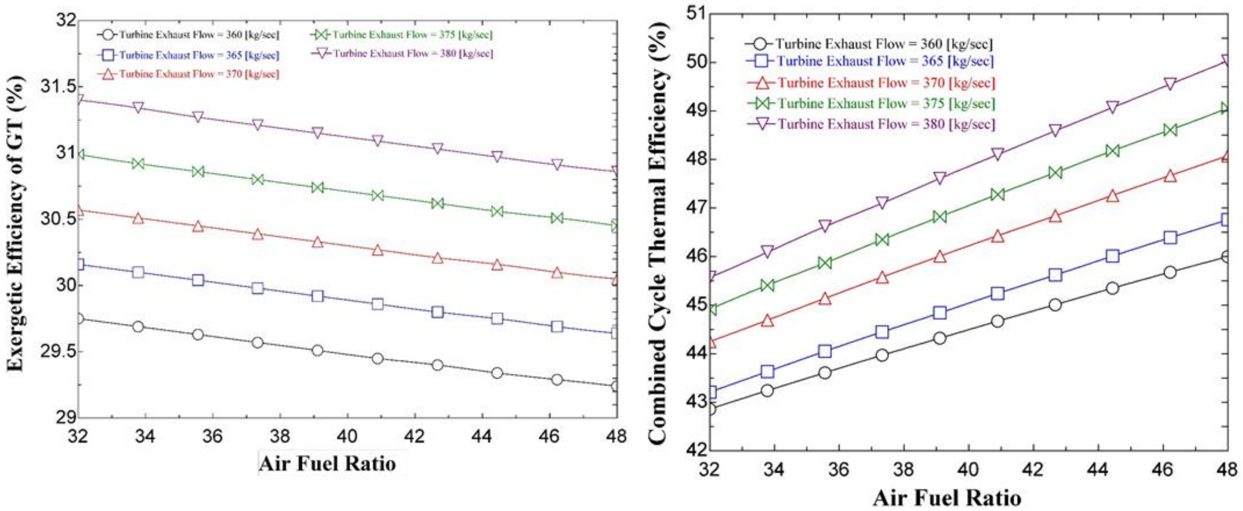

Figure 4. Exergetic Efficiency and Combined cycle thermal efficiency vs Air Fuel Ratio

Effect of Cycle Pressure Ratio on Exergetic Efficiency of Gas Turbine and overall cycle thermal efficiency

The exergetic efficiency of gas turbine decreases with increase in pressure ratio. As the TIT increases it is evident that the exergetic efficiency also increases. The thermal efficiency of combined cycle increases with increase in pressure ratio.

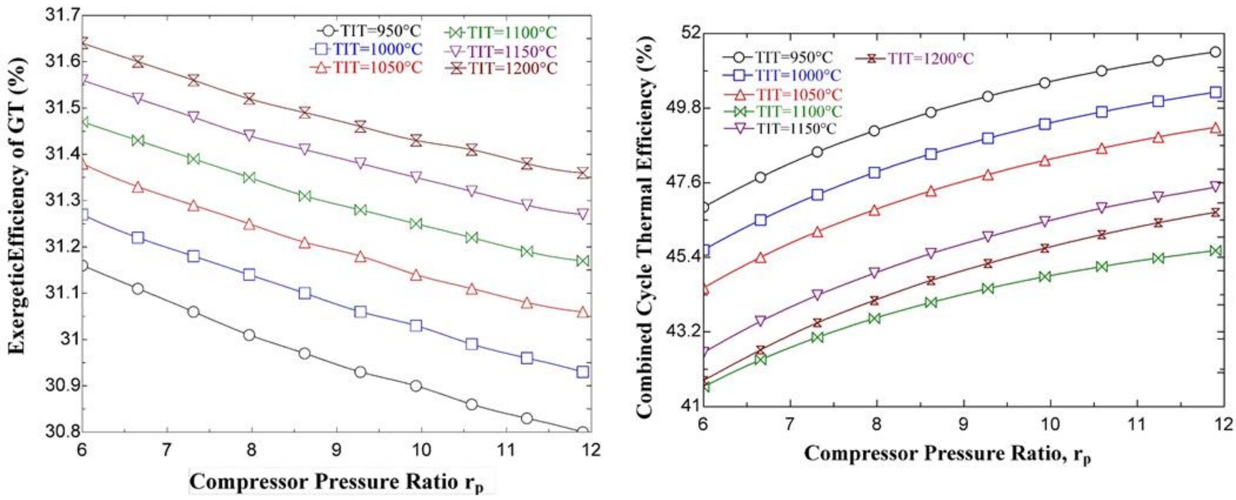

Figure 5. Exergetic Efficiency and Combined cycle thermal efficiency vs Pressure ratio

Conclusion

The variation of exergetic efficiency of gas turbine for different operating parameters were analysed. The efficiency is found to vary from 33.8 to 28.7 and combined cycle thermal efficiency varies between 42 and 55 as various parameters are varied.

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