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Performance Analysis of Coal Based KWU Designed Thermal Power Plants using Actual Data at Different Load Conditions

R. B. Chokshi[1*], Neeraj K. Chavda[2], Dr. A. D. Patel[3]**

[1] *Ph. D. Scholar, CHARUSAT University, Changa-388421, India.*
[1]*Mechanical Engineering Department, A. D. Patel Institute of Technology, New Vallabh Vidyangar-388121, Dist: Anand, Gujarat, India*
[2] *Associate Professor, Mechanical Engineering Department, A. D. Patel Institute of Technology, New Vallabh Vidyangar, Gujarat, India.*
*** ORCID : 0000-0001-6250-1810*
[3] *Principal, C. S. Patel Institute of Technology, CHARUSAT University, Changa-388 421, Gujarat, India.*
**Corresponding Author E mail: rajeshbchoksi@yahoo.com*

Abstract

Most of coal-based thermal plants having KWU design and 210 MW capacity are in operation since many years in India. On the basis of actual sets of operational parameters from different TG sets, energy and exergy performance is evaluated and analyzed for TG cycle of power plant at three ranges of operating load between 75 % to 100 % of full capacity of generating load to understand the actual performance for its improvement. Energy and exergy analysis together give complete picture of performance and also indicate the location along with scope of improvement. This analysis revealed that if the condition of TG set along with its major components and proper operating parameters are well maintained, better performance can be achieved even in middle and low load ranges in existing TG sets running since more than 20 years. Moreover, it is observed that the performance of a boiler has major influence on overall plant performance as boiler is found with maximum exergy destruction share in overall exergy destruction.

Keywords: Coal-based Thermal Power Plant, 210MW Capacity, Energy, Exergy, Exergy destruction, Irreversibility

Nomenclature

h	Enthalpy
m	Mass Flow Rate
P	Power Supplied
S	Entropy
BHEL	Bharat Heavy Electriccals Limited
Cp	Specific Heat
DM	De-mineralized
DS	Dead State
ED	Exergy Destruction
Ex	Exergy
GCV	Gross Calorific Value
GE	General Electric
IR	Irreversibility
KWU	Kraft Werk Union
LMZ	Leningradsky Metallichesky Zavod
T,t	Temperature
TG	Turbo Generator
TGS	Turbo Generator Set
W	Work Done
η	Efficiency
Subscript	
i	i^{th} component
0	Deadstate
cw	Cooling Water (Circulating Water)
f	Fuel
fw	Feed Water
g	Generation
I	First Law Efficiency
II	Second Law Efficiency
in	Inlet Condition
isen	Isentropic
out	Outlet Condition

INTRODUCTION

Energy is essential for all economic activities carried out in a country. One of the parameters to measure the growth of any country is energy consumption. Power consumption is directly related to power generation. As per the data provided in [1], the installed capacity of India is 329205 MW as in April, 2017. For the year 2016-2017 plant load factor observed was 60 %, about 61 % of the power was generated using thermal route and approximately 59 % of power was generated using coal as a fuel. Majority of the power is generated using coal-based thermal power plants in India.

Looking at the history of power generation in India, the growth of power generation has increased after the independence. The power plants of capacity ranging from 10 MW to 67.5 MW were installed by 1960s in various parts of India. The G. E. make 67.5 MW single cylinder turbo-generators are still operational in many power stations. With the advancement in technology and requirement in power intensive industries, machines of capacity ranging from 100 MW to 140 MW of Polish, French, British and German designs were installed during 1970-80s. Later on BHEL adopted the technology for manufacturing 210 MW steam turbines from LMZ, USSR. Many power plants have been installed with C. E. design boiler and LMZ design 210 MW turbines during 1980-90s. The design consists of one high pressure, one intermediate pressure and one low pressure turbine having flow of steam in single direction. In the late 1980s, KWU (Siemens), West Germany modified LMZ design by using double flow of steam in low pressure turbine having higher efficiency of the plant. Therefore, BHEL collaborated with KWU (Siemens) for installing power plants having capacity of 120 MW to 500 MW in India. However, KWU design having 210 MW capacity was preferred by most of state electricity boards and private power companies. With the increase in demand of the power, 500 MW plants and supercritical power plants have been installed. Yet majority of the power plants in India are operating with 210 – 250 MW capacity turbo-generator having KWU design. Since the plants have been installed, they are continuously operated in different states of India. Therefore, it is essential to evaluate and analyze the thermal performance of each of the components of the plant and if possible to modify as per the requirements to increase the thermal performance of the plant.

Thermal performance of a power plant can be analyzed on the basis of the efficiency calculated using two approaches viz. (1) first law efficiency which is known as energy efficiency and (2) second law efficiency popularly termed as exergy efficiency. Traditionally, energy efficiency of a system is evaluated on the basis of the heat balance of the system. Energy efficiency of any system is calculated based on the first law of thermodynamic which only focuses on the quantity of energy lost from the system. For example, when considering a thermal power plant cycle, the first law efficiency is defined as the proportion of the net work done by the cycle and the heat input to the cycle. Hence, for accurate identification of the loss of energy, along with the external loss of energy (quantity of energy) internal loss of energy (quality of energy) should be taken into consideration during analysis. Exergy analysis which is based on the second law of thermodynamics and which considers both the ‘‘quality’’ and the ‘‘quantity’’ of energy is important for analyzing any thermal system. Exergy efficiency is defined as the ratio of useful exergy from the system to total exergy to the system. Exergy is defined as the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment by means of processes in which the system interacts only with this environment. The thermodynamic analysis of the system carried out on the basis of the exergy allows us to assess the exact point of inefficiencies and compare different thermal systems. Although exergy analysis approach is more robust as compared to energy analysis, both the methods should be used. Energy analysis provides an initial glimpse of efficiencies, while exergy analysis should be used as a tool for more detailed investigation of the imperfections in thermal systems.

Enrico Sciubba and Goran Wall [2] in 2007 have published an exhaustive review of literature based on 2600 literatures related to history, development and application of exergy analysis to various systems. They reported that Gibbs (1973) who had defined the thermodynamic function “available energy” was the first person to explicitly introduce the notion of available work including the diffusion term and at a scientific meeting in 1953, the Slovenian Zoran Rant suggested that the term exergy (in German Exergie) should be used to denote technical working capacity. They looked into a future where exergy analysis will be a part of any system analysis and will be combined with the other methods for better understanding of the system.

Exergy analysis of a thermal power plant gives us the complete insight of the plant. A thermal power plant is operated continuously under different circumstances such as shortage of fuel, sudden change in demand, sudden change in operating conditions, etc. at various loads other than the design load. Therefore, it becomes essential to know the energetic and exergetic performance of different components and plants at the operating loads. It may be also possible that by changing one or two parameters at that operating load, energetic and exergetic performance of the system may improve. It seems essential to know the energetic and exergetic performance of the plant at various loads and the effect of critical parameters on them. Instant calculation of energetic and exergetic performance of the plant when change in plant operating load is going on and set the parameters as per the calculated energetic and exergetic performance of the plant is essential which can be implemented through various techniques of artificial intelligence.

The exergy analysis of thermal power plants began from 1970s. In the last decade, this method has been widely applied to a wide range of thermal power plants. The review of studies related to exergy analysis of 200 to 300 MW capacity thermal power plants has been carried out and presented in Table 1.

Table 1. Review of Literatures related To Exergy Analysis of 200 to 300 MW Capacity Thermal Power Plants

Sr. No.	Name of Researchers (Year)	Capacity, Design	Parameters Studied	Component Studied	Data	IPT
1	Geng Liu et. al. (1993) [3]	267 MW, NA	Energy and Exergy Efficiency	Boiler, HPT, Reheater, IPT, LPT, Condenser, CEP,GCS, DC, LPH 1, LPH 2, LPH 3,LPH4, Deaerator, BFP, HPH 5 and HPH 6	Data Provided by Power Plant	Single Flow, Coal
2	G. P. Verkhivker and B. V. Kosoy (2001) [4]	232.6 MW, NA	Energy and Exergy Efficiency	NA	NA	NA
3	S. Sengupta et al. (2007) [5]	210 MW, NA	Energy Efficiency, Exergy Efficiency.	Boiler, HPT, Reheater, IPT, LPT, Condenser, CEP, LPH 1, LPH 2, LPH 3, Deaerator, BFP, HPH 5 and HPH 6	Design Data at 40 %, 60 %, 80 % and 100 % Load	Single Flow, Coal
4	Hasan Huseyin Erdem et. al. (2009) [6]	210 MW, NA	Energy and Exergy Efficiency	Boiler, HPT, Reheater, IPT, LPT, Condenser, CEP, LPH 1, LPH 2, LPH 3, LPH4, LPH5, Deaerator, BFP, HPH 5, HPH 6 and HPH7	Data Provided by Power Plant	Single Flow, Lignite
5	Mohammad Ameri et al. (2009) [7]	250 MW, NA	Energy and Exergy Efficiency	Boiler, HPT, Reheater, IPT, LPT,Condenser, CEP, LPH 1, LPH 2, LPH 3, LPH 4, LPH 5, Deaerator, BFP, HPH 5, HPH 6 and HPH 7	NA	Single Flow, Natural Gas
6	V. Siva Reddy et al. (2011) [8]	210 MW, NA	Energy Efficiency, Exergy Efficiency.	As Per Sr. No. 5	100 % Load Design Data	Single Flow, Coal with Solar
7	Amirabedin Ehsan and M. Zeki Yilmazoglu (2011) [9]	240 MW, NA	Energy Efficiency, Exergy Efficiency,	As Per Sr. No. 3 + LPH 4, HPH 7, Cooling Tower, Air Preheater, Fan, Stack	Arbitrary data	Single Flow, lignite coal
8	R. Mahamud et al. (2013) [10]	280 MW, NA	Energy Efficiency, Exergy Efficiency,	Boiler, HPT, Reheater, IPT, LPT, Condenser, CEP, LPH 1, LPH 2, LPH 3, Deaerator, BFP, HPH 5 and HPH 6	Data Provided by Power Plant	Double Flow, Coal
9	Varun Goyal et al. (2014) [11]	210 MW, NA	Energy Efficiency, Exergy Efficiency,	As Per Sr. No. 3	Actual Data of Power Plant	Double Flow, Coal
10	Shailendra Pratap Singh and Vijay Kumar Dwivedi (2014) [12]	210 MW, LMZ	Energy Efficiency, Exergy Efficiency.	As Per Sr. No. 3 + Gland Cooler, Cold Reheat, Ejector, LPH 4, HPH 7	Not Available	Single Flow, Bituminous Coal
11	Muhib Ali Rajper et al. (2016) [13]	210 MW, NA	Energy Efficiency, Exergy Efficiency.	As Per Sr. No. 3 + LPH 4, HPH 7	Design Data of 200 MW	Single Flow, Oil and Gas
12	Gholam Reza Ahmadi and Davood Toghraie, (2016) [14]	200 MW, NA	Energy Efficiency, Exergy Efficiency.	As Per Sr. No. 3 + Gland Cooler, Gland Compressor, CEP2, Cold Reheat, Ejector, LPH 4, HPH 7	Design Data	Single Flow, Natural Gas

NA : Not Available

Geng Liu et al. [3] in 1993 have numerically investigated energy and exergetic efficiency of 267 MW steam power plant using data provided by the Sierra Pacific Power Company. They reported that (1) combustion, heat transfer inside the boiler and conversion of thermal energy to electricity are responsible for most of the exergy destruction followed by condenser and (2) second law analysis is a powerful tool of thermodynamic research for power plants and other thermal systems. G. P. Verkhivker and B. V. Kosoy [4] in 2001 have analyzed the performance of a conventional power plant of 232.6 MW capacity using exergy analysis. They reported that reduction in exergy destruction is achieved by increasing the value of thermodynamic parameters of working fluid supplied to the turbine and by reducing the temperature differences of the net heaters.

S. Sengupta et al. [5] in 2007 have carried out an exergy analysis of 210 MW coal-based thermal power plant with design data at different operating conditions. They observed that exergy destruction is maximum (almost 60 %) in boiler at all loads under study. They also reported that (1) At reduced load, throttling of control valves increases the exergy destruction and its increase is more at lower load, (2) Condenser pressure has little influence on the exergy efficiency of the turbo-generator, (3) Exergy efficiency decreases when high pressure heaters are withdrawn and (4) At part load, less throttling at the control valves with sliding pressure mode of operation helps to reduce exergy destruction in the plant. Hasan Huseyin Erdem et al. [6] in 2009 have analyzed comparatively the performance of nine thermal power plants under control central governmental bodies in Turkey, from energetic and exergetic viewpoint. Out of them capacity of one power plant, i.e. Orhaneli power plant is 210 MW. Based on comparative analysis they reported that (1) the most two important performance criteria in terms of exergetic analysis are exergy efficiency and exergetic performance coefficient, (2) exergetic performance of the power plants increases with reduction in the exergetic performance coefficient and increment of exergy efficiency and (3) boilers are vital components needed to be investigated principally for enhancing plants' overall exergetic performance.

Mohammad Ameri et al. [7] in 2009 have performed the energy, exergy and exergoeconomic analysis for the Hamedan steam power plant working on natural gas as fuel and having capacity of 250 MW at different load. They concluded that (1) when the ambient temperature is increased from 5 to 24 ^{O}C, the irreversibility rate of the boiler, turbine, feed water heaters, pumps and the total irreversibility rate of the plant increases, (2) as the load varies from 125 to 250 MW (i.e. full load) the exergy efficiency of the boiler and turbine, condenser and heaters increases and (3) the boiler has the highest cost of exergy destruction. V. Siva Reddy et al. [8] in 2011 have carried out exegetic analysis of 210 MW coal fired power plant with and without solar aided feed water heater (SAFWH) using design data. They observed (1) An instantaneous increase in power generation capacity of about 35% by substituting turbine bleed streams to all the low and high pressure feed water heaters with SAFWH, (2) Consumption of coal is increased by 3.5 % for reheat of steam by replacement of high pressure feed water heaters with SAFWH, (3) With SAFWH in coal fired thermal power plant, energetic efficiency decreases from 34.19% to 31.81% & exergetic efficiency increases from 32.47% to 35.73%.

Amirabedin Ehsan and M. Zeki Yilmazoglu [9] in 2011 have designed a thermal power plant and performed an exergy analysis of 240 MW thermal power plant using arbitrary data. They have also modeled the plant under study assuming various types of Turkish lignite coal as a fuel in the power plant. They found that (1) main exergy destruction takes place in the boiler with an exergetic efficiency of 83.29% and (2) increasing ambient temperature causes an increase in fuel consumption and consequently diminishes the exergetic efficiency. R. Mahamud et al. [10] in 2013 have carried out exergy analysis of 240 MW coal fired thermal power plant in Queensland using data provided by the plant. They reported that (1) the boiler of a subcritical power generation plant is the major source of useful energy lost, (2) there are opportunities to improve energy efficiency of power plants by improving the performance of the boilers and the turbine system, and (3) in order to achieve significant improvement in energy efficiency the boiler and turbine systems need to be altered and the current trends towards ultra-supercritical power plant cycles are consistent with this aim.

Varun Goyal et al. [11] in 2014 have evaluated energy and exergetic performance of 210 MW thermal power plant using data collected during actual operation of the plant. They concluded that a boiler is the source of major irreversibility rather than condenser and approximately 42 % of exergy is lost in boiler. Shailendra Pratap Singh and Vijay Kumar Dwivedi [12] in 2014 have investigated the effect of ambient temperatures (278 to 318 K in step of 5 K) on exergetic performance of 210 MW fossil fuel based thermal power plant. They reported that (1) increase in ambient temperature decreases exergetic performance of the plant from 83.83 % to 82.55 % and increases irreversibility from 39.52 to 41.42 MW due to turbines and (2) increase in ambient temperature by 1 ^{O}C increases total irreversibility rate of the plant by 0.047 MW.

Muhib Ali Rajper et al. [13] in 2016 have prepared a model of 210 MW dual fire thermal power plant using design data of 200 MW using EES software and validated the model data supplied by the manufacturer. The model has been then employed to carry out parametric analysis in order to evaluate the effect of condenser pressure, main steam pressure and temperature on energy and exergetic efficiency of the thermal power plant. They concluded on the basis of parametric analysis that the performance improves with an increase in the main steam pressure and temperature as well, whereas it decreases with an increase in condenser pressure. Gholam Reza Ahmadi and Davood Toghraie [14] in 2016 have investigated the energy and energetic performance of 200 MW thermal power plant. They reported that (1) for each 0.01 bar increase in condenser pressure approximately 0.7 MW power generation is reduced, (2) by increasing the condenser pressure from 0.09 bar to 0.32 bar the load unit reduced from 200 MW to 183.7 MW and (3) the boiler covers the major part of exergy loss. They have also reported several suggestions with positive effects on improving power plant efficiency and saving energy consumption.

The review of literature reveals that most of coal-based thermal plants having KWU design and 210 MW capacity are in operation since many years. It is essential to evaluate and analyze the thermal performance of each component of the power plant to increase the performance. Exergy analysis based on second law of thermodynamics is the appropriate tool to evaluate and analyze the thermal performance of a power plant. Prediction of the exergetic performance of the power plant is essential when a power plant is operated at various loads to select the proper operating parameters and an artificial neural network is a powerful learning tool to predict the performance. It has also been observed that exergetic evaluation of coal-based thermal power plant of

KWU design and 210 MW capacity based on actual data of the plant at various operating loads and various environmental conditions and prediction of the exergetic performance of the plant under study have not been reported.

The objectives of this work are to evaluate and analyze the energetic and exergetic performance of the 210 MW coal-based thermal power plant of KWU design situated in Western Region of India using actual data of the power at various operating load conditions and to suggest remedies for improving the performance the plant.

THERMAL POWER PLANT

The plant under study is situated in the Western Region of India and has power generating units of LMZ and KWU design. The work was carried out on three KWU design units of the power plant. Each of these turbo-generator sets has a capacity of 210 MW, 3000 RPM, 15.75 KV, 247 MVA at 0.85 P.F. The required coal is received from the coal mines of the state of Bihar, Madhya Pradesh, Orissa, and West Bengal via railway. The main water sources for water make-up to power plant are river main canal and tube wells. Clarifier and DM plant are provided to remove the impurities from raw water to make the water suitable for the boiler. Each unit is equipped with Electro-Static Precipitator (ESP) which collects most of the ash from the flue gases liberated through chimney. The collected ash is disposed off in ash pond through an ash plant. Being coal-based thermal power station, it is provided with coal plant comprising of wagon tripplers, stacker-reclaimer and primary & secondary crusher houses. Each unit consists of six coal mills (each with a capacity of 39.6 T/H), two Force Draft (FD) fans, Air Pre Heaters (APHs), two Induced Draft (ID) fans, and two Primary Air (PA) fans. This pulverized coal coming from the coal mills is transported to the boiler along with primary air. The secondary air is supplied to the boiler by FD fans. The balanced draft is maintained by FD fans and ID fans. In the boiler, pulverized coal is fired from six elevations of burners located in each corner. The coal combustion takes place in the furnace, and the liberated heat is utilized to generate superheated steam from the water.

This work focuses on coal-based 210 MW KWU design turbine cycle which consists of a set of major components including a boiler, a High Pressure Turbine (HPT), an Intermediate Pressure Turbine (IPT), a Low Pressure Turbine (LPT), a condenser (surface type single shell, two pass), Condensate Extraction Pumps (CEPs), 3 Low Pressure Feed Water Heaters (LPHs), a deaerator, 2 Boiler Feed Pumps (BFPs) and 2 High Pressure Feed Water Heaters (HPHs).

The KWU steam turbine is a tandem compounded, three cylinders, single reheat, condensing turbine provided entirely with reaction blading. Being a coal-based thermal power plant (Overall designed plant energy efficiency 37.3%), the boiler utilizes bituminous coal (GCV 18410 KJ/Kg) as a fuel. The boiler generates superheated steam (690 T/H, 155 kg/cm2) and sends it to the HPT. Superheated steam (150 kg/cm^2 abs, 535 ^{0}C) enters the High Pressure Turbine (HPT) through two initial steam stop and control valves. HP cylinder has a throttle control. HPT comprises of 25 single flow stages. From HPT, Cold Reheat steam (CRH) (38.4 kg/cm2, 338.2 ^{0}C) goes for reheating in the boiler and after reheating Hot Reheat steam (HRH) (34.6 kg/cm2, 535 ^{0}C) enters IPT through two combined reheat stop and control valves. Intermediate Pressure Turbine (IPT) is a double flow turbine with 20 reaction stages per flow. From IPT the steam goes to double flow Low Pressure Turbine (LPT) with 8 reaction stages per flow. The steam from LPT gets exhausted to condenser at a back pressure of 0.1195 kg/cm^2 (48.6 ^{0}C). Extraction steam is bled from six bleeding points (3 extractions from LPT to LPH-1, LPH-2, and LPH-3 respectively, 2 extractions from IPT to deaerator and HPH-5 respectively, 1 extraction from HPT to HPH-6). The individual turbine rotors and the generator rotor are connected by rigid couplings. Cascaded backward is designed for drips obtained from LPHs. The final drip which is received from LPH-1 is provided to the condenser. Condensate is pumped with the help of CEPs and fed to the deaerator through LPH-1, LPH-2 & LPH-3. The temperature of feed water increases in these LPHs with the help of steam extraction taken from LPT. From deaerator, feed water is fed to HPH-5 & HPH-6 through BFPs. With further increase in temperature in HPHs with the help of steam extractions from IPT and HPT, feed water is finally fed to the economizer.

The layout of the plant is presented in Figure 1. The plant has three turbo-generator sets, i.e. TGS-1, TGS-2 and TGS-3. They are operated at various load conditions. Steady state online data from different turbo-generator sets have been extracted during actual operation of the plant at various load conditions. Extracted data for TGS-1, TGS-2 and TGS-3 have been presented in Table 2. The data also has been arranged in ascending order of operating load conditions and presented in Table 3.

PERFORMANCE EVALUATION OF THERMAL POWER PLANT

In a power plant, the major focus is on transforming maximum possible energy into useful work. In order to know where energy is lost in a system, energy analysis is carried out based on the first law of thermodynamics, which talks about conservation of energy. This first law of thermodynamics takes into consideration important factors like thermal efficiency and output power.

In this analysis, to evaluate the performance of the system, required values of parameters like pressure, temperature, mass flow rate, enthalpy, entropy etc. have been measured / calculated at inlets and outlets of plant components. Here, changes in kinetic and potential energy have been ignored. The aforesaid energy analysis suffers from some drawbacks: (1) It does not consider the system environment properties (2) It ignores degradation of energy quality and (3) It does not consider irreversibility of the system. Thus this energy analysis fails in providing a correct and comprehensive picture of system performance.

The second law of thermodynamics states that not all energy input is converted into useful work because of thermodynamic irreversibility. The part of energy that can be converted into maximum useful work is referred to as an Exergy. It is viewed as maximum theoretical possible work potential of a system that can be obtained from a system when its state is brought to reference dead state. Higher value of exergy indicates a greater value of obtainable work. Exergy is not conserved as energy. Exergy destruction indicates measure of irreversibility, and it is the source of performance loss. Exergy has four parts: (i) physical, (ii) chemical, (iii) kinetic, and (iv) potential. In this analysis, the kinetic exergy and potential exergy are not considered. It is worth noting that the exergy analysis does not replace energy analysis, but it complements it.

Exergy analysis is useful in identifying exergy destruction at various locations in the system. The exergy destruction indicates entropy generation which leads to inefficiency because of irreversibility. Exergy at any point can be calculated using the equation number 1. Energy, Exergy, Entropy Generation, Energy Efficiency, Exergy Efficiency, Exergy Destruction and Irreversibility of each component in a thermal power plant has been evaluated using the equations presented in Table 4.

Exergy at any point,

$$E_{x,i} = (h_i - h_0) - T_0 * (S_i - S_0) \ldots\ldots..(1)$$

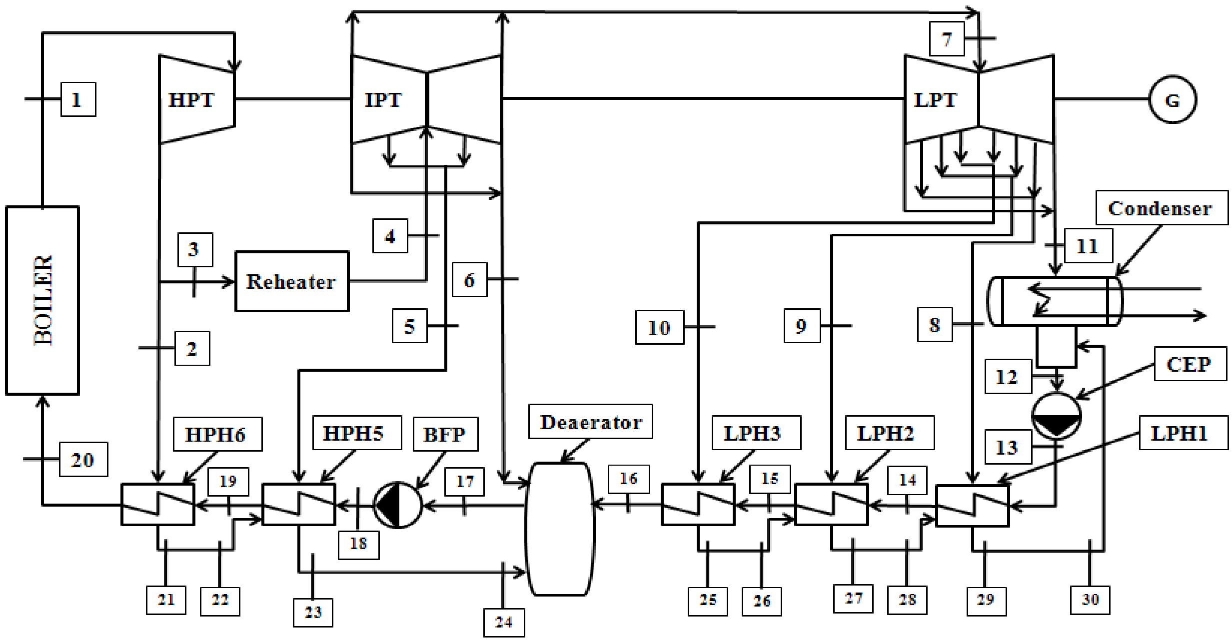


Figure 1. The Layout of the Thermal Power Plant

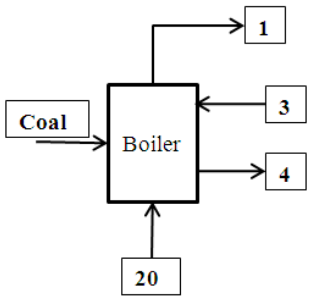
Table 2. Thermal Power Plant data arranged as per Turbo-Generator Sets

Unit wise Load of the Power Plant	Different Load Conditions of the Power Plant	Power Plant Load, in MW	Pressure of Steam at Turbine Inlet, in kg/cm2	Temp. of Steam at Turbine Inlet, OC	Mass Flow Rate of Steam at Turbine Inlet, kg/sec	Mass Flow Rate of Coal, in kg/sec	Gross Calorific Value of Coal, in kJ/kg
TGS1-L1	P1	209.44	150.4	541.3	179.6	38.61	16610.48
TGS1-L2	P5	184.07	151.6	540.8	161.6	34.68	16610.48
TGS1-L3	P9	159.82	149.7	533.2	140.0	30.14	16610.48
TGS2-L1	P3	208.75	148.9	534.3	183.2	37.96	16577.01
TGS2-L2	P7	171.29	151.4	525.2	151.0	29.51	16577.01
TGS2-L3	P8	163.85	151.2	536.5	145.8	31.90	16577.01
TGS3-L1	P2	209.35	149.4	532.8	183.7	39.18	16577.01
TGS3-L2	P4	204.01	153.2	544.7	181.2	35.94	16577.01
TGS3-L3	P6	178.27	152.4	545.2	157.5	33.89	16577.01
TGS3-L4	P10	159.33	150.8	533.0	142.2	29.22	16577.01

Table 3. Thermal Power Plant data arranged in ascending order of Operating Load Conditions

Different Load Conditions of the Plant	Power Plant Load, in MW	Pressure of Steam at HPT Inlet, in kg/cm^2	Temp. of Steam at HPT Inlet, ^oC	Mass Flow Rate of Steam at HPT Inlet, kg/sec	Mass Flow Rate of Coal, in kg/sec	Gross Calorific Value of Coal, in kJ/kg
P1	209.44	150.4	541.3	179.6	38.61	16610.48
P2	209.35	149.4	532.8	183.7	39.18	16577.01
P3	208.75	148.9	534.3	183.2	37.96	16577.01
P4	204.01	153.2	544.7	181.2	35.94	16577.01
P5	184.07	151.6	540.8	161.6	34.68	16610.48
P6	178.27	152.4	545.2	157.5	33.89	16577.01
P7	171.29	151.4	525.2	151.0	29.51	16577.01
P8	163.85	151.2	536.5	145.8	31.90	16577.01
P9	159.82	149.7	533.2	140.0	30.14	16610.48
P10	159.33	150.8	533.0	142.2	29.22	16577.01

Table 4. Equations to Evaluate Energy and Exergetic Performance of Various Components of the Thermal Power Plant



Energy:

$$(m_f \times GCV) + (m_{20} \times h_{20}) + (m_3 \times h_3) = (m_1 \times h_1) + (m_4 \times h_4)$$

Exergy:

$$\begin{pmatrix}\text{Coal}\\\text{Exergy}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\\text{Point 20}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\\text{Point 3}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\\text{Point 1}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\\text{Point 4}\end{pmatrix}$$

Entropy Generation:

$$S_{g,Boiler} = (m_1 S_1 + m_4 S_4) - (m_3 S_3 + m_{20} S_{20}) - \frac{m_f \times GCV}{T_{steam}}$$

Energy efficiency:

$$\eta_{I,Boiler} = \frac{\{(m_1 \times h_1) - (m_{20} \times h_{20})\} + \{(m_4 \times h_4) - (m_3 \times h_3)\}}{m_f \times CV} \times 100$$

Exergy Efficiency

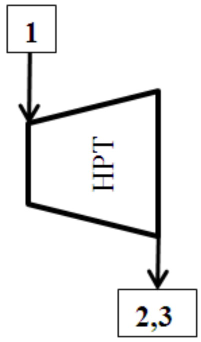
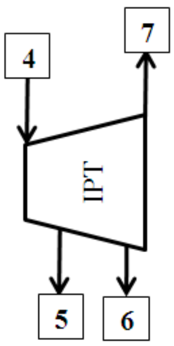
$$\eta_{II,Boiler} = \frac{\left\{\begin{pmatrix}\text{Exergy at}\\\text{Point 1}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\\text{Point 20}\end{pmatrix}\right\} + \left\{\begin{pmatrix}\text{Exergy at}\\\text{Point 4}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\\text{Point 3}\end{pmatrix}\right\}}{Exergy\ of\ Coal} \times 100$$

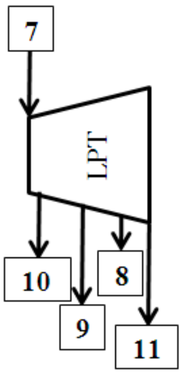
Exergy Destruction:

$$ED_{Boiler} = \left\{\begin{pmatrix}Exergy\\of\ Coal\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\\text{Point 20}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\\text{Point 3}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\\text{Point 1}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\\text{Point 4}\end{pmatrix}\right\}$$

Irrersibility:

$$IR_{Boiler} = T_0 \times S_{g,Boiler}$$

	Energy: $(m_1 \times h_1) = (m_2 \times h_2) + (m_3 \times h_3)$ Exergy: $\binom{\text{Exergy at}}{\text{Point 1}} = \binom{\text{Exergy at}}{\text{Point 2}} + \binom{\text{Exergy at}}{\text{Point 3}}$ Entropy Generation: $S_{g,HPT} = (m_2 S_2 + m_3 S_3) - (m_1 S_1)$ Energy efficiency: $\eta_{I,HPT} = \frac{\{(h_1) - (h_2)\}}{\{(h_1) - (h_{isen,2})\}} \times 100$ Exergy Efficiency $\eta_{II,HPT} = \frac{W_{HPT}}{\left\{\binom{\text{Exergy at}}{\text{Point 1}} - \binom{\text{Exergy at}}{\text{Point 2}} - \binom{\text{Exergy at}}{\text{Point 3}}\right\}} \times 100$ Exergy Destruction: $ED_{HPT} = \left\{\binom{\text{Exergy at}}{\text{Point 1}} - \binom{\text{Exergy at}}{\text{Point 2}} - \binom{\text{Exergy at}}{\text{Point 3}}\right\} - \{W_{HPT}\}$ $W_{HPT} = \left\{\binom{\text{Exergy at}}{\text{Point 1}} - \binom{\text{Exergy at}}{\text{Point 2}} - \binom{\text{Exergy at}}{\text{Point 3}}\right\} - \{DS \times S_{g,HPT}\}$ Irrersibility: $IR_{HPT} = T_0 \times S_{g,HPT}$
	Energy: $(m_4 \times h_4) = (m_5 \times h_5) + (m_6 \times h_6) + (m_7 \times h_7)$ Exergy: $\binom{\text{Exergy at}}{\text{Point 4}} = \binom{\text{Exergy at}}{\text{Point 5}} + \binom{\text{Exergy at}}{\text{Point 6}} + \binom{\text{Exergy at}}{\text{Point 7}}$ Entropy Generation: $S_{g,IPT} = (m_5 S_5 + m_6 S_6 + m_7 S_7) - (m_4 S_4)$ Energy efficiency: $\eta_{I,IPT} = \frac{m_5 \times \left\{\frac{h_4 - h_5}{h_4 - h_{isen,5}}\right\} + m_6 \times \left\{\frac{h_5 - h_6}{h_5 - h_{isen,6}}\right\} + m_7 \times \left\{\frac{h_6 - h_7}{h_6 - h_{isen,7}}\right\}}{m_4} \times 100$ Exergy Efficiency $\eta_{II,IPT} = \frac{W_{IPT}}{\left\{\binom{\text{Exergy at}}{\text{Point 4}} - \binom{\text{Exergy at}}{\text{Point 5}} - \binom{\text{Exergy at}}{\text{Point 6}} - \binom{\text{Exergy at}}{\text{Point 7}}\right\}} \times 100$ Exergy Destruction: $ED_{IPT} = \left\{\binom{\text{Exergy at}}{\text{Point 4}} - \binom{\text{Exergy at}}{\text{Point 5}} - \binom{\text{Exergy at}}{\text{Point 6}} - \binom{\text{Exergy at}}{\text{Point 7}}\right\} - \{W_{IPT}\}$ $W_{IPT} = \left\{\binom{\text{Exergy at}}{\text{Point 4}} - \binom{\text{Exergy at}}{\text{Point 5}} - \binom{\text{Exergy at}}{\text{Point 6}} - \binom{\text{Exergy at}}{\text{Point 7}}\right\} - \{DS \times S_{g,IPT}\}$ Irrersibility: $IR_{IPT} = T_0 \times S_{g,IPT}$



Energy:

$$(m_7 \times h_7) = (m_8 \times h_8) + (m_9 \times h_9) + (m_{10} \times h_{10}) + (m_{11} \times h_{11})$$

Exergy:

$$\begin{pmatrix}\text{Exergy at}\\ \text{Point 7}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix}$$

Entropy Generation:

$$S_{g,LPT} = (m_8 S_8 + m_9 S_9 + m_{10} S_{10} + m_{11} S_{11}) - (m_7 S_7)$$

Energy efficiency:

$$\eta_{I,LPT} = \frac{m_{10} \times \left\{\frac{h_7 - h_{10}}{h_7 - h_{isen,10}}\right\} + m_9 \times \left\{\frac{h_{10} - h_9}{h_{10} - h_{isen,9}}\right\} + m_8 \times \left\{\frac{h_9 - h_8}{h_9 - h_{isen,8}}\right\} + m_{11} \times \left\{\frac{h_8 - h_{11}}{h_8 - h_{isen,11}}\right\}}{m_7} \times 100$$

Exergy Efficiency

$$\eta_{II,LPT} = \frac{W_{LPT}}{\left\{\begin{pmatrix}\text{Exergy at}\\ \text{Point 7}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix}\right\}} \times 100$$

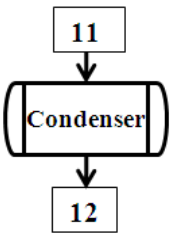
Exergy Destruction:

$$ED_{LPT} = \left\{\begin{pmatrix}\text{Exergy at}\\ \text{Point 7}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix}\right\} - \{W_{LPT}\}$$

$$W_{LPT} = \left\{\begin{pmatrix}\text{Exergy at}\\ \text{Point 7}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix}\right\} - \{DS \times S_{g,LPT}\}$$

Irrersibility:

$$IR_{LPT} = T_0 \times S_{g,LPT}$$



Energy:

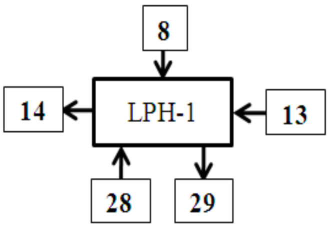
$$(m_{11} \times h_{11}) = (m_{12} \times h_{12})$$

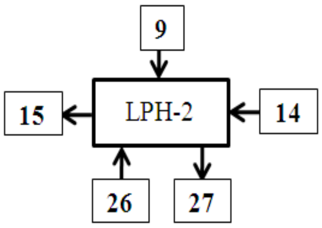
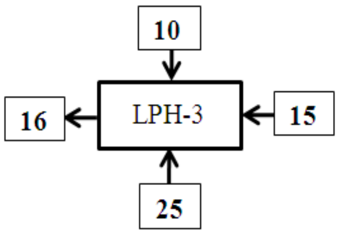
Exergy:

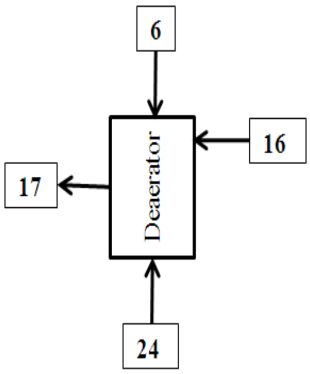
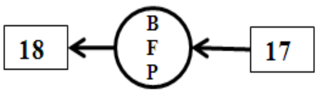
$$(\text{Loss of Exergy to cw}) = \begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 12}\end{pmatrix}$$

Entropy Generation:

$$S_{g,Condenser} = (m_{12} S_{12}) - (m_{11} S_{11}) + m_{cw} C_{p,cw} (t_{cw,out} - t_{cw,in})$$

	Energy efficiency: $\eta_{I,Condenser} = \frac{m_{11} \times (h_{11} - h_{12}) - m_{cw} \times C_{p,cw} \times (t_{cw,out} - t_{cw,in})}{m_{11} \times (h_{11} - h_{12})} \times 100$ Exergy Efficiency $\eta_{II,Condenser} = \frac{\begin{pmatrix}\text{Exergy of}\\ \text{cw, out}\end{pmatrix} - \begin{pmatrix}\text{Exergy of}\\ \text{cw, in}\end{pmatrix}}{\begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 12}\end{pmatrix}} \times 100$ Exergy Destruction: $ED_{Condenser} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 11}\end{pmatrix} + \begin{pmatrix}\text{Exergy of}\\ \text{cw, in}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 12}\end{pmatrix} - \begin{pmatrix}\text{Exergy of}\\ \text{cw, out}\end{pmatrix}$ Irrersibility: $IR_{Condenser} = T_0 \times S_{g,Condenser}$
	Energy: $(m_8 \times h_8) + (m_{13} \times h_{13}) + (m_{28} \times h_{28}) = (m_{14} \times h_{14}) + (m_{29} \times h_{29})$ Exergy: $\begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 13}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 28}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 14}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 29}\end{pmatrix}$ Entropy Generation: $S_{g,LPH1} = (m_{14}S_{14} + m_{29}S_{29}) - (m_8S_8 + m_{13}S_{13} + m_{28}S_{28})$ Energy efficiency: $\eta_{I,LPH1} = \frac{m_{13} \times C_{pf,w} \times (t_{14} - t_{13})}{m_8 \times (h_8 - h_{29}) + m_{28} \times (h_{28} - h_{29})} \times 100$ Exergy Efficiency $\eta_{II,LPH1} = \frac{\begin{pmatrix}\text{Exergy at}\\ \text{Point 14}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 13}\end{pmatrix}}{\begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 29}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 28}\end{pmatrix}} \times 100$ Exergy Destruction: $ED_{LPH1} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 8}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 13}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 14}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 29}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 28}\end{pmatrix}$ Irrersibility: $IR_{LPH1} = T_0 \times S_{g,LPH1}$
	Energy: $(m_9 \times h_9) + (m_{14} \times h_{14}) + (m_{26} \times h_{26}) = (m_{15} \times h_{15}) + (m_{27} \times h_{27})$

 	Exergy: $\begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 14}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 26}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 15}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 27}\end{pmatrix}$ Entropy Generation: $S_{g,LPH2} = (m_{15}S_{15} + m_{27}S_{27}) - (m_9S_9 + m_{14}S_{14} + m_{26}S_{26})$ Energy efficiency: $\eta_{I,LPH2} = \frac{m_{14} \times C_{p,fw} \times (t_{15} - t_{14})}{m_9 \times (h_9 - h_{27}) + m_{26} \times (h_{26} - h_{27})} \times 100$ Exergy Efficiency $\eta_{II,LPH2} = \frac{\begin{pmatrix}\text{Exergy at}\\ \text{Point 15}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 14}\end{pmatrix}}{\begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 27}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 26}\end{pmatrix}} \times 100$ Exergy Destruction: $ED_{LPH2} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 9}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 14}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 15}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 27}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 26}\end{pmatrix}$ Irrersibility: $IR_{LPH2} = T_0 \times S_{g,LPH2}$
 	Energy: $(m_{10} \times h_{10}) + (m_{15} \times h_{15}) = (m_{16} \times h_{16}) + (m_{25} \times h_{25})$ Exergy: $\begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 15}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 16}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 25}\end{pmatrix}$ Entropy Generation: $S_{g,LPH3} = (m_{16}S_{16} + m_{25}S_{25}) - (m_{10}S_{10} + m_{15}S_{15})$ Energy efficiency: $\eta_{I,LPH3} = \frac{m_{15} \times C_{p,fw} \times (t_{16} - t_{15})}{m_{10} \times (h_{10} - h_{25})} \times 100$ Exergy Efficiency $\eta_{II,LPH3} = \frac{\begin{pmatrix}\text{Exergy at}\\ \text{Point 16}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 15}\end{pmatrix}}{\begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 25}\end{pmatrix}} \times 100$ Exergy Destruction: $ED_{LPH3} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 10}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 15}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 16}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 25}\end{pmatrix}$

	Irrersibility: $IR_{LPH3} = T_0 \times S_{g,LPH3}$
	Energy: $(m_6 \times h_6) + (m_{24} \times h_{24}) + (m_{16} \times h_{16}) = (m_{17} \times h_{17})$ Exergy: $\begin{pmatrix}\text{Exergy at}\\ \text{Point 17}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 6}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 16}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 24}\end{pmatrix}$ Entropy Generation: $S_{g,Deaerator} = (m_{17}S_{17}) - (m_6S_6 + m_{16}S_{16} + m_{24}S_{24})$ Energy efficiency: $\eta_{I,Deaerator} = \frac{m_{16} \times C_{p,fw} \times (t_{17} - t_{16})}{m_6 \times (h_6) + m_{24} \times (h_{24})} \times 100$ Exergy Efficiency $\eta_{II,Deaerator} = \frac{\begin{pmatrix}\text{Exergy at}\\ \text{Point 17}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 16}\end{pmatrix}}{\begin{pmatrix}\text{Exergy at}\\ \text{Point 6}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 24}\end{pmatrix}} \times 100$ Exergy Destruction: $ED_{Deaerator} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 6}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 16}\end{pmatrix} - \begin{pmatrix}\text{Exergy at}\\ \text{Point 17}\end{pmatrix} + \begin{pmatrix}\text{Exergy at}\\ \text{Point 24}\end{pmatrix}$ Irrersibility: $IR_{Deaerator} = T_0 \times S_{g,Deaerator}$
	Energy: $(m_{17} \times h_{17}) = (m_{18} \times h_{18})$ Exergy: $\begin{pmatrix}\text{Exergy at}\\ \text{Point 17}\end{pmatrix} = \begin{pmatrix}\text{Exergy at}\\ \text{Point 18}\end{pmatrix}$ Entropy Generation: $S_{g,BFP} = (m_{18}S_{16}) - (m_{17}S_{17})$ Energy efficiency: $\eta_{I,BFP} = \frac{m_{17} \times (h_{18} - h_{17})}{P_{In}} \times 100$

<table>
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Exergy Efficiency

$$\eta_{II,BFP} = \frac{\binom{\text{Exergy at}}{\text{Point 18}} - \binom{\text{Exergy at}}{\text{Point 17}}}{P_{BFP}} \times 100$$

Exergy Destruction:

$$ED_{BFP} = \binom{\text{Exergy at}}{\text{Point 18}} - \binom{\text{Exergy at}}{\text{Point 17}} + P_{In}$$

Irrersibility:

$$IR_{BFP} = T_0 \times S_{g,BFP}$$
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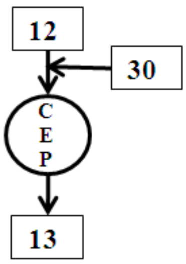

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<td>
Energy: $(m_{12} \times h_{12}) + (m_{30} \times h_{30}) = (m_{13} \times h_{13})$

Exergy: $\binom{\text{Exergy at}}{\text{Point 12}} + \binom{\text{Exergy at}}{\text{Point 30}} = \binom{\text{Exergy at}}{\text{Point 13}}$

Entropy Generation:

$$S_{g,CEP} = (m_{13}S_{13}) - (m_{12}S_{12} + m_{13}S_{13})$$

Energy efficiency:

$$\eta_{I,CEP} = \frac{m_{Condensate} \times g \times h}{P_{CEP}} \times 100$$

Exergy Efficiency

$$\eta_{II,CEP} = \frac{\binom{\text{Exergy at}}{\text{Point 13}} - \left\{\binom{\text{Exergy at}}{\text{Point 12}} + \binom{\text{Exergy at}}{\text{Point 30}}\right\}}{P_{In}} \times 100$$

Exergy Destruction:

$$ED_{CEP} = \binom{\text{Exergy at}}{\text{Point 13}} - \left\{\binom{\text{Exergy at}}{\text{Point 12}} + \binom{\text{Exergy at}}{\text{Point 30}}\right\} + P_{In}$$

Irrersibility: $IR_{CEP} = T_0 \times S_{g,CEP}$
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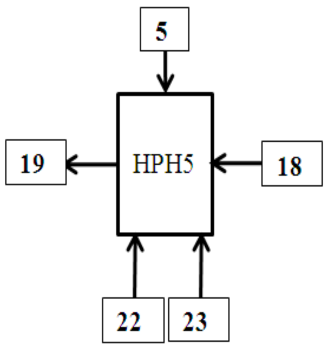

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<td>
Energy:

$$(m_5 \times h_5) + (m_{18} \times h_{18}) + (m_{22} \times h_{22}) = (m_{19} \times h_{19}) + (m_{23} \times h_{23})$$

Exergy:

$$\binom{\text{Exergy at}}{\text{Point 5}} + \binom{\text{Exergy at}}{\text{Point 18}} + \binom{\text{Exergy at}}{\text{Point 22}} = \binom{\text{Exergy at}}{\text{Point 19}} + \binom{\text{Exergy at}}{\text{Point 23}}$$

Entropy Generation:

$$S_{g,HPH5} = (m_{19}S_{19} + m_{23}S_{23}) - (m_5S_5 + m_{18}S_{18} + m_{22}S_{22})$$

Energy efficiency:

$$\eta_{I,HPH5} = \frac{m_{18} \times C_{p,fw} \times (t_{19} - t_{18})}{m_5 \times (h_5 - h_{23}) + m_{22} \times (h_{22} - h_{23})} \times 100$$

Exergy Efficiency

$$\eta_{II,HPH5} = \frac{\binom{\text{Exergy at}}{\text{Point 19}} - \binom{\text{Exergy at}}{\text{Point 18}} + \binom{\text{Exergy at}}{\text{Point 22}} - \binom{\text{Exergy at}}{\text{Point 23}}}{\binom{\text{Exergy at}}{\text{Point 22}} + \binom{\text{Exergy at}}{\text{Point 5}} - \binom{\text{Exergy at}}{\text{Point 23}}} \times 100$$

Exergy Destruction:

$$ED_{HPH5} = \binom{\text{Exergy at}}{\text{Point 5}} + \binom{\text{Exergy at}}{\text{Point 18}} - \binom{\text{Exergy at}}{\text{Point 19}} - \binom{\text{Exergy at}}{\text{Point 23}} + \binom{\text{Exergy at}}{\text{Point 22}}$$
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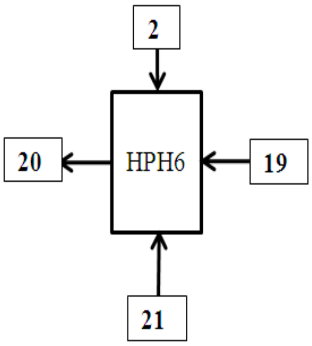
	Irrersibility: $IR_{HPH5} = T_0 \times S_{g,HPH5}$
	Energy: $(m_2 \times h_2) + (m_{19} \times h_{19}) = (m_{20} \times h_{20}) + (m_{21} \times h_{21})$ Exergy: $\left(\begin{matrix}\text{Exergy at}\\ \text{Point 2}\end{matrix}\right) + \left(\begin{matrix}\text{Exergy at}\\ \text{Point 19}\end{matrix}\right) = \left(\begin{matrix}\text{Exergy at}\\ \text{Point 20}\end{matrix}\right) + \left(\begin{matrix}\text{Exergy at}\\ \text{Point 21}\end{matrix}\right)$ Entropy Generation: $S_{g,HPH6} = (m_{20}S_{20} + m_{21}S_{21}) - (m_2S_2 + m_{19}S_{19})$ Energy efficiency: $\eta_{I,HPH6} = \frac{m_{19} \times C_{p,fw\times}(t_{20} - t_{19})}{m_2 \times (h_2 - h_{21})} \times 100$ Exergy Efficiency: $\eta_{II,HPH6} = \frac{\left(\begin{matrix}\text{Exergy at}\\ \text{Point 20}\end{matrix}\right) - \left(\begin{matrix}\text{Exergy at}\\ \text{Point 19}\end{matrix}\right)}{\left(\begin{matrix}\text{Exergy at}\\ \text{Point 2}\end{matrix}\right) - \left(\begin{matrix}\text{Exergy at}\\ \text{Point 21}\end{matrix}\right)} \times 100$ Exergy Destruction: $ED_{HPH6} = \left(\begin{matrix}\text{Exergy at}\\ \text{Point 2}\end{matrix}\right) + \left(\begin{matrix}\text{Exergy at}\\ \text{Point 19}\end{matrix}\right) - \left(\begin{matrix}\text{Exergy at}\\ \text{Point 20}\end{matrix}\right) - \left(\begin{matrix}\text{Exergy at}\\ \text{Point 21}\end{matrix}\right)$ Irrersibility: $IR_{HPH6} = T_0 \times S_{g,HPH6}$

RESEARCH METHODOLOGY

The steps followed for this research are as follows:

(1) Study of existing 210 MW KWU coal-based thermal power plant layout and its working.

(2) Extracting the steady state online data of the plant and arranging at various actual load conditions unit wise. The extracted data are presented in Table 2 and Table 3 respectively.

(3) Development of a program in EES software to obtain the various properties such as pressure, temperature, quality of steam, enthalpy, entropy and mass of working medium at inlet and outlet points of components for turbine cycle of the power plant at dead state temperature of 25 ^{O}C.

(4) Calculation of energy efficiency of major components of turbine cycle as well as of the overall plant at dead state temperature of 25 ^{O}C using equations presented in Table 4.

(5) Calculation of exergy efficiency and exergy destruction of major components of a turbine cycle as well as of the overall plant dead state temperature of 25 ^{O}C using equations presented in Table 4.

(6) Calculation of irreversibility of major components of turbine cycle as well as of the overall plant using at dead state temperature of 25 ^{O}C using equations presented in Table 4.

(7) Comparison of results.

RESULTS AND DISCUSSION

In the present paper, energetic and exergetic performance of critical components of 210 MW KWU design thermal power plant has been evaluated at various operating loads in three different ranges between 75 % to 100 % of full generating capacity using actual data of the power plant. The steady state online actual data of the power plant has been extracted and presented in Table 2 and Table 3. The thermal performance of the power plant has been evaluated as per the research methodology presented in the previous section. The results have been analyzed on the basis of TG set wise load conditions, different load conditions and step of the load conditions (i.e. low load range of around 75% of total generating capacity, middle load range of around 85% of total generating capacity and higher load range of around 95 % to100 % of total generating capacity) on the thermal power plant. They have been presented in subsections such as energetic performance of the power plant, exergetic performance of the power plant, comparison of energetic and exergetic performance of the power plant and overall findings.

ANALYSIS ON THE BASIS OF TG SET WISE LOAD CONDITIONS OF THE THERMAL POWER PLANT

Component wise energetic performance of TGS-1, TGS-2 and TGS-3 at various operating load conditions is presented in Figure 2, Figure 3 and Figure 4 respectively. Energy efficiency of various major components as well as overall plant is calculated on the basis of actual operating data taken at three different generating load of TGS-1, TGS-2 and TGS-3. Load L1 is greater than load L2 and load L2 is greater than L3. For TGS-1, overall plant efficiency is higher at load L1 than load L2 and L3. Though overall plant efficiency is more at load L2 than at load L3, no major difference in overall plant efficiency is observed for loads L2 and L3 mainly due to better performance of boiler at load L2. Poor boiler performance restricts the overall plant efficiency in this particular TGS-1. For TGS-2 overall plant efficiency is higher at load L2 than load L1 and L3 mainly because of better operating performance of boiler at load L2. For TGS-3, overall plant efficiency is higher at load L2 than at other loads and at load L4 than L3 mainly because of better operating performance of boiler.

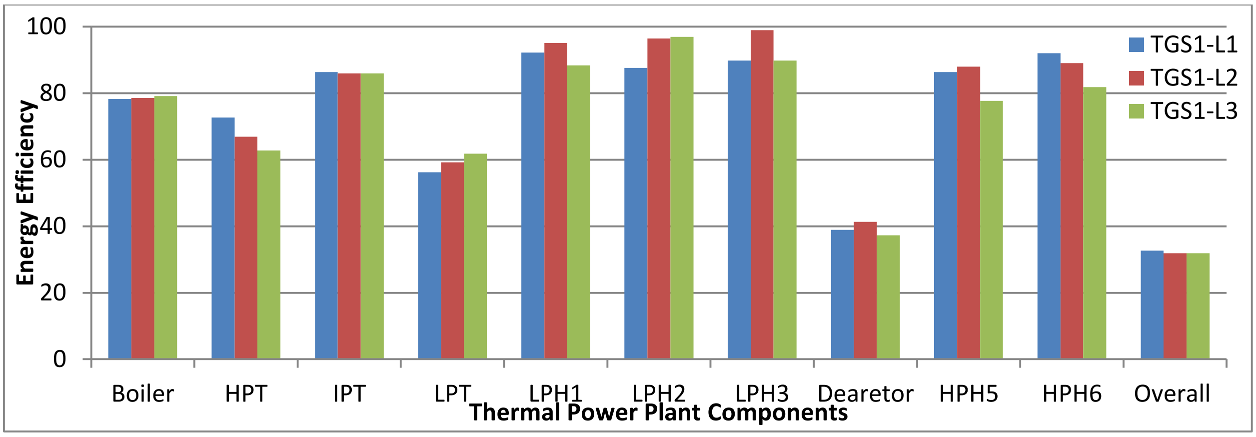


Figure 2. Components wise Energetic Performance of Turbo-Generator Set-1 at Various Operating Loads

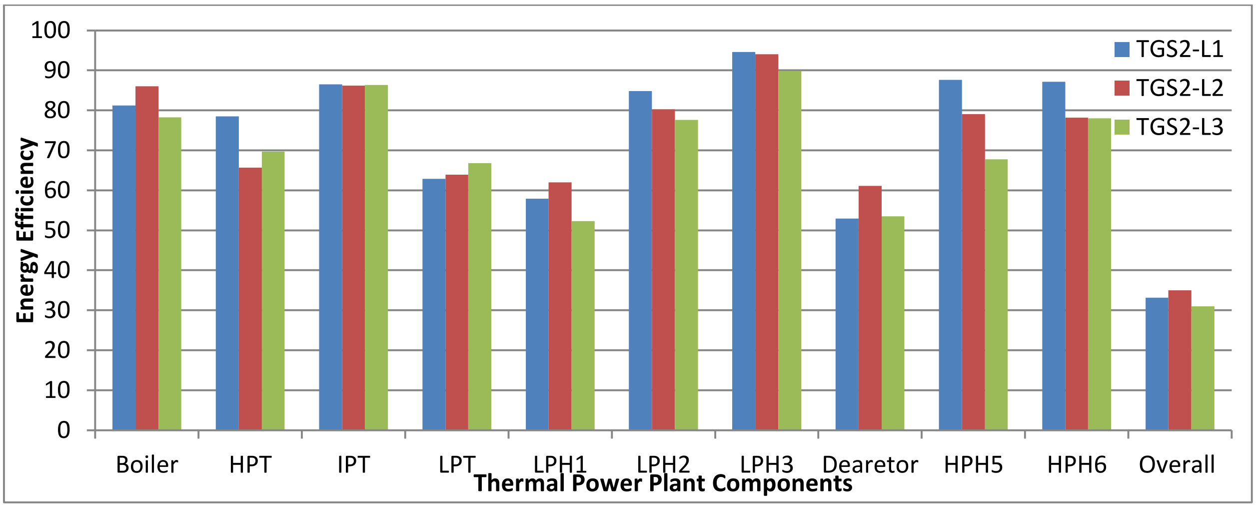


Figure 3. Components wise Energetic Performance of Turbo-Generator Set-2 at Various Operating Loads

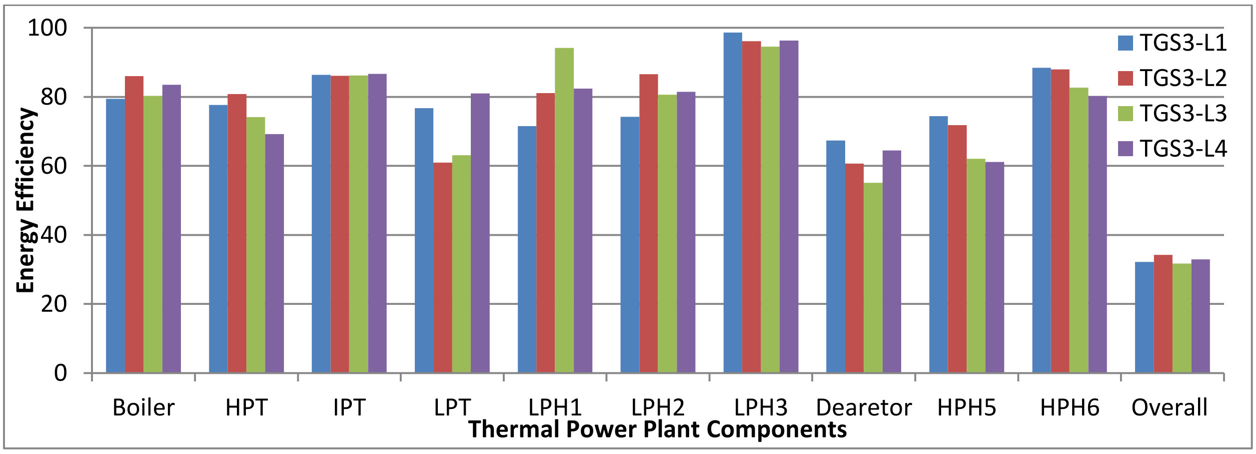


Figure 4. Components wise Energetic Performance of Turbo-Generator Set-3 at Various Operating Loads

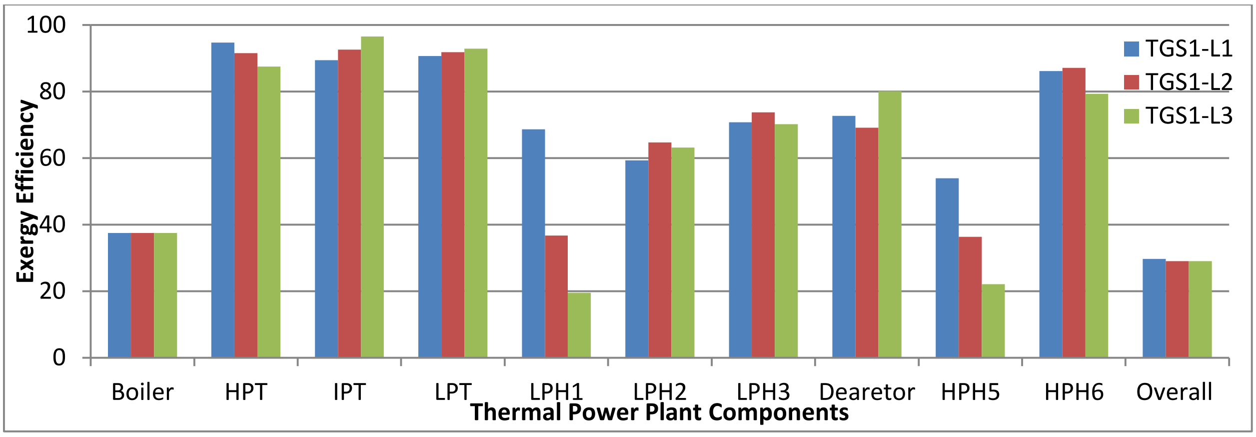


Figure 5. Components wise Exergetic Performance of Turbo-Generator Set-1 at Various Operating Loads

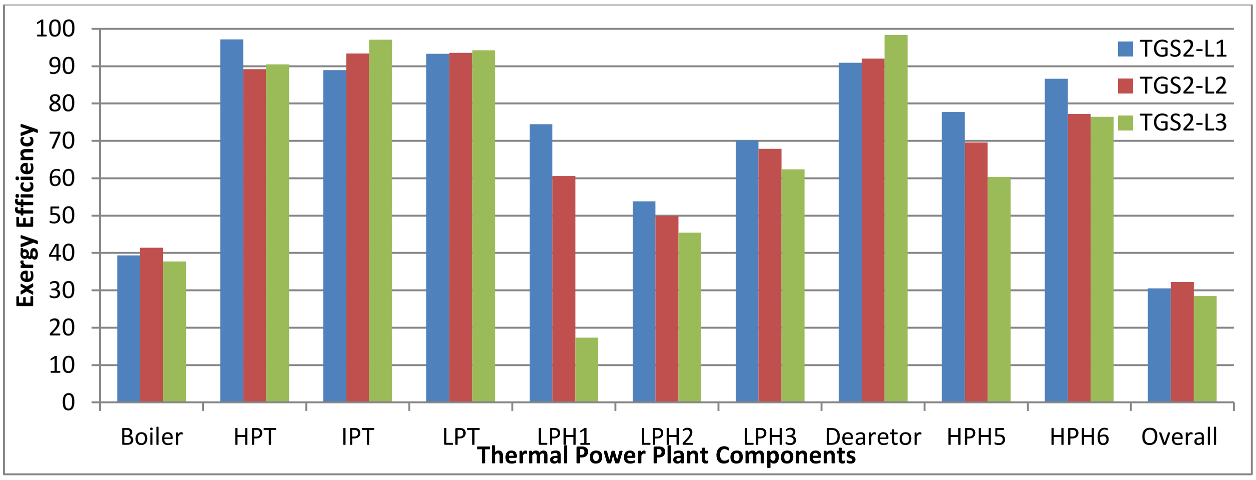


Figure 6. Components wise Exergetic Performance of Turbo-Generator Set-2 at Various Operating Loads

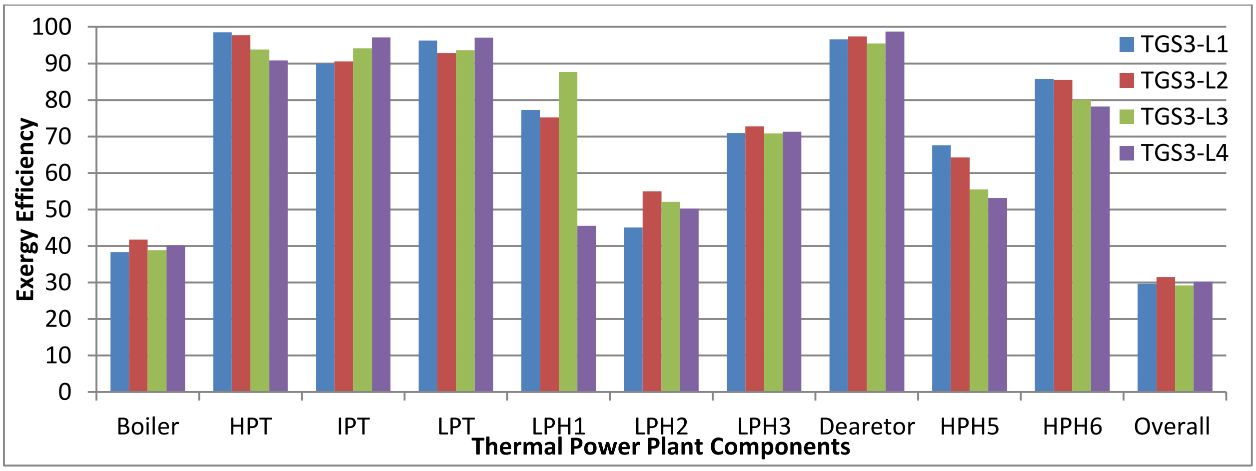


Figure 7. Components wise Exergetic Performance of Turbo-Generator Set-3 at Various Operating Loads

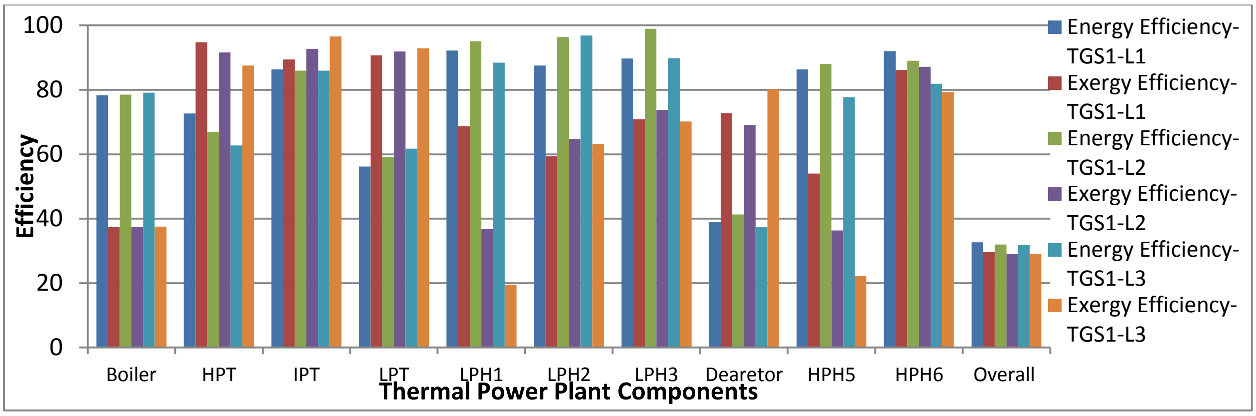


Figure 8. Components wise Comparison of Energy and Exergetic Efficiency of Turbo-Generator Set-1 at Various Operating Loads

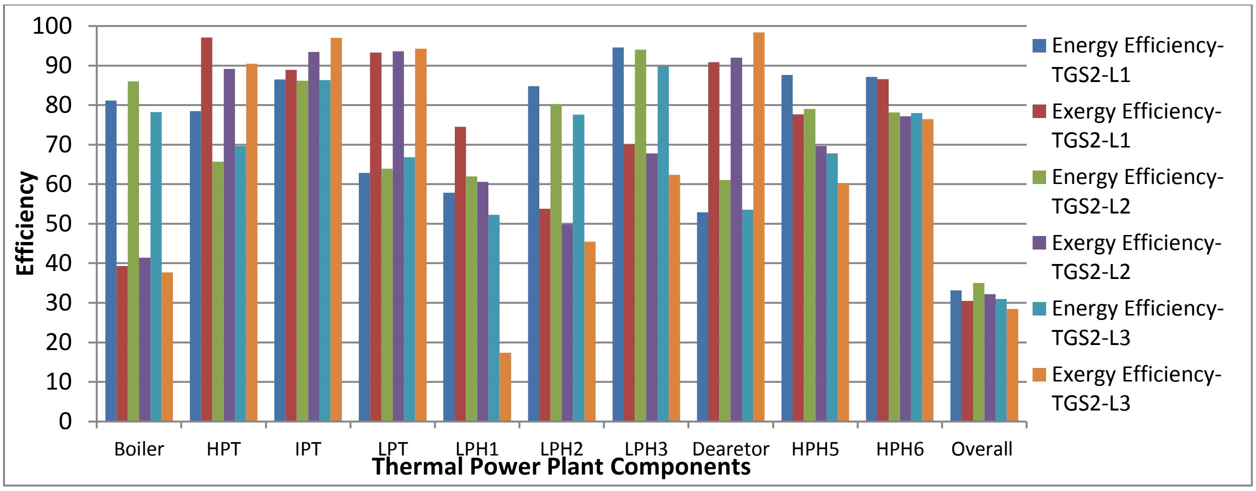


Figure 9. Components wise Comparison of Energy and Exergetic Efficiency of Turbo-Generator Set-2 at Various Operating Loads

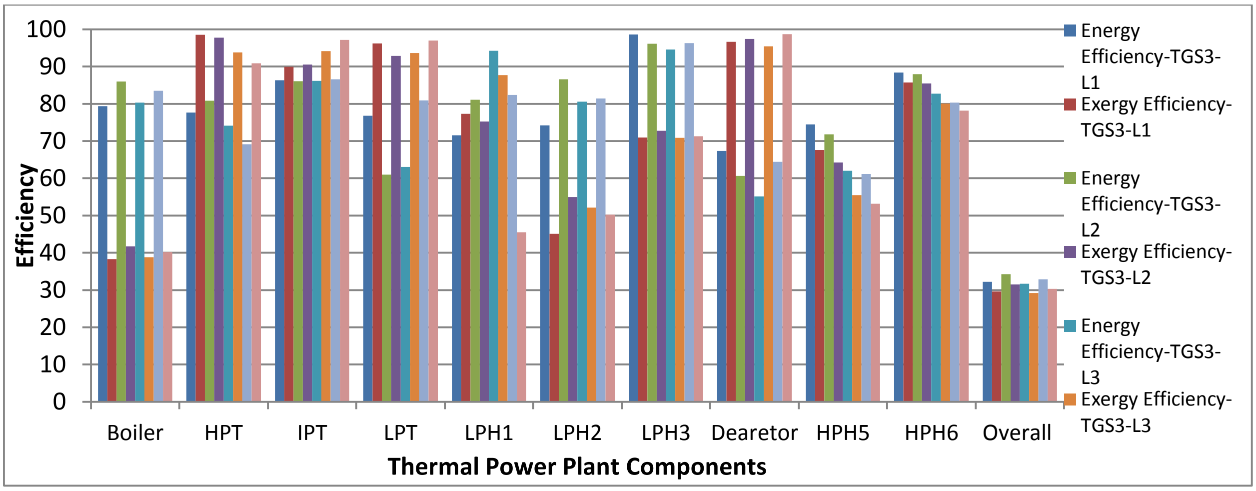


Figure 10. Components wise Comparison of Energy and Exergetic Efficiency of Turbo-Generator Set-3 at Various Operating Loads

Component wise exergetic performance of TGS-1, TGS-2 and TGS-3 at various operating load conditions is presented in Figure 5, Figure 6 and Figure 7 respectively. Overall plant exergy efficiency for TGS-1, TGS-2 and TGS-3 is observed to be lower than energy efficiency at all loads but follows almost same trend in line with energy efficiency. Component wise Comparisons of Energy and Exergetic Efficiency of TGS-1, TGS-2 and TGS-3 at Various Operating Loads are presented in Figure 8, Figure 9 and Figure 10 respectively.

Exergy destruction of boiler and overall thermal plant exergy destruction have been plotted for TGS-1, TGS-2 and TGS-3 at various operating loads and presented in Figure 11, Figure 12 and Figure 13 respectively. Maximum exergy destruction is observed in the boiler at all given loads in all TG sets. At load L2 on TGS-2 as well as on TGS-3, contribution of exergy destruction in the boiler is lower than all other loads on all three TG sets. These results match with the observations made as reasoning statement given for higher energy and exergy efficiency.

Component wise irreversibly evaluated for TGS-1, TGS-2 and TGS-3 at various operating load conditions is presented in Figure 14, Figure 15 and Figure 16 respectively. Irreversibility indirectly shows the entropy generation. In the TGS-1, irreversibility observed higher in feed water heaters LPH2 & LPH3 as well as in HPH5 & HPH6. In view of higher contribution of irreversibility and lower exergy efficiency, there is a scope to improve the performance of LPH2 and HPH5. Similarly in TGS-2, there is substantial scope to improve the performance of LPH2, LPH3 and HPH5 at higher load. While in TGS-3, LPH2 and HPH5 are having more scope for the performance improvement.

OVERALL FINDINGS

Poor boiler performance restricts the overall plant efficiency in this particular TGS-1. Overall plant exergy efficiency is observed low than energy efficiency at all loads but follows almost same trend in line with energy efficiency. For TGS-2, the overall plant efficiency is higher at load L2 than load L1 and L3 mainly because of better operating performance of boiler at load L2. Overall plant exergy efficiency is observed low than energy efficiency at all loads but follows almost same trend in line with energy efficiency. Because of better operating performance of boiler found in TGS-2, the overall plant efficiency is higher at load L2 than at other loads and at load L4 than L3. Overall plant exergy efficiency is observed low than energy efficiency at all loads but follows almost same trend in line with energy efficiency.

Maximum exergy destruction is observed in boiler at all given loads in all TG sets. At load L2 on TGS-2 as well as on TGS-3, contribution of exergy destruction in the boiler is lower than all other loads on all three TG sets, These results match with the observations made as reasoning statement given for higher energy and exergy efficiency. In the TGS-1 irreversibility is observed higher in feed water heaters LPH2 & LPH3 as well as in HPH5 & HPH6. In view of higher contribution of irreversibility and lower exergy efficiency, there is a scope to improve the performance of the LPH2 and HPH5. Similarly in TGS-2, there is substantial scope to improve performance of LPH2, LPH3 and HPH5 at higher load. While in TGS-3, LPH2 and HPH5 are having more scope for performance improvement. Energy efficiency and exergy efficiency of the overall plant are better in TGS-2 than TGS-1 and TGS-3. Out of TGS-1, and TGS-3, TGS-3 is better.

This indicates that if the TG set (mainly condition of feed water heaters, furnace, APH, ID fans etc) is well maintained and operated, better performance can be achieved even in middle and low load ranges.

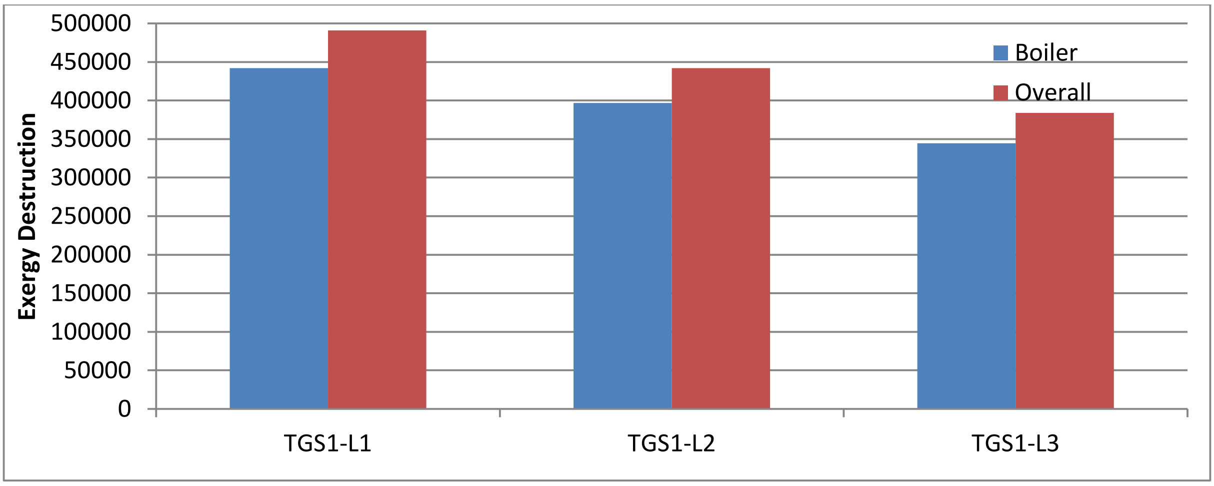


Figure 11. Exergy Destruction of Turbo-Generator Set-1 at Various Operating Loads

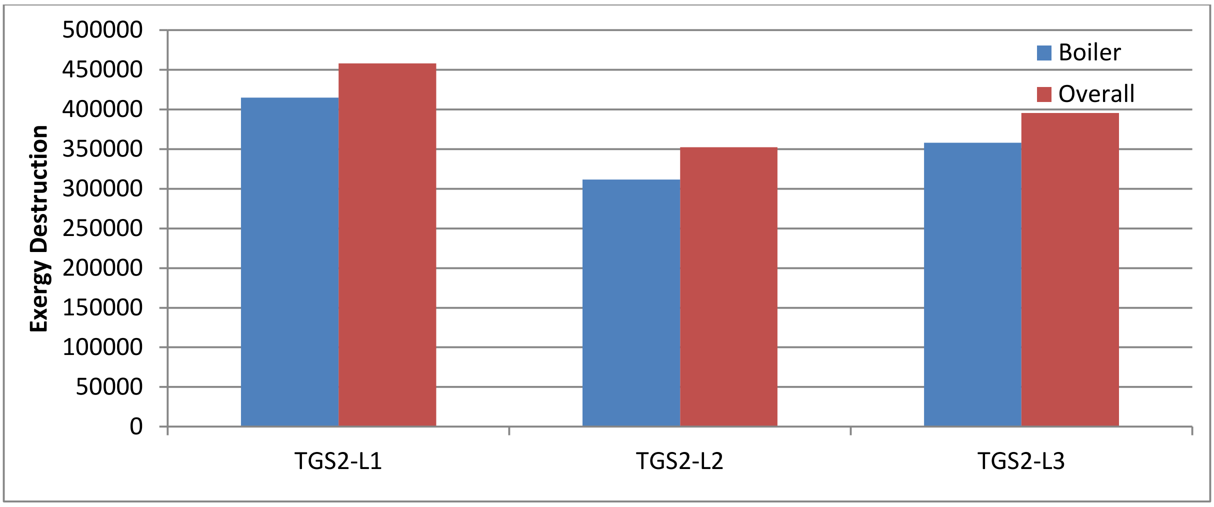


Figure 12. Exergy Destruction of Turbo-Generator Set-2 at Various Operating Loads

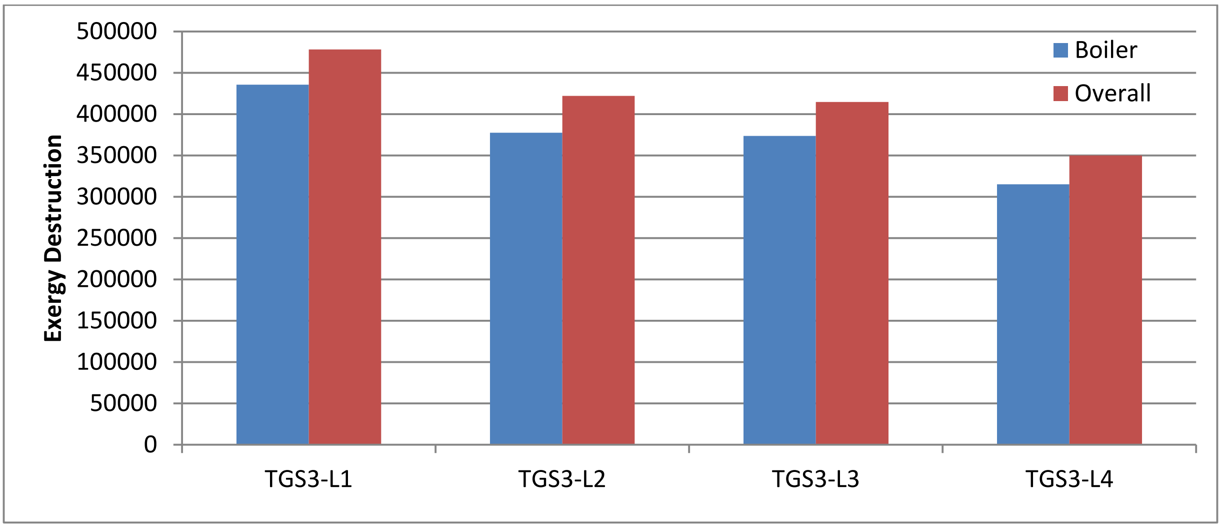


Figure 13. Exergy Destruction of Turbo-Generator Set-3 at Various Operating Loads

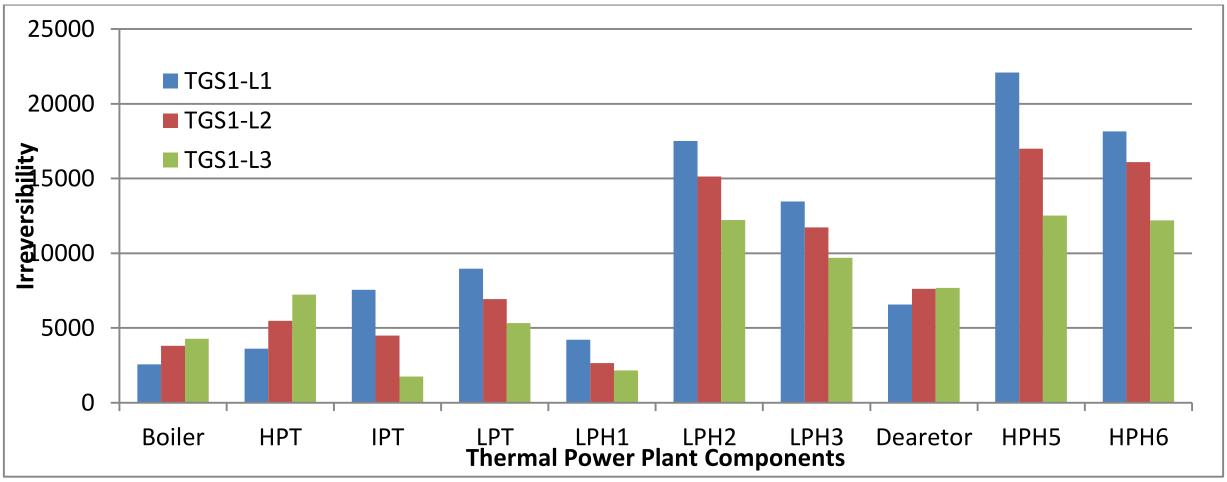


Figure 14. Components wise Irreversibility of Turbo-Generator Set-1 at Various Operating Loads

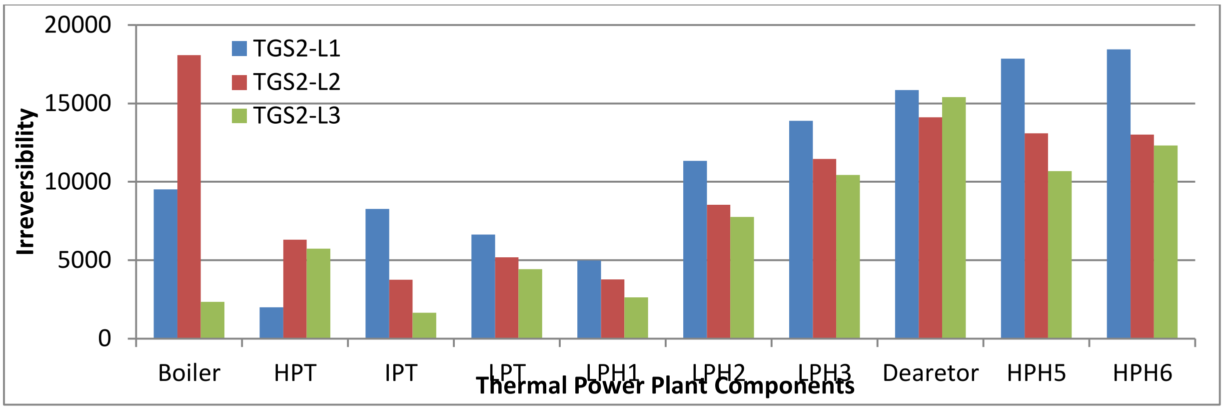


Figure 15. Components wise Irreversibility of Turbo-Generator Set-2 at Various Operating Loads

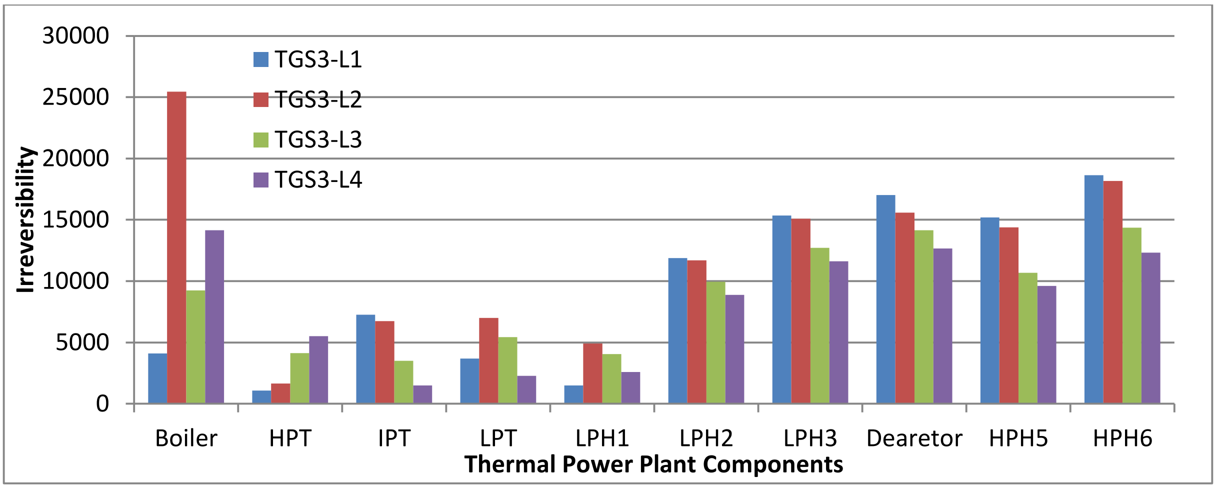


Figure 16. Components wise Irreversibility of Turbo-Generator Set-3 at Various Operating Loads

ANALYSIS ON THE BASIS OF DIFFERENT LOAD CONDITIONS OF THE THERMAL POWER PLANT

Component wise energetic and exergetic performance of thermal power plant at various operating loads is presented in Figure 17 and Figure 18 respectively. Load P1 to load P10 is in descending order. Overall plant energy efficiency at generating load P3, P4, P7 and P10 is better. These all four loads are in different range representing higher (P3 & P4), middle (P7) and low (P10) load range respectively. Energy efficiency of IPT remains high and there is not much variation with change in load. Energy efficiency of HPT is observed better for load of higher range in each TG set. LPT and feed water heaters show fluctuations due to different maintenance conditions of FW heaters resulting into variation in actual parameters than expected.

Exergetic efficiency is not varying much more for Boiler, HPT, IPT, LPT, LPH3, HPH6 and overall plant. LPH1, LPH2, Deaerator and HPH5 show more fluctuations due to reasons discussed for energy efficiency.

Exergy destruction in boiler and overall exergy destruction of the plant at various operating loads have been presented in Figure 19, while component wise irreversibility of thermal power plant at various operating loads has been presented in Figure 20. Generating load P1 to P10 is in descending order. Barring P5 general trend of exergy destruction is downward in line with load reduction. However, exergy destruction depends on the actual condition of a plant and hence it differs for same load range in different TG sets. With reduction in generating load, irreversibility is also observed to be reduced in general except HPT. In higher load range, HPT is having less irreversibility than at load for remaining middle as well as low range. It implies that though performance is better for middle and low range load, still there is a scope for its improvement.

OVERALL FINDINGS

Energy efficiency at generating load P3, P4, P7 and P10 is better. These all four loads are in different range representing higher (P3 & P4), middle (P7) and low (P10) load range respectively. It can be seen that for these four loads, overall plant energy efficiency is also better. Energy efficiency of IPT remains high and there is not much variation with change in load. Energy efficiency of HPT is observed better for load of higher range in each TG set. LPT and feed water heaters show fluctuations due to different maintenance conditions of FW heaters resulting into variation in actual parameters than expected. Exergetic efficiency is not varying much more for Boiler, HPT, IPT, LPT, LPH3, HPH6 and overall plant at different load. LPH1, LPH2, Deaerator and HPH5 show more fluctuations due to reasons discussed for energy efficiency.

Exergy destruction: General trend of exergy destruction is downward in line with load reduction. However, exergy destruction depends on the actual condition of plant and hence it differs for same load range in different TG set. Irreversibility: With reduction in generating load, irreversibility is also observed to be decreased in all major components except HPT. In higher load range, HPT is having less irreversibility than at load for remaining middle as well as low range. It implies that though performance is better for middle and low range load, still there is a scope for its improvement.

This indicates that if the proper operating parameters are well maintained, better performance can be achieved even in middle and low load ranges.

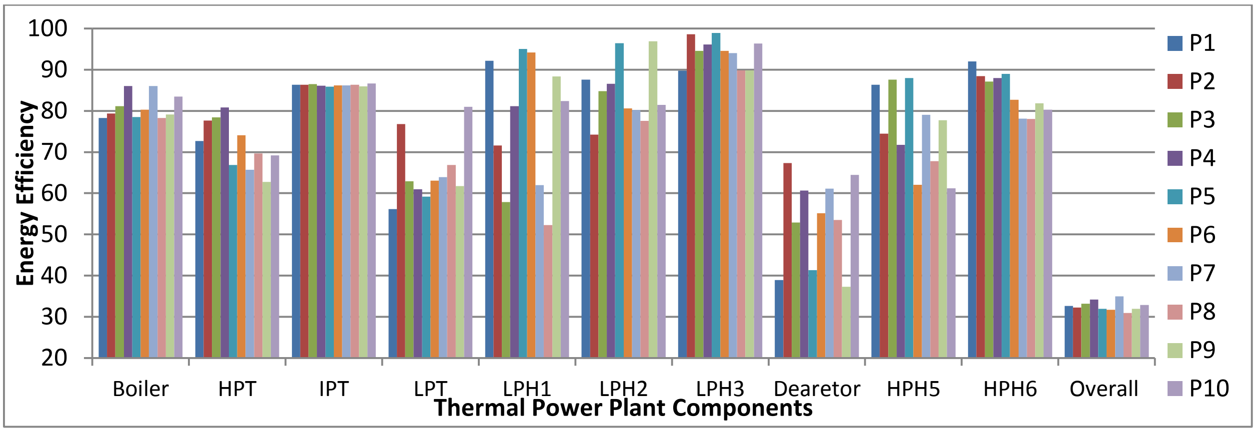


Figure 17. Component wise energetic performance of Thermal Power Plant at Various Operating Loads

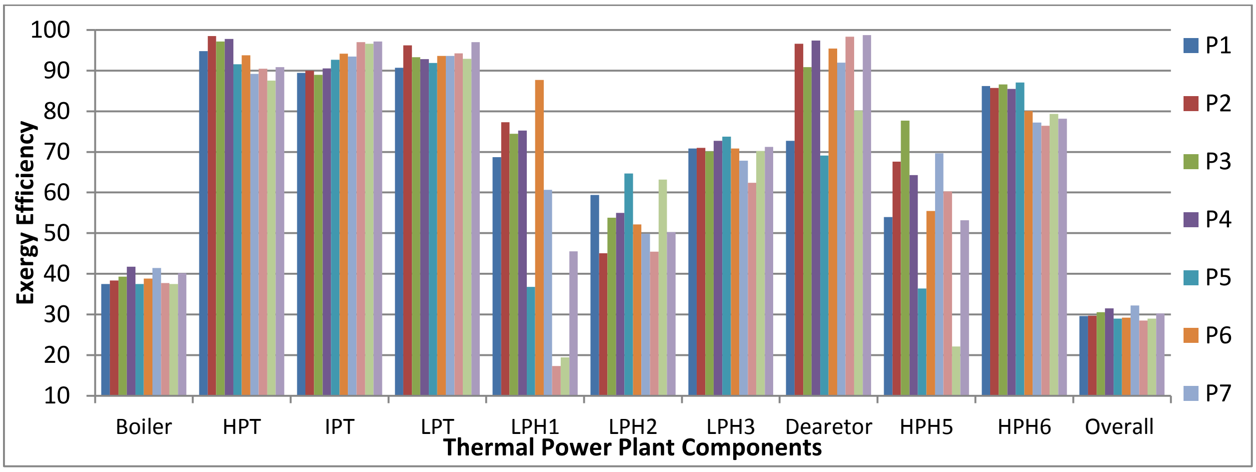


Figure 18. Component wise Exergetic Performance of Thermal Power Plant at Various Operating Loads

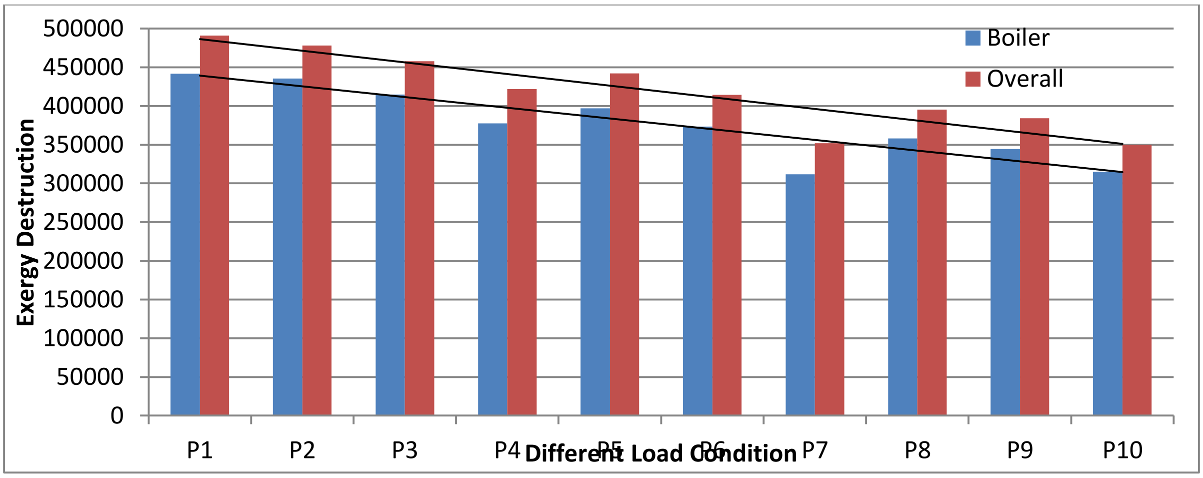


Figure 19. Exergy Destruction of Thermal Power Plant at Various Operating Loads

ANALYSIS ON THE BASIS OF STEP OF LOAD CONDITIONS ON THE THERMAL POWER PLANT

Component wise energy and exergy efficiency of thermal power plant for low, middle and higher operating load ranges are presented in Figure 21, Figure 22, Figure 23, Figure 24, Figure 25 and Figure 26 respectively. While component wise comparison of energetic and exergetic performance of thermal power plant at lower, middle and higher operating loads are presented in Figure 27, Figure 28 and Figure 29 respectively. In all three generating load ranges energy and exergy efficiency is found better at lower load mainly due to better performance in boiler.

Exergy destruction in boiler and overall exergy destruction of thermal power plant at low, middle and high operating loads are presented in Figure 30, Figure 31 and Figure 32. Component wise irreversibility of thermal power plant at low, middle and high operating loads are presented in Figure 33, Figure 34 and Figure 35. Exergy destruction ratio of boiler to overall plant is found less at low load in each load range. However, in low load range the same is found slightly different for load P9 and load P10 though both P9 and P10 are nearly same. For P9 it is lower than P10. It is to be noted here that P9 and P10 are from different TG sets. Irreversibility for boiler is found increasing with decrease in load in each load range. Same trend is found for the overall plant also (not shown in the graph).

OVERALL FINDINGS

In higher load range, energy and exergy efficiency are found better at load L2 (TGS-3). This shows that in the same TG set there is a possibility of performance improvement at load L1. In the middle range of load, energy and exergy efficiency are found better at load L2 (TGS-2). This shows that there is a possibility of performance improvement at load L1 in the same TG set. In the Lower load range, at load L4 (TGS-3) energy and exergy efficiency are found better, which indicate that there is a possibility of performance improvement at load L3 in the same TG set.

Out of all sets of readings taken at different loads, maximum value of energy and exergy efficiency is found at load L2 (TGS-2), which is in middle range. It should also be noted here that better performance is observed at lowest load L4 (TGS-3) than higher load L1 (TGS-1), L2 (TGS-1), L3 (TGS-1), L3 (TGS-2), L1 (TGS-3) and L3 (TGS-3). Irreversibility for boiler is found increasing with decrease in load in each load range. Same trend is found for the overall plant also (not shown in the graph).

CONCLUSION

Though the age is nearly same of all three TG sets under study, energy efficiency and exergy efficiency of overall plant are better in TGS-2 than TGS-1 and TGS-3. Out of TGS-1 and TGS-3, TGS-3 is better. It is also observed that performance at lower load is better in one TG set than at higher load in another TG set. Performance observed at middle range load in TGS-2 is well enough even after operation of more than 20 years. This observation implies that if the (1) condition of TG set along with its major components and (2) proper operating parameters (pressure and temperature of main steam, excess air percentage etc.) are well-maintained, nearly design performance (only around 2% less) can be achieved in all said three load ranges of TG sets running since more than 20 years. Irreversibility shows the possibility of improvement in performance. It is possible that irreversibility may be high in case of better energy and exergy efficiency and vice versa. Exergy destruction in the boiler is found maximum and hence boiler performance is having major impact on overall plant performance. Thus, boiler is a key area to focus for improvement in the overall plant performance.

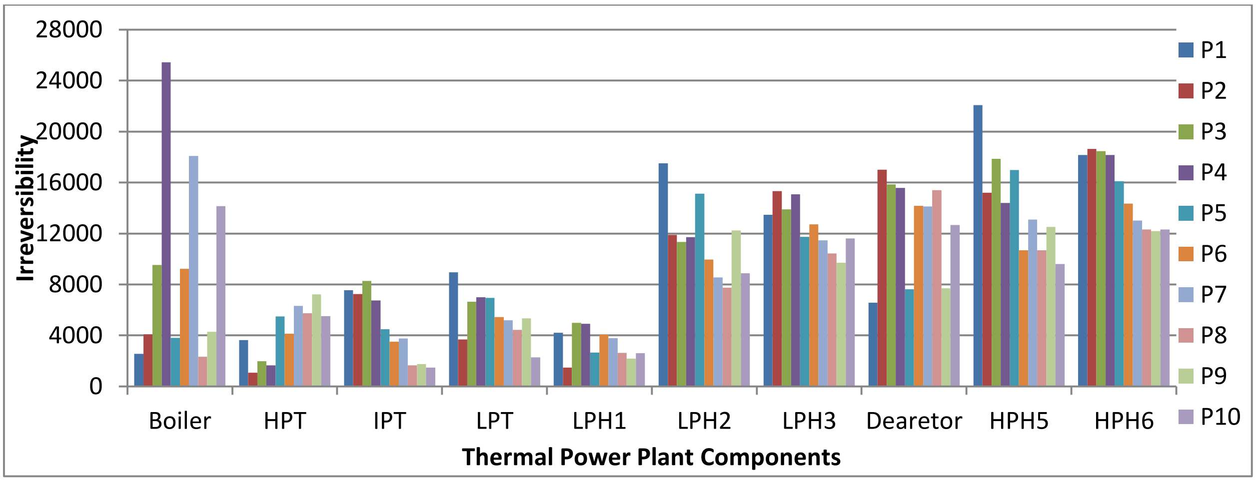


Figure 20. Component wise Irreversibility of Thermal Power Plant at Various Operating Loads

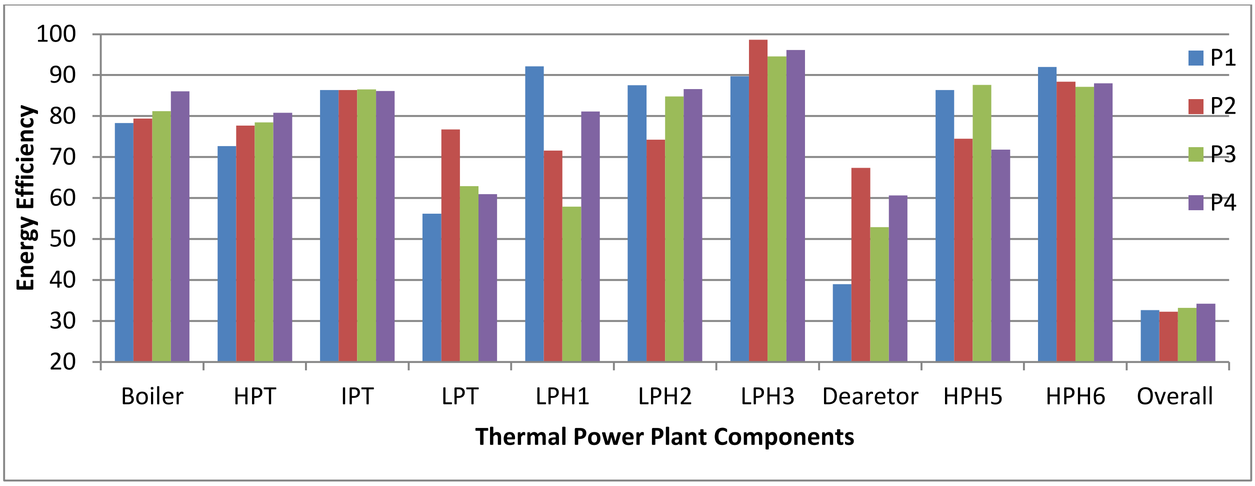


Figure 21. Component wise Energy Efficiency of Thermal Power Plant for Low Operating Load Range

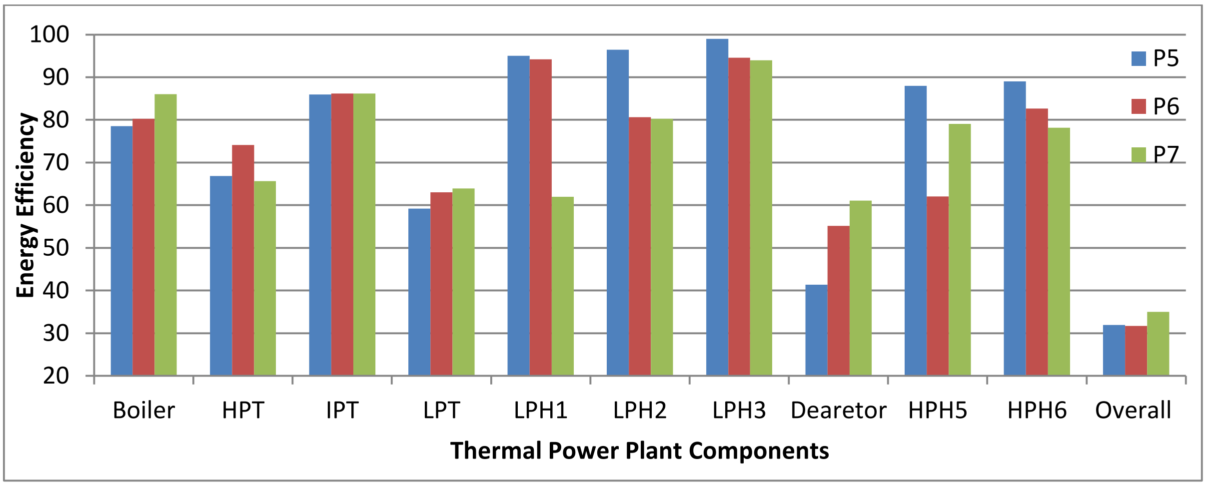


Figure 22. Component wise Energy Efficiency of Thermal Power Plant for Middle Operating Load Range

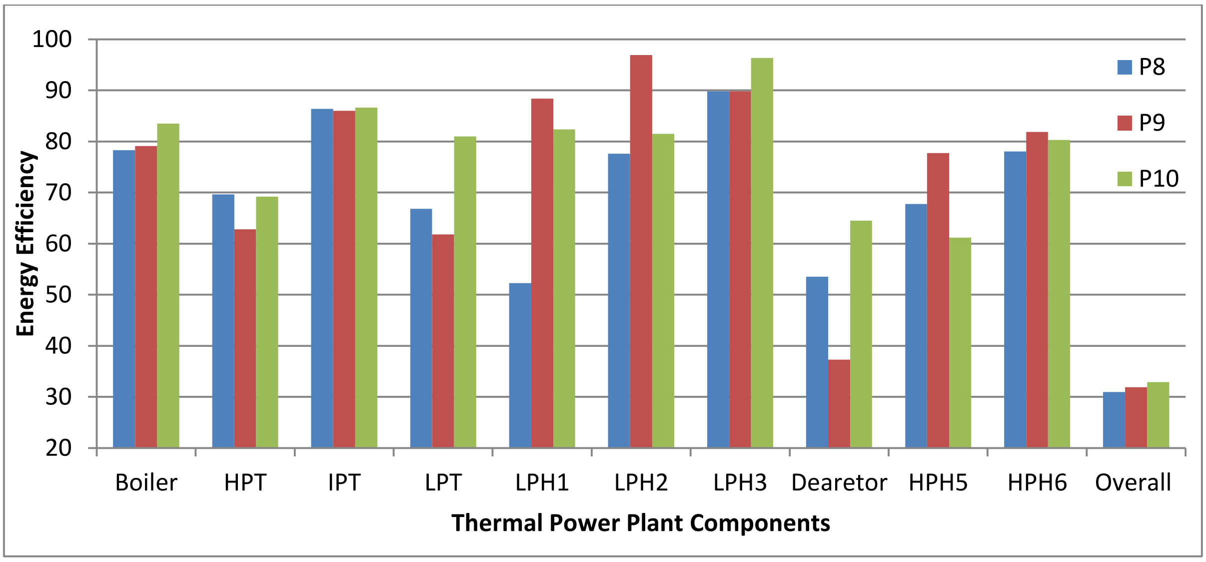


Figure 23. Component wise Energy Efficiency of Thermal Power Plant for Higher Operating Load Range

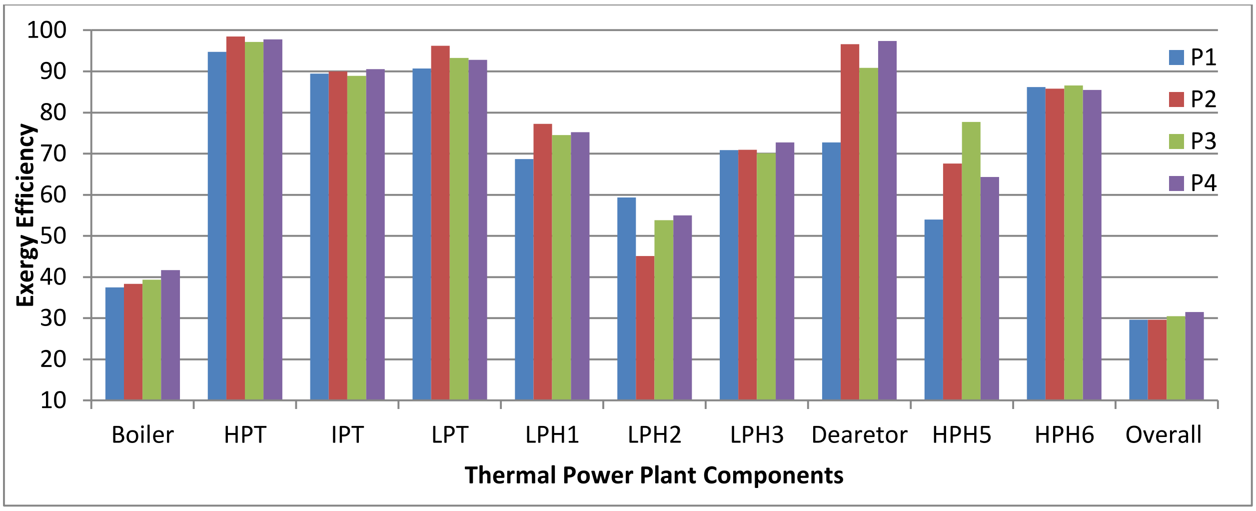


Figure 24. Component wise Exergy Efficiency of Thermal Power Plant for Low Operating Load Range

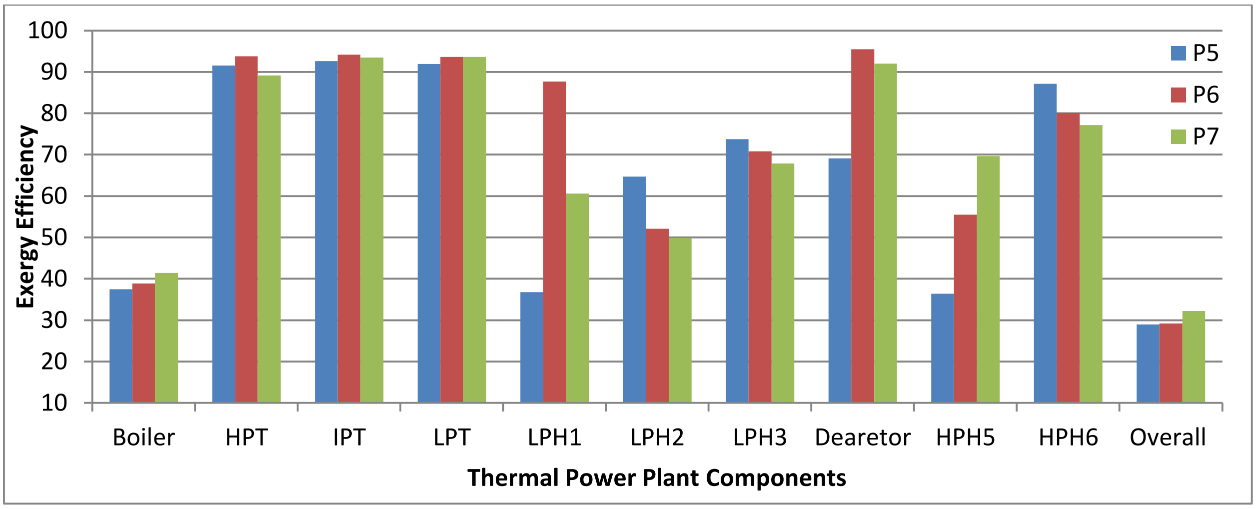


Figure 25. Component wise Exergy Efficiency of Thermal Power Plant for Middle Operating Load Range

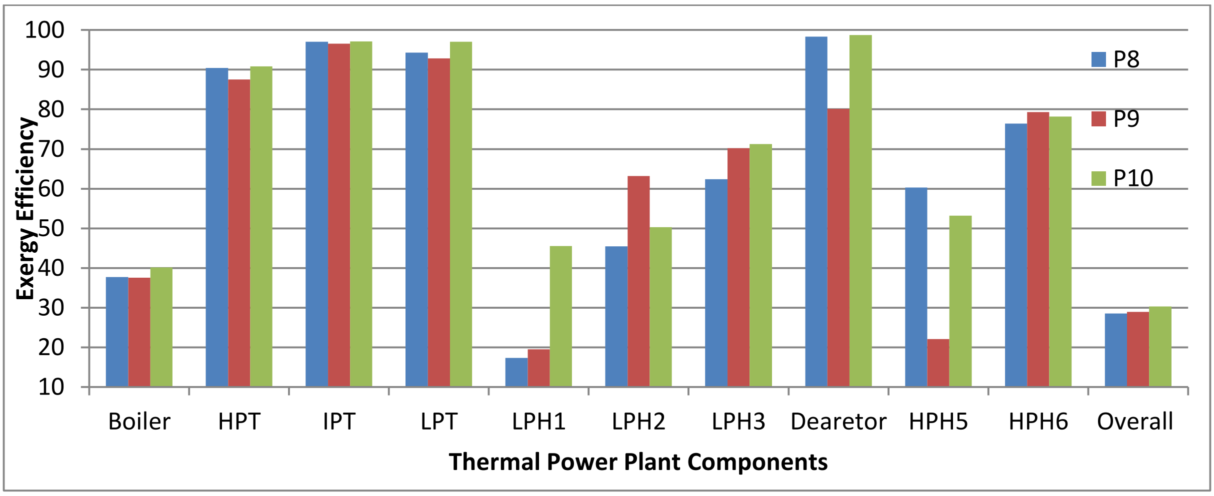


Figure 26. Component wise Exergy Efficiency of Thermal Power Plant for Higher Operating Load Range

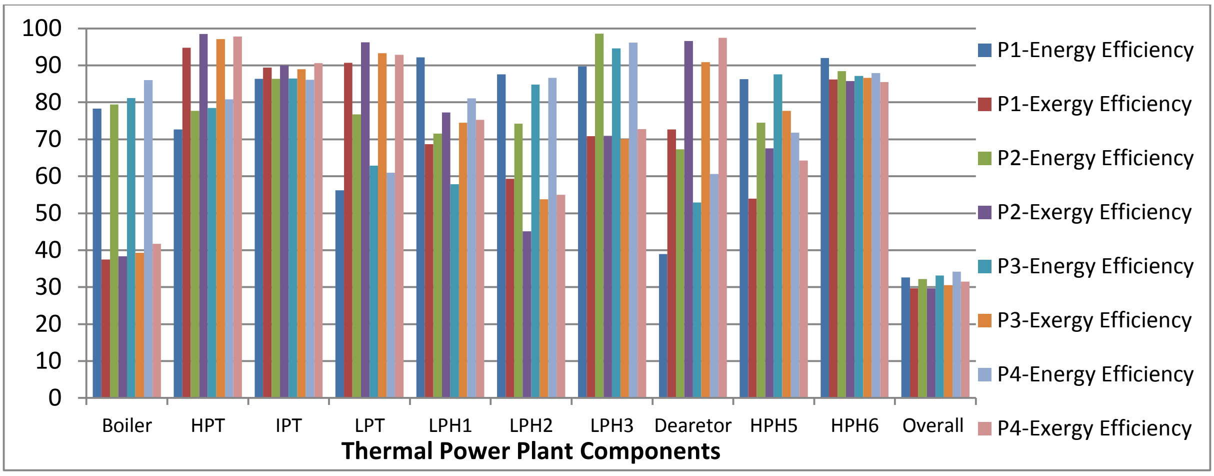


Figure 27. Component wise Comparison of Energetic and Exergetic Performance of Thermal Power Plant at Lower Operating Loads

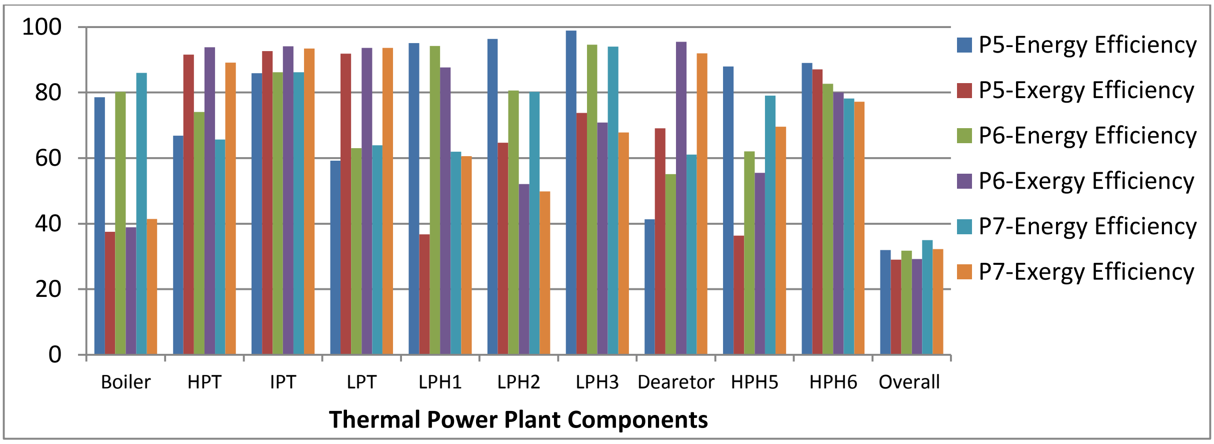


Figure 28. Component wise Comparison of Energetic and Exergetic Performance of Thermal Power Plant at Middle Operating Loads

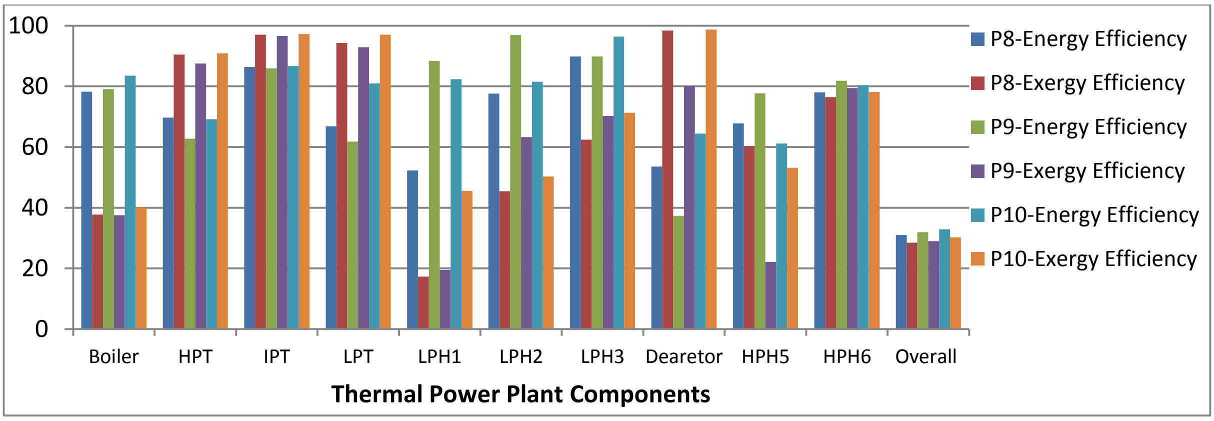


Figure 29. Component wise Comparison of Energetic and Exergetic Performance of Thermal Power Plant at Higher Operating Loads

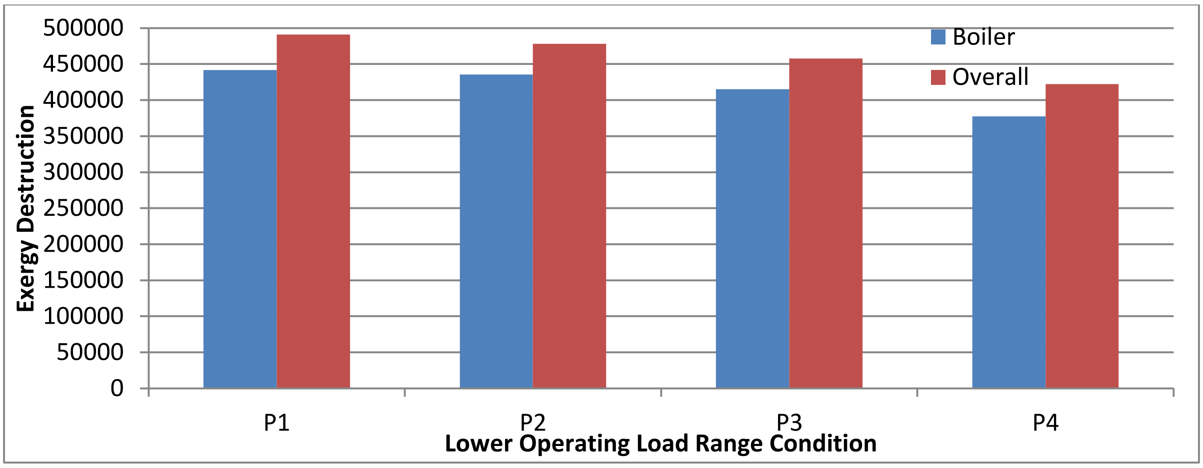


Figure 30. Exergy Destruction of Thermal Power Plant at Low Operating Loads

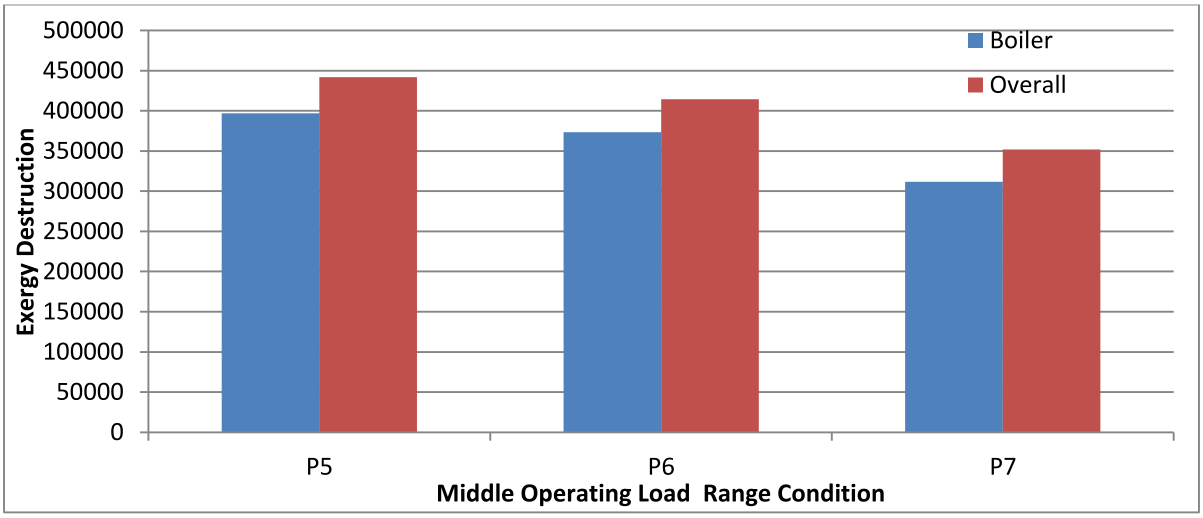


Figure 31. Exergy Destruction of Thermal Power Plant at Middle Operating Loads

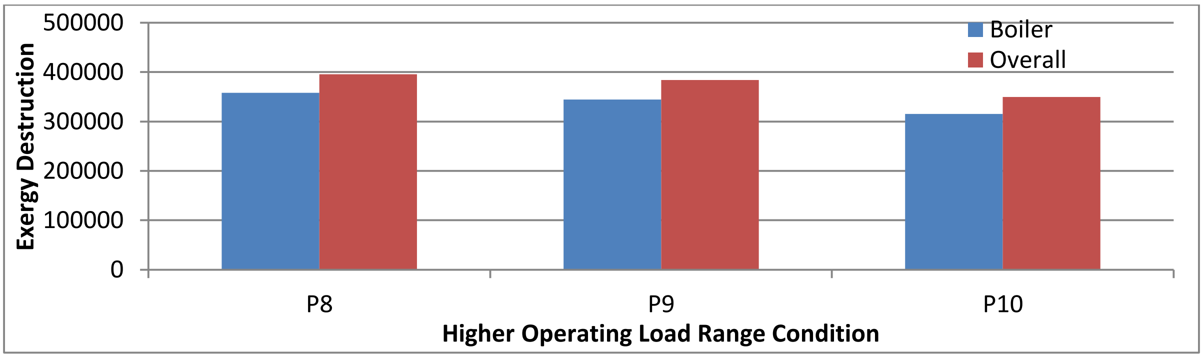


Figure 32. Exergy Destruction of Thermal Power Plant at High Operating Loads

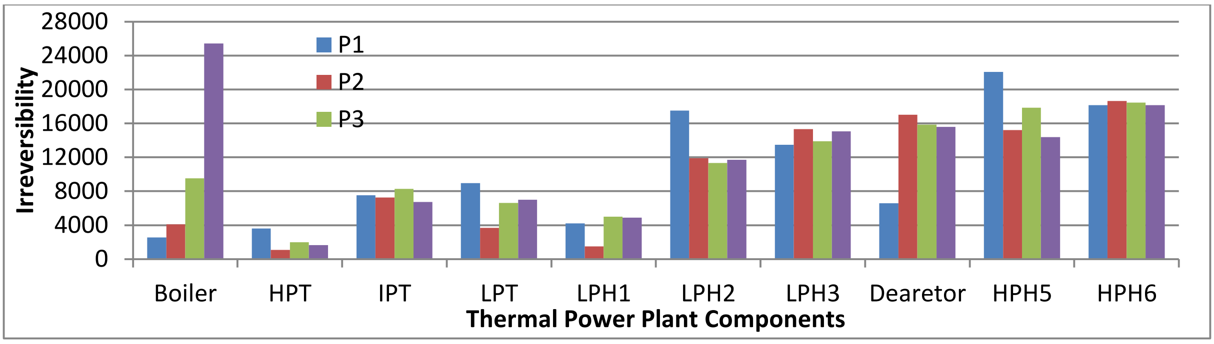


Figure 33. Component wise Irreversibility of Thermal Power Plant at Low Operating Loads

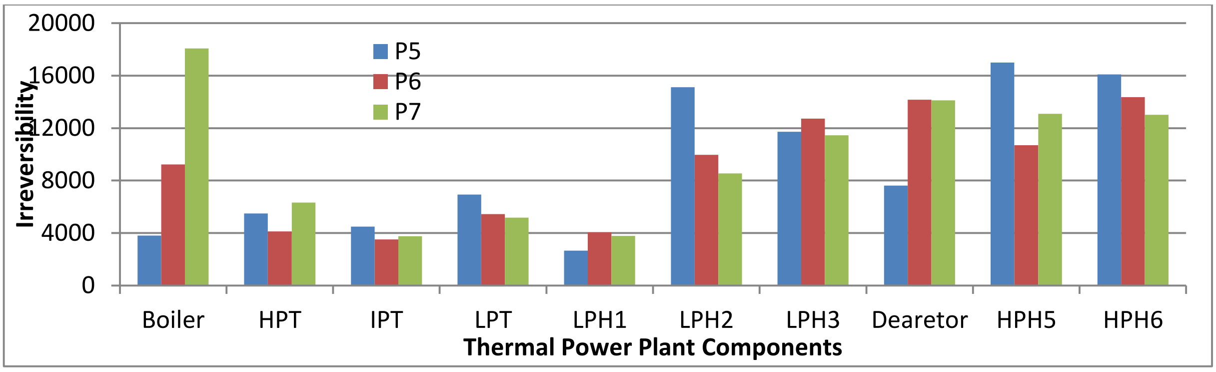


Figure 34. Component wise Irreversibility of Thermal Power Plant at Middle Operating Loads

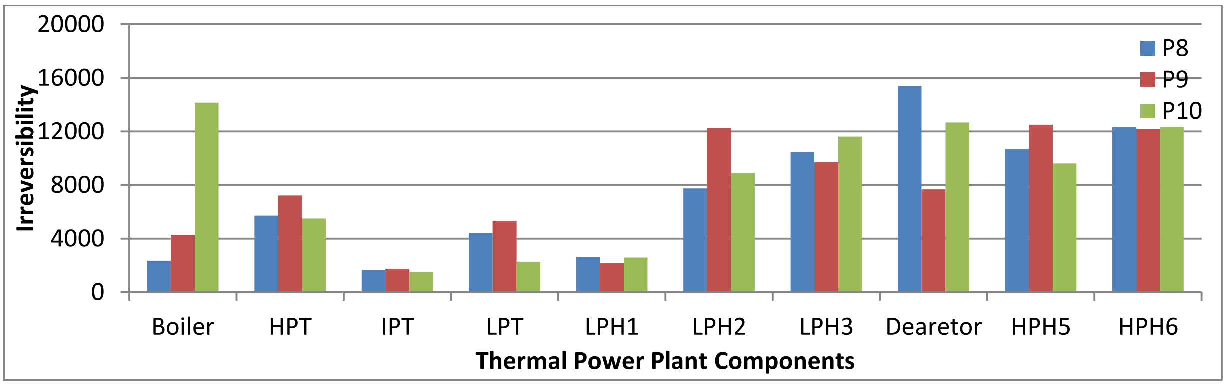


Figure 35. Component wise Irreversibility of Thermal Power Plant at High Operating Loads

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