Available online www.jsaer.com

***Journal of Scientific and Engineering Research*, 2017, 4(7):215-229**

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Energy and Exergy Analysis of a Coal Fired Thermal Power Plant with Varying Load Conditions

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Abstract This article aims to identify the energetic and exergetic efficiencies and the losses in different components of a 250 MW coal based thermal power plant. The analysis has been carried out by considering the design data as well as the operational data at varying load conditions. The distribution of the exergy losses in power plant components has been assessed to locate the process irreversibility. Basically, the power plants are designed based on first law of thermodynamics that does not afford to calculate useful energy losses of the system due to the quality and quantity of energy difference. This study deals with the comparison of energy and exergy analyses of the Barapukuria coal fired thermal power plant of Bangladesh, which deals with both first and second law of thermodynamics. Operation and maintenance decisions based on exergy analysis (second law analysis) would be more effective for operation of the thermal power plant.

Keywords Thermodynamic analysis; energy efficiency; exergy analysis; coal fired plant; thermal power plant

Introduction

Electricity plays a vital role in developing any country as well as living standards of communities. To meet the increasing demand, the electricity is being produced from the various form of fuel. From the statistics of International Energy Agency (IEA), 64.81% electricity in the world is being produced from fossil-fuels (coal, gas, and oil), 6.57% from nuclear energy and late portion (28.62%) from renewable energy sources including hydraulic, wind, solar, geothermal and biogas [1]. In generally, the performance of thermal power plants is evaluated through energetic performance criteria based on first law of thermodynamics, including electrical power and thermal efficiency [2]. In recent decades, the exergetic performance based on the second law of thermodynamics has found as useful method in the design, evaluation, optimization and improvement of thermal power plants. Therefore, performing exergetic and energetic analyses together can give a complete delineation of power plant items [3]. Energy is always conserved in every device or process. Unlike energy, exergy is not generally conserved but is destroyed [4]. The performance of the plant was estimated by a component-wise modeling followed by computer program, “Cycle-Tempo”. The loss of exergy or irreversibility provides a quantitative measure of process inefficiency [5].

As per the statistics of 2014, among 5940 GW of total electricity generation, 1880 GW is generated from coal [1] which is the 31.64% of total generation. As per recent statistics (February 01, 2017) of Bangladesh Power Development Board (BPDB), the electricity production by coal is only 1.90% of total electricity generation of country [6]. Bangladesh has up to 2.7 billion short tons of high-quality coal reserves [7] and thus coal-based thermal power plants can play an important role for Bangladesh to produce electricity. There exists large number of research concerning energetic and exergetic performances of coal-fired thermal power plants. For instance, Datta et al. [8] presented work on exergy analysis of a coal-based thermal power plant using the design data from a 210 MW thermal power plant. Rosen [9] presented energy and exergy-based comparison of coal-fired and nuclear steam power plants. The results are reported of energy and exergy-based comparisons of coal-fired and nuclear electrical generating stations. Ganapathy et al. [10] determined the energy losses and the exergy losses of the individual components of the lignite fired thermal power plant. The comparison between the first law efficiency (energy efficiency) and the second law efficiency (exergy efficiency) of the individual components of the plant also calculated. Suresh et al. [11] described efficiency improvement in various components of a power generating system. Sachdevaet al. [12] worked to identify the magnitude, location and source of thermodynamic inefficiencies. Rudra et al. [13] examined to increase coalfired steam power plant efficiency by advance steam parameters. Heat can be lost from boilers by a variety of methods, including hot flue gas losses, radiation losses and, in the case of steam boilers, blow-down losses [14] etc. Since most of the heat losses from the boiler appear as heat in the flue gas, the recovery of this heat can result in substantial energy saving [15]. The technology involved in a boiler can be seen as having reached a plateau, with even marginal increase in efficiency painstakingly hard to achieve [16]. Bejan [17] draw outlines the fundamentals of the methods of exergy analysis and entropy generation minimization (or thermodynamic optimization-the minimization of exergy destruction). Tapan et al. [18] presented a 500 MW steam turbine cycle to identify the components that offer significant work potential saving opportunity. Kaushik et al. [19] presented the comparison of energy and exergy analyses of thermal power plants stimulated by coal and gas. Therefore, exergy analysis is as important as energy analysis for design, operation and maintenance of different equipment and systems of a power plant. It is important that the performance monitoring of an operative power station includes exergy analysis besides the energy analysis.

However, elaborate exergy analysis has not yet been practiced widely in power stations because of a lack of clearly defined codes and standards for this.Although a substantial research has been carried out, but more effective research is indispensible to investigate results on thermodynamic aspect of coal fired thermal power plant with various loading conditions which did not focus on the previous study. This work has been taken an inventiveness to predict the exergy and energy analysis of the coal based thermal power plant. In order to perform the exergy analysis of the plant, the detail steam properties, mass, energy and exergy balances for the unit were conducted. The exergy values of each component are calculated by assuming that the component is in an open (control volume) system and there are only physical exergy associated with the material streams.

Process Description

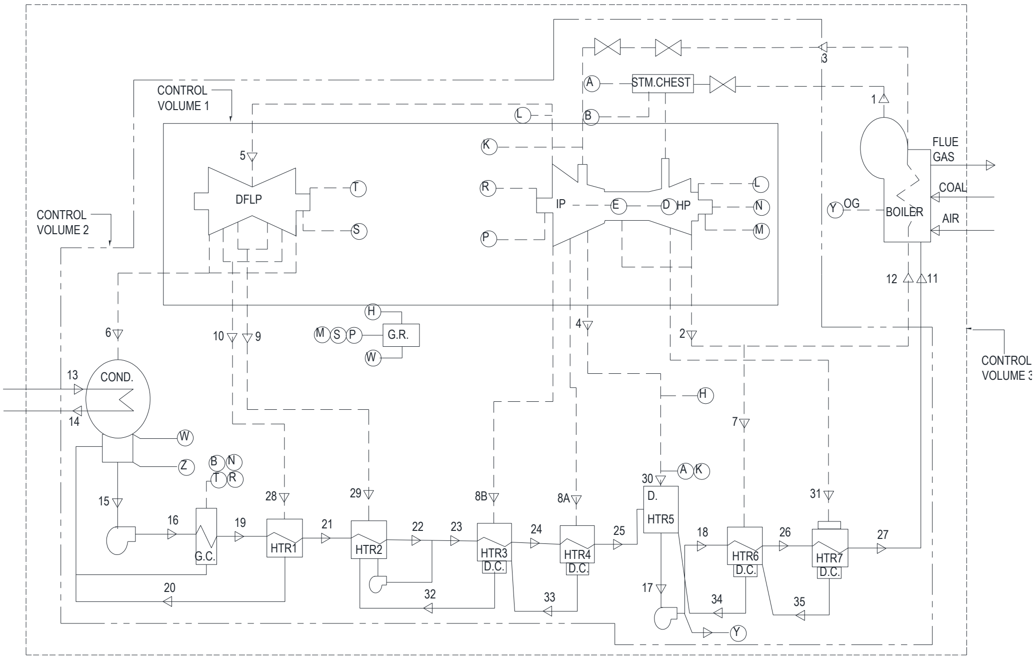

Figure 1: Flow diagram of Barapukuria 2 x 125 MW coal fired thermal power plant

The first coal-fired power plant in Bangladesh started commercial production with the capacity of 250 MW at Barapukuria, Parbotipur in January, 2006. The plant is operated under Bangladesh Power Development Board (BPDB), which consists of 2 units (2 x 125 MW). This plant is operating on sub-critical steam conditions. Coal fired thermal power plant generally operates on Rankine cycle [20]. The schematic arrangement of equipments of this power plant is shown in Fig. 1.

The major components of the plant are high, intermediate and differential low-pressure turbines (HPT, IPT and DFLP), boiler (B), pumps (P), deaerator (D), generator (G), condenser (C), low and high-pressure feed water heaters etc. The thermodynamic models of this power plant are based on fundamental mass, energy and exergy balances. Using the mass, energy and exergy balance equations for each component of the power plant, it is possible to compute energy and exergy flows at each node of the plants, energy and exergy efficiencies and irreversibilities of the component and so on. The plant consists of three turbines, namely high, intermediate and low pressure (HP, IP and LP) and is connected to the generator. The energy and exergy flows are computed using the plant operation design and operating data at different unit loads. Steam flows to HP Turbine (point 1) with high energy and high exergy, after producing work on expansion in HP turbine, cold reheat steam (point 12) with low energy and exergy flows back to boiler for reheating, hot reheat steam (point 3) with high energy and exergy flows to IP turbine and then LP turbine, where further expansion takes place and work is produced. Wet steam (vapour fraction = 0.92) is exhausted from LP turbine to condenser at a very low pressure, of the order of 86 kPa (abs). A large quantity of circulating water (CW) flows to the condenser (point 13) almost at ambient temperature, takes away heat of condensation and flows back to the river (point 14).The condensate exits the condenser (point 15) with low energy and almost negligible exergy and is pumped by the condensate extraction pump (CEP) to the deaerator through LP heaters (HTR1 to HTR4). Deaerator feeds (point 17) to BFP, which raise the pressure of feed water flow (point 18) to sufficiently high value to flow through high pressure heaters (HTR6 and HTR7) and back to the boiler (point 11) for generation of steam and the cycle continues. Thus, energy and exergy flows associated with the flow of the working fluid to the control region of the turbine cycle through three streams (point 1, 3 and 13), and from the control region through three streams (point 11, 12 and 14).Final feed water (point 11) temperature rises across feed heaters by transferring heat from turbine extraction steam and facilitates high temperature heat addition in boiler. Some baseline data of the Barapukuria 250 MW coal based power plant are presented in Table 1.

Table 1: Designed standard data of the Barapukuria 250 MW coal based thermal power plant

Dimension	**Value**
Coal flow	55 t/h
Ash production	6.6 t/h
Flue gas flow	700,000 Nm^3/h
Flue gas temperature	150 ^oC
Emission SO_x on average	0.600 t/h
Emission SO_x max	0.735 t/h
Emission NO_x max	500 mg/Nm^3
Particulate matter	50 mg/Nm^3
Stack height	95m
Circulating cooling water	14,000 m^3/h

Mathematical Equations

The energy rate of a stream can be calculated from the following governing equation:

$$En = m_{in}\left(h_{in} - h_o\right) \tag{1}$$

And the specific physical exergy of the stream can be calculated from the following equation:

$$e_{in} = \left(h_{in} - h_o\right) - T_0(S_{in} - S_0) = \Delta h - T_0 \Delta S \tag{2}$$

Overall Energy Efficiency

To calculate the overall efficiency of the plant, the control volume 3 (Fig. 1) is considered. The coal ofthe power plant represents the typical coal of Bangladesh (Barapukuria coal mine) with lower heating value 22.7 MJ/Kg.The rate of energy entering the control volume with fuel (coal) can be calculated by-

$$En_{in}^{f} = m_{in}^{f} \times LHV \tag{3}$$

Where, m_{in}^{f} is the mass flow rate of coal at inlet and LHV is the lower heating value of the coal. The total energy flow rate entering the control volume 3 is written as-

$$En_{in} = En_{in}^{f} + En_{13} \tag{4}$$

Considering the energy input with fuel and circulating water, the following composition (by mass) of coal has been considered: 83% C, 5.1% H_2, 9.4% O_2, 1.7% N_2, Ash 12.4%, H_2O 10%. Considering the complete combustion of the coal in oxygen and that the hydrogen in coal (as H_2) is fully oxidized during combustion, the stoichiometric equation becomes as follow-

$$C + 0.37H_2 + 1.18O_2 = CO_2 + 0.37H_2O \tag{5}$$

The energy flow rate leaving the control volume 3 with flue gas is-

$$En_{out}^{9} = \sum m_j^{9} h_j^{9} \tag{6}$$

The total energy flow rate leaving the control volume 3 with flue gas and circulating water-

$$En_{out} = En_{out}^{9} + En_{14} \tag{7}$$

The net power output from the control volume 3 is-

$$P_{net} = G - P_{out} \tag{8}$$

The energy efficiency (or the first law efficiency) of the control volume 3 is written as follows-

$$\eta_1 = \frac{P_{net}}{En_{in} - En_{out}} \tag{9}$$

Overall Exergy Efficiency

Rate of exergy entering the control volume with fuel:

$$Ex_{in}^{f} = m_{in}^{f} n_c \frac{\bar{e}_{in}^{f}}{M_c} \tag{10}$$

Where, η_C is the mass fraction of carbon in coal and M_C is the molecular weight of carbon. The exergy efficiency or the second law efficiency of the control volume 3 is evaluated accordingly using the following equation:

$$\eta_2 = \frac{P_{net}}{Ex_{in} - Ex_{out}} \tag{11}$$

Energy analysis for the component

In an open flow system, there are three types of energy transfer across the control surface namely- work transfer, heat transfer, and energy associated with mass transfer and/or flow. The first law of thermodynamics or energy balance for the steady flow process of an open system is given by:

$$\sum Q_k + m(h_j + \frac{c_1^2}{2} + gZ_1) = m(h_0 + \frac{c_0^2}{2} + gZ_0) + W \tag{12}$$

Where, Q_k is the heat transfer to system from source at temperature T_k, and W is the net work developed by the system. The other notations- C is the bulk velocity of the working fluid, Z is the altitude of the stream above the sea level, g is the specific gravitational force. To analyze the possible realistic performance, a detailed energy analysis of the coal fired thermal power plant system has been carried out by ignoring the kinetic and potential energy change. To calculate specific enthalpy and specific entropy, thermodynamic property tables are used for water and steam.

Results and Discussion

The design data of the plant components of Barapukuria 2 x 125 MW coal based thermal power plant have been used for the current energy and exergy analysis to calculate the energy and exergy flow at different state points. The energy and the exergy efficiencies of these components have been determined using the equations given in the previous section. Energy and exergy flow rates, for the complete power cycle are computed from the plant design data at approximately 100%, 80% and 50% of loading condition.

T-s Diagram of the Complete Cycle

The total cycle of the power plant consists of six closed feed water and an open feed water heater (Deaerator). The T-s diagram is shown in Fig. 2,which represents the principal states of the complete cycle. The working fluid passes isentropically through the turbine stages and pumps, and there are no pressure drops accompanying the flow through the other components. The steam does not expand to the condenser pressure in a single stage.

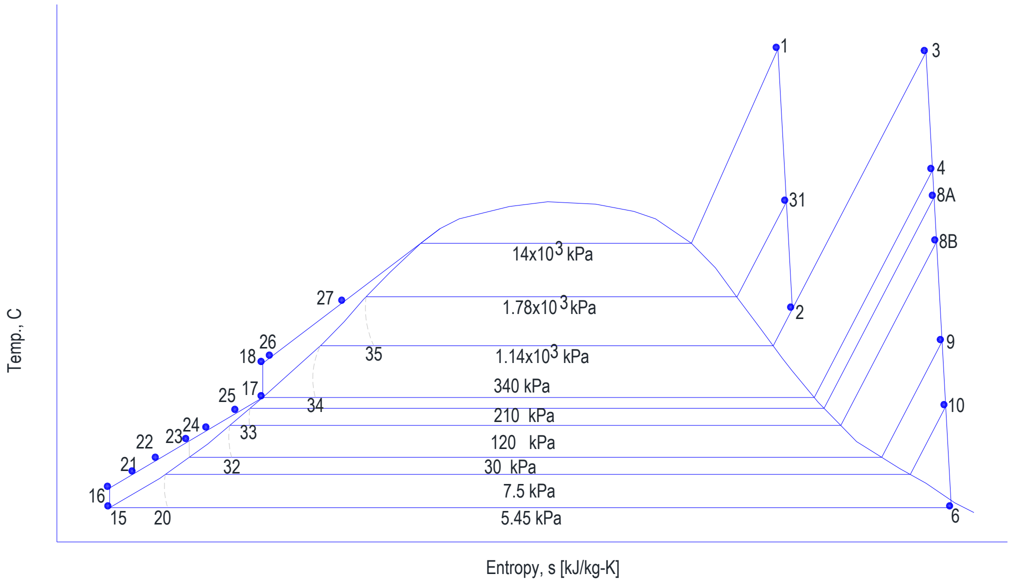

Figure 2: T-s diagram of total power cycle

The steam (Temp. 515°C, 14.00 Mpa) enters the HP turbine at state 1 and expands to state 2, where a fraction of the total flow is extracted, or bled, into two closed feed water heater HTR6 and HTR7 (state 7 and state 31). The steam is then reheated. After reheating, the steam (Temp. 510°C, 1.078 Mpa) enters the IP turbine at state 3 and expands to state 5.A fraction of the total flow is extracted, or bled, into one open feed water heater HTR5 (deaerator, state 30) and two closed feed water heater HTR3 and HTR4 (state 8B and state 8A).The rest of the steam expands through the LP turbine to state 6.This portion of the total flow is condensed to saturated liquid at state 15. The mass flow rates of the streams entering the feed water heater are chosen so that the stream exiting the feed water heater is a saturated liquid at the extraction pressure. The liquid at state 15 is then pumped by the condensate extraction pump. Finally, after increasing the temperature by the feed water heater and increasing the pressure by the boiler feed pump to the steam generator pressure and enters the steam generator at state 27. The cycle is completed as the working fluid is heated in the steam generator at constant pressure from state 27 to 1.

Comparison of Energy and Exergy Efficiency

Energy and exergy efficiencies of the overall power plant are shown in Fig. 3 as a function of 50%, 80%, 100% and 106% of loading condition for the design data. The figure shows that as per design data, with the increase of loading condition the energy efficiency increases linearly, but the exergy efficiency decreases slowly. The overall energy efficiencies of the plant are 35.48%, 56.77%, 70.96% and 75.67% and the overall exergy efficiencies are 44.25%, 33.31%, 30.78 % and 30.21% for 50%, 80%, 100% and 106% loading conditions respectively for the design data.

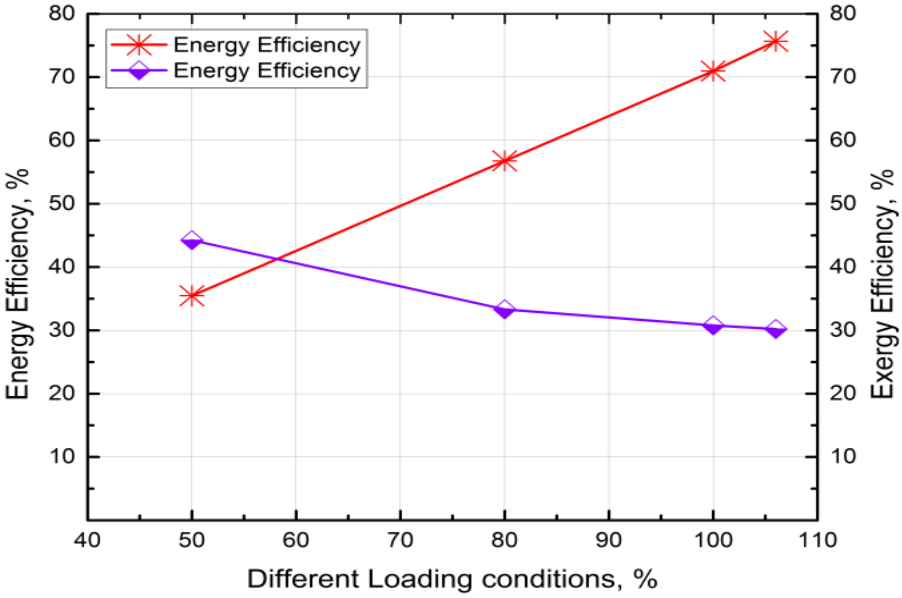

Figure 3: Energy and exergy efficiencies of the overall power plant for design data

Energy and exergy efficiencies of the overall power plant are shown in Fig. 4 as a function of 57% and 67% of loading condition based on operation data. The figure shows that as per operating condition with the increase of loading condition the energy efficiency increases slowly, but the exergy efficiency decreases very slowly.

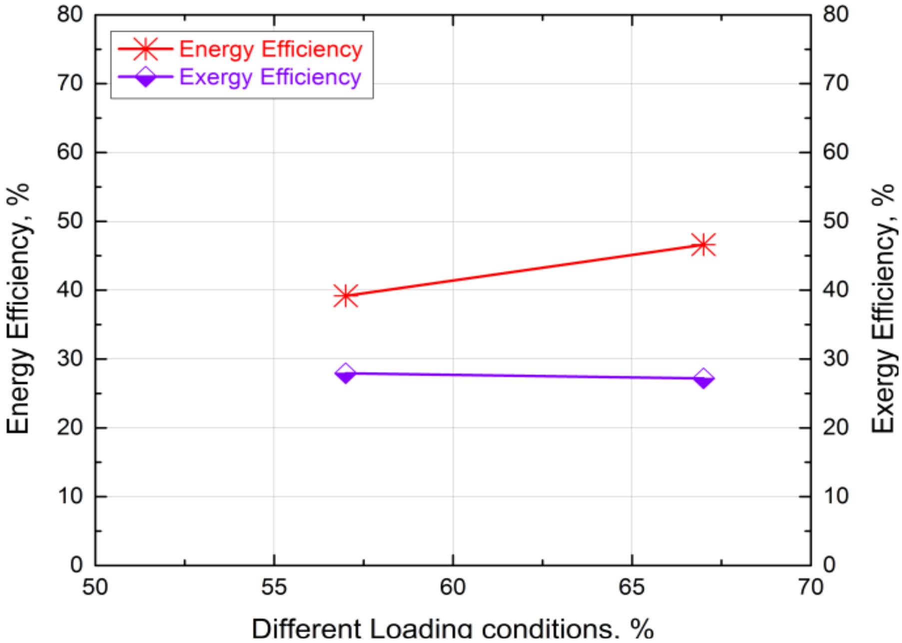

Figure 4: Energy and exergy efficiencies of the overall power plant for operation data

Both the Fig. 3 and 4 show that, an increase in overall energy efficiency and decrease in exergy efficiency with the increase in load percentage. It is understandable from Fig. 4 that, operation of the plant below 56% of the designed capacity results in the significant increase of exergy efficiency and at that point energy and exergy efficiency is same. The decrease in exergy efficiency is attributed to the loss of exergy in the steam generation unit (Boiler) and turbine. There is a striking difference in the composition of the represented energy and exergy balances. It is noted that the exergy analysis has enabled the identification of the causes of process inefficiencies in detail when compared to the energy analysis. However, the overall energy and exergy efficiencies of the power plant during operation are 39.2%, 46.6% and 27.9 %, 27.2% for 57% and 67% loading conditions respectively, which are lower than the design value.

Component Wise Energy and Exergy Analysis

The comparisons of energy efficiency and exergy efficiency as well as losses between different components of the power plant are represented from Fig. 5 -10 for different loading conditions.

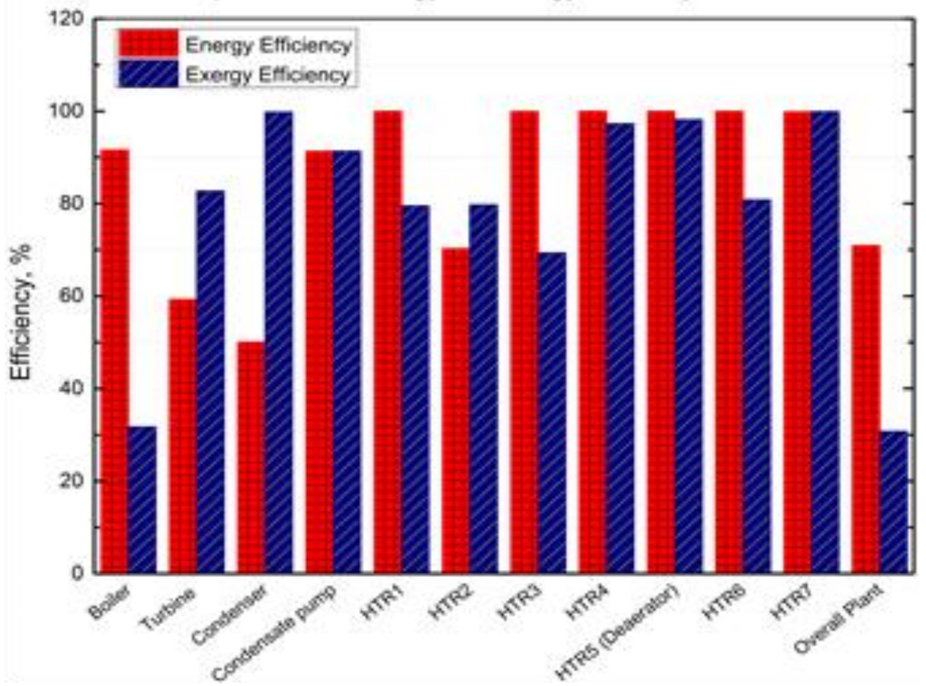

Figure 5: Comparison of energy and exergy efficiency of the plant components for 50% load

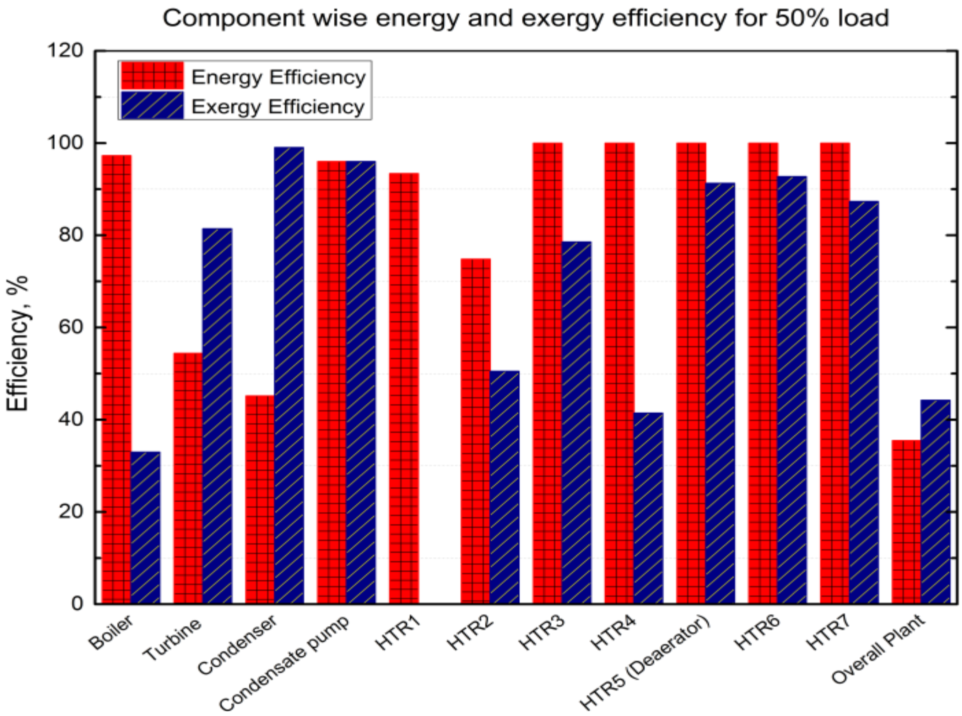

Figure 6: Comparison of energy and exergy efficiency of the plant components for 80% load

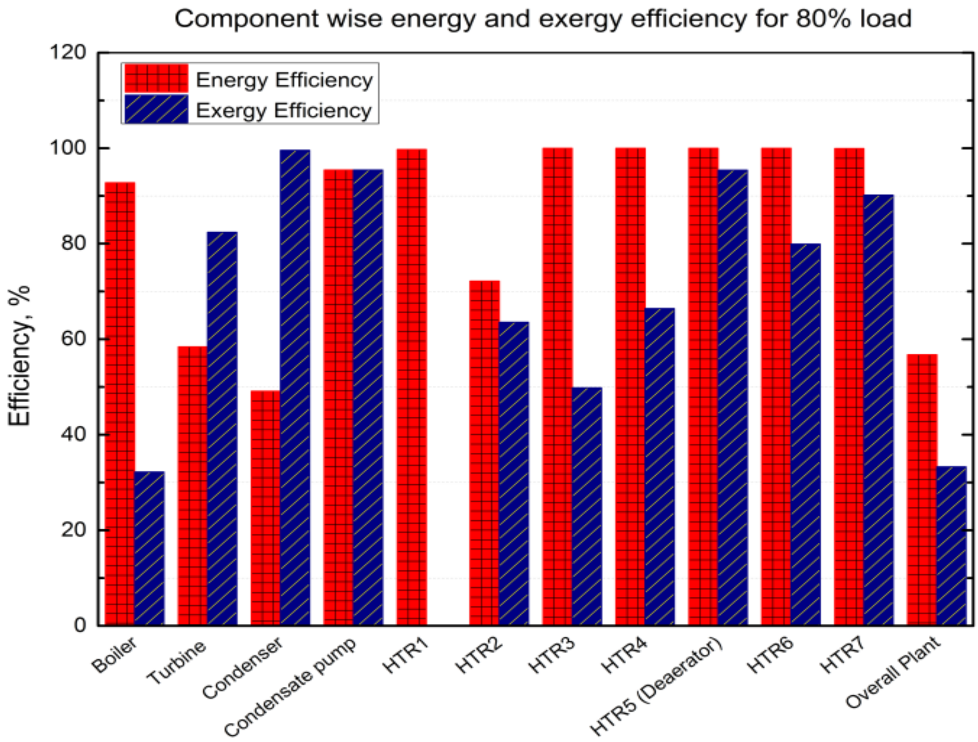

Figure 7: Comparison of energy and exergy efficiency of the plant components for 100% load

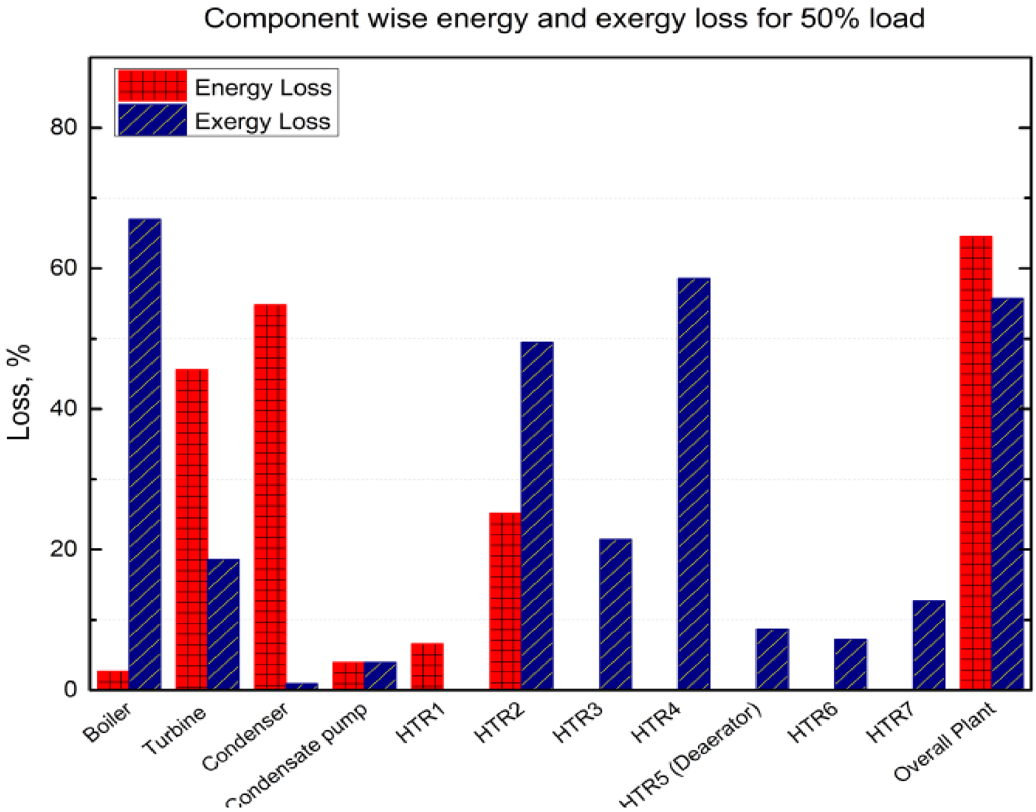

Figure 8: Comparison of energy and exergy loss of the plant components for 50% load

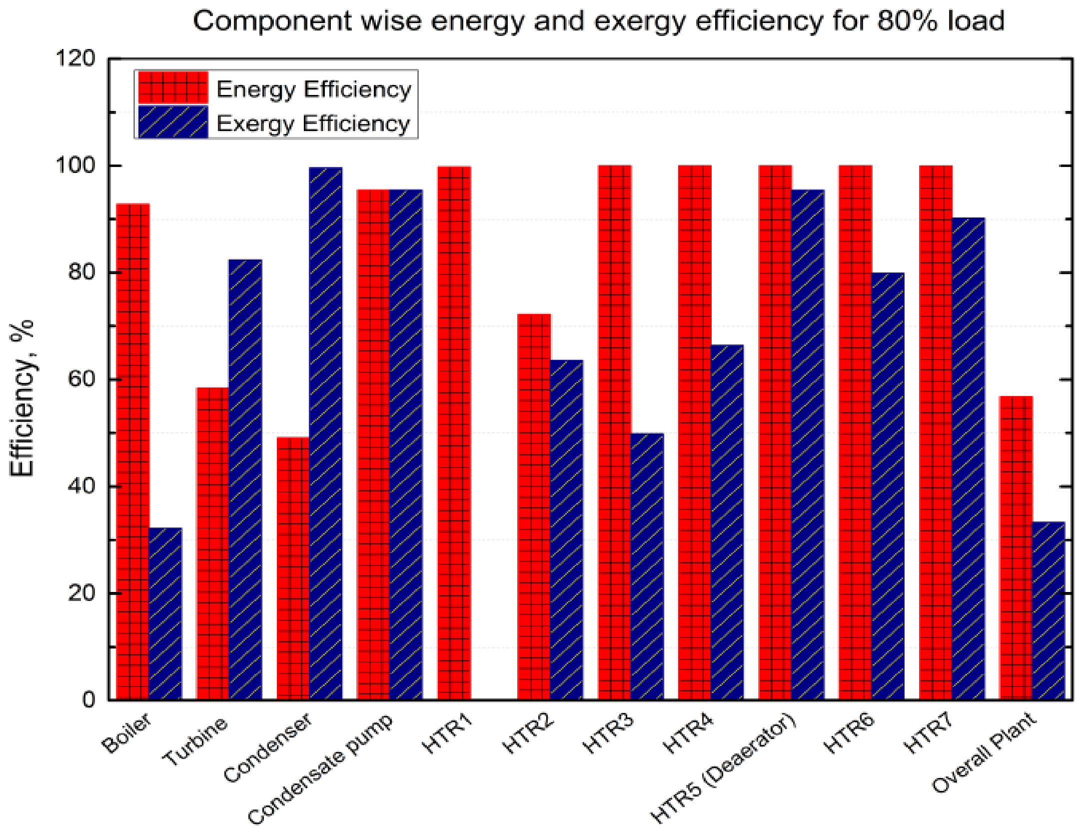

Figure 9: Comparison of energy and exergy loss of the plant components for 80% load

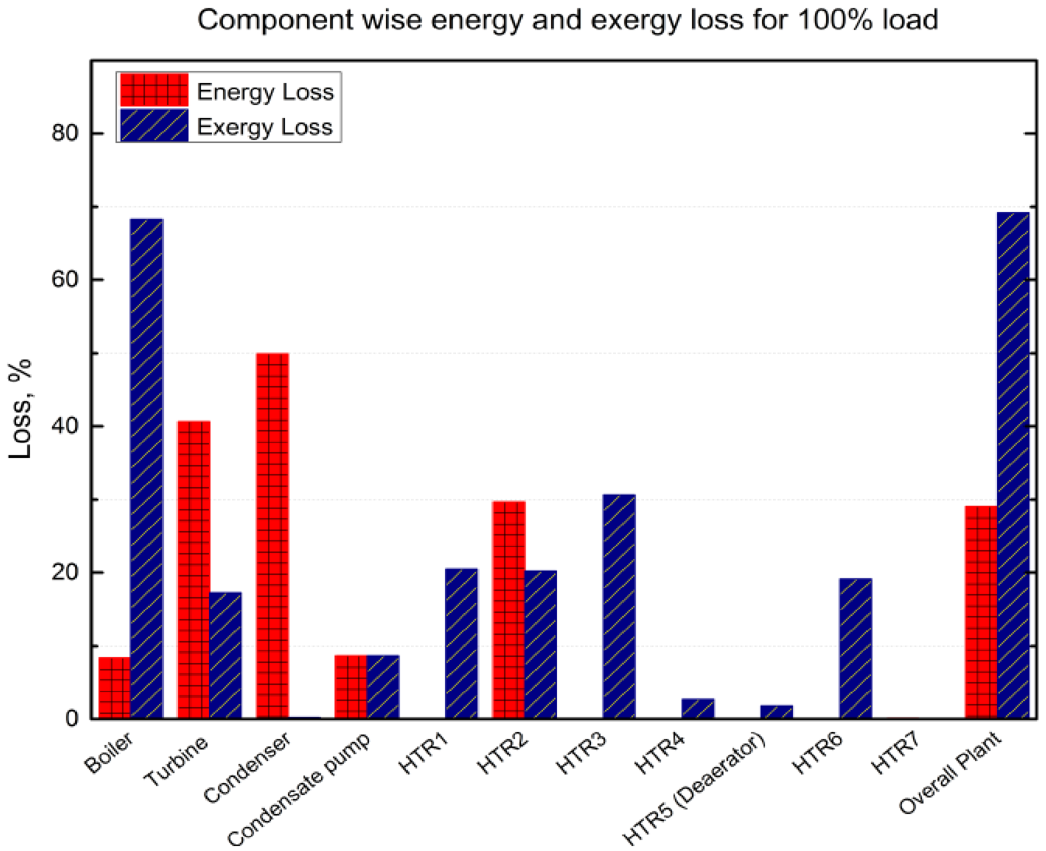

Figure 10: Comparison of energy and exergy loss of the plant components for 100% load

Comparison of Energy and Exergy Efficiency

The comparison of energy efficiency and exergy efficiency between different components of the power plant is represented in Fig. 5- 7 for different loading conditions. The energy efficiency of the boiler is always higher from the exergy efficiency for all loading conditions. The energy efficiency of the turbine is always lower than the exergy efficiency for all loading conditions. But the energy efficiency of the heaters varies significantly with the exergy efficiency for all loading conditions. The overall plant energy efficiency is higher than the exergy efficiency for 50% and 100% loading conditions but lower for 80% loading condition. So, poor part-load energy efficiency is attributed to higher relative energy rejection. On the contrary, poor part-load exergy efficiency is not due to higher relative exergy rejection but caused by higher relative exergy consumption.

Comparison of Energy and Exergy Loss

The comparison of energy efficiency and exergy losses between different components of the power plant is represented in Fig. 8- 10 for different loading conditions. The energy loss of the boiler as well as turbineare always significantly lower than exergy loss for 50% and 100% loading conditions but higher for 80% loading condition. The overall plant energy loss is higher than the overall plant exergy loss for 50% and 80% loading condition but lower for 100% loading condition. From the Fig. 10, it can be observed that the maximum energy loss (49.92% at 100% load) occurred in the condenser. Thus the first law analysis (energy analysis) diverts our attention towards the condenser for the plant performance improvement. Approximately half of the total plant energy losses occur in the condenser only and these losses are practically useless for the generation of electric power. Thus the analysis of the plant based only on the first law principles may mislead to the point that the chances of improving the electric power output of the plant is greater in the condenser by means of reducing its huge energy losses, which is almost impracticable. Hence the first law analysis (energy analysis) cannot be used to pinpoint prospective areas for improving the efficiency of the electric power generation. However, the second law analysis (exergy analysis) serves to identify the true power generation inefficiencies occurring throughout the power station.

Component Wise Energy and Exergy Losses

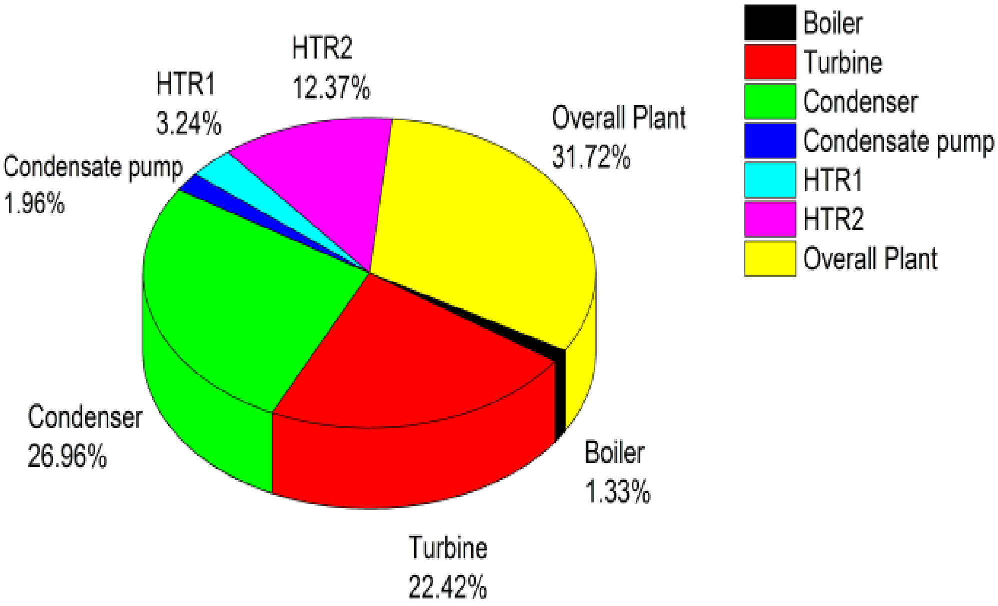

Figure 11: Comparison of energy loss of the plant components for 50% load

The comparison of energy exergy losses between the different subsystems of the plant are shown in Fig. 11 - 14. It is observed from the pie-charts (Fig. 11- 14) there is great difference between the energy and exergy analysis of the components. It can be noted that the maximum exergy loss occurs in the boiler subsystem (68.27% at

100% load). This may be due to the irreversibility of the combustion process in the combustor (boiler). The exergy destruction rate of the condenser is only 0 .21%. The real loss is primarily back in the boiler where entropy was produced. Contrary to the first law of thermodynamics analysis, this demonstrates that significant improvements exist in the boiler system rather than in the condenser. The calculated exergy efficiency of the power cycle is 30.78% at 100% load. This indicates that remarkable opportunities are available for improvement. However, part of this irreversibility cannot be avoided due to physical, technological, and economic constraints. Exergy analysis can also be effectively used to take important decisions pertaining to operation as well as maintenance. There are cases, when conventional performance parameters do not indicate, whether an off-design operating condition is beneficial or detrimental to the overall cycle performance. Any operation decisions based on the energy analysis will be incorrect for the overall plant performance.

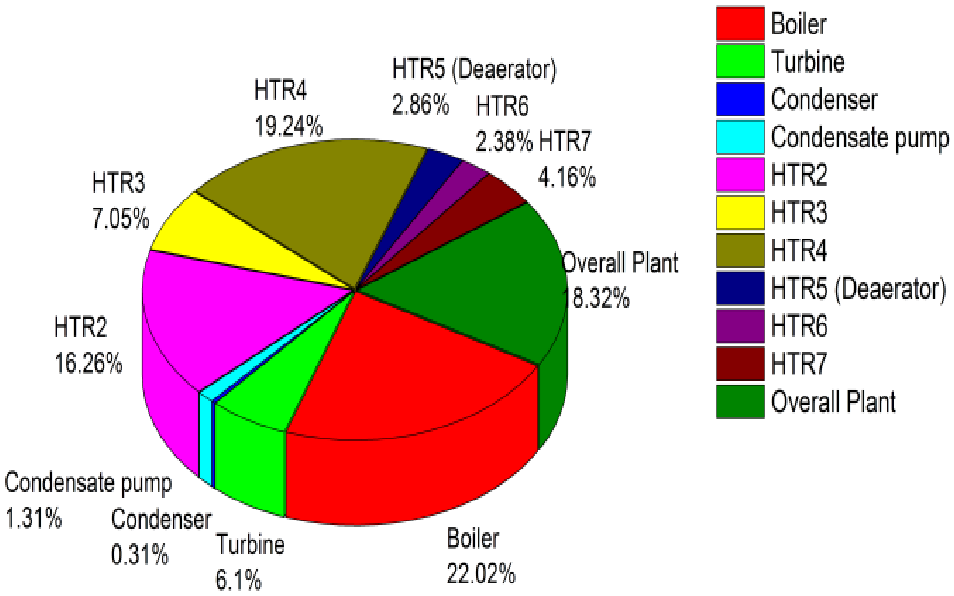

Figure 12: Comparison of exergy loss of the plant components for 50% load

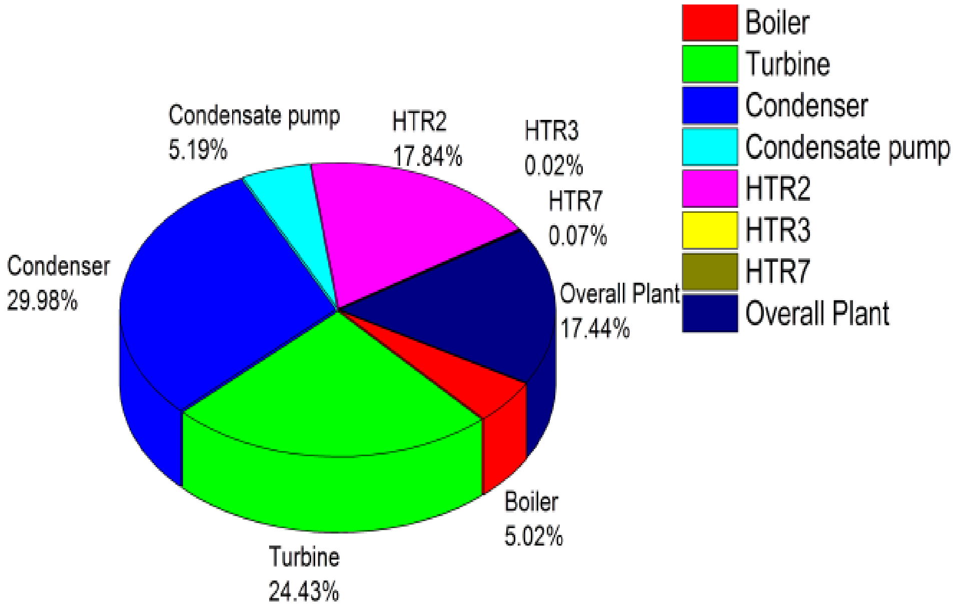

Figure 13: Comparison of energy loss of the plant components for 100% load

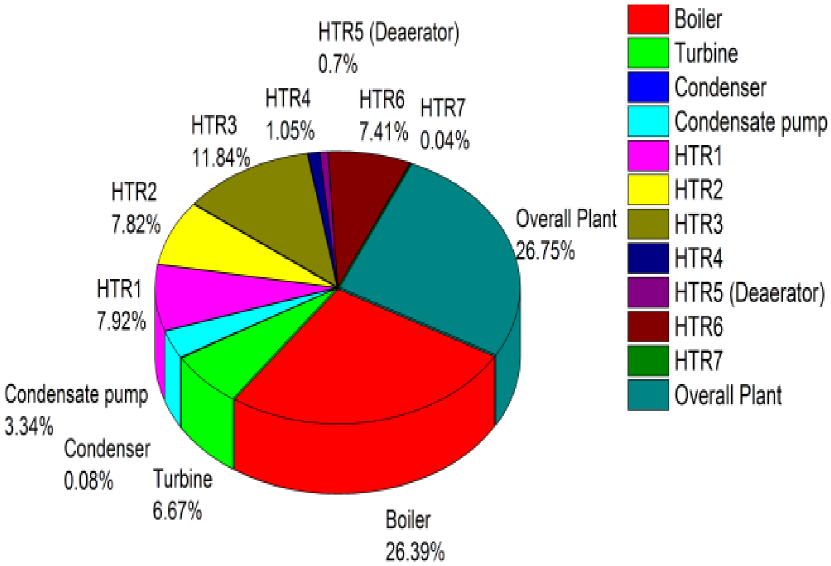

Figure 14: Comparison of exergy loss of the plant components for 100% load

The exergy consumption during a process is proportional to entropy creation, which accounts for inefficiencies due to the irreversibilities. The exergy consumption or order of destruction is a form of environmental damage. By preserving exergy through increased efficiency (i.e. degrading exergy as little as possible for a process), environmental damage is reduced [21].Operation and maintenance decisions based on exergy analysis of the power plants proved more effective. Power station equipment involves high density of exergy transfer and therefore, it is important that exergy destruction is minimized in such devices. Exergy-based approach of performance monitoring in operating power plants helps in better management of energy resources and environment.

Energy and Exergy Efficiency of Turbine

Energy efficiency of the turbine cycle is low (47.25% at 100% load) due to a large quantity of energy rejection in the condenser. The derived exergy efficiency of the turbine is high (83.14 % at 100% load), due to the reason of little exergy associated with turbine exhaust steam enters condenser, part of which is rejected to CW and partly consumed due to irreversibilities.

Energy and Exergy Efficiency of Heater

Extraction steam to LP heaters (HTR1 to HTR4) are at low pressure and temperature and have low exergy. Deaerator has high exergy efficiency, since exergy flow to it is high in comparison to all other heaters, and large surface area provided for heat transfer and deaeration also reduces irreversibilities (exergy consumption) which are shown in the Table 2.

Table 2: Exergy flows and exergy efficiencies at 100% loading condition of heater

Components	**Net exergy input rate (MW)**	**Useful exergy output rate (MW)**	**Exergy Cons. Rate (MW)**	**Exergy efficiency (%)**
HTR1	0.3	0.2	0.1	79.52
HTR2	2.2	1.8	0.5	79.77
HTR3	3.6	2.5	1.1	69.36
HTR4	2.3	2.3	0.1	97.29
HTR5 (Deaerator)	9.8	9.7	0.2	98.18
HTR6	10.2	8.2	2.0	80.84
HTR7	5.33	5.32	0.01	99.90

Higher exergy consumption rate in HTR6 is due to increased irreversibilities caused by higher temperature difference between hot 217 °C and cold streams 164.9 °C in HTR6. Exergy analysis across HTR6 under this condition shows larger consumption of exergy than the design. This corroborates to the overall plant performance degradation. First law of thermodynamics analysis alone also often does not reflect properly the performance deterioration level of a single component. For example, if the plant runs always with reheat spray (due to some unavoidable limitation at the boiler side), any degradation of the HTR6 performance over time (e.g., due to scale formation on the heat transfer surfaces) would be difficult to trace by energy analysis alone, since the heater would always show better-than-design performance. If an exergy analysis performed across HTR6, it immediately shows that exergy consumption in HTR6 has markedly increased over its design value, warranting remedial actions. The first level of corrective actions is taken in operation level by proper adjustment of drip level, proper venting of air. The next tier of remedial actions can be taken in maintenance level. For instance, after a number of years of service, heater performance deteriorates through film build up (scaling) on heat transfer surfaces. Re-tubing or replacement of the heater can rectify this problem.

Exergy analysis can benefit by pinpointing the sources of irreversibility in different components of a power cycle. Performance tests of a cycle, if conducted on the basis of exergy, can quantify the contribution of individual equipment towards the total deviation of cycle efficiency from the design values. Increase in exergy consumption by one component can be interpreted directly as the "lost power", and hence, the "lost revenue". The cost of maintenance can be weighed against the "lost revenue", making maintenance decision easier. An exergy analysis can identify locations of energy degradation and rank them in terms of their significance. The exergetic analyses not only determine magnitudes, location and causes of irreversibilities in the plants, but also provides more meaningful assessment of plant individual component efficiency. Energy and exergy analyses are shown in this study to be able to understand the performance of coal fired thermal power plants and identify design possible efficiency improvements. It provides logical solution improving the power production opportunities in thermal power plants.

Conclusions

From the presented data and the subsequent analysis, following conclusions can be drawn:

-The comparison between the energy losses and the exergy losses of the individual components of the plant shows that the maximum energy losses (~49.92%) occur in the condenser, whereas the maximum exergy losses (~68.27%) occur in the boiler.

-It has been observed that 68.27% exergy loss occur in boiler. This refers to boiler is not fully adiabatic and combustion is not complete. This large exergy loss is mainly due to the combustion reaction and to the large temperature difference during heat transfer between the combustion gas and steam. Other factors that may contribute to the high amount of exergy loss are tubes fouling, defective burners, fuel quality, inefficient soot blowers, valves steam traps and fouling in air heaters. Inspections of those equipments need to be carried out during the boiler outage. This study pin points that the boiler requires necessary modification to reduce exergy destructions thereby plant performance can be improved.

-The major energy destruction occurs in the condenser which leads to inefficient heat transfer between hot stream (flue gas) and cold stream (water and air).

Acknowledgements

The authors would like to acknowledge the authority of Barapukuria 250 MW coal based thermal power plant and Bangladesh Power Development Board (BPDB) to help during the collection of data from the plant and conduct research. The authors also like to acknowledge Bangladesh University of Engineering and Technology to provide financial support for the research.

Nomenclature/ Appendix

G	Generator output power (kW)
h	Specific enthalpy (kJ/kg)
s	Specific entropy (kJ/kg K)

m	Mass flow rate
n	Mass fraction
C_p	Specific heat of the fluid at constant pressure
En	Energy flow (kW)
Ex	Exergy flow (kW)
η_1	Energy efficiency
η_2	Exergy efficiency
$I_{destroyed}$	Irreversibility rate (kW)
W	Work done (kW)
Mpa	Mega-pascal
n_C	Mass fraction of carbon in coal
M_C	Molecular weight of carbon

Abbreviation

HPT	High pressure turbine
IPT	Intermediate pressure turbine
DFLP	Differential low pressure turbine
CW	Cooling water
CEP	Condensate extraction pump
BFP	Boiler feed pump
HTR	Heater
BPDB	Bangladesh Power Development Board
LHV	Lower Heating Value
Nm^3/h	Normal cubic Meter per hour

Subscripts/Superscripts

a	Air
f	Fuel
g	Flue gas
in	Inlet
j	Species /stream identification
out	Outlet
o	Reference state

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