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Exergy Analysis of a Thermal Power Plant

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***Abstract* -_The research is based on the exergy analysis of a thermal power plant, for which M/s. Bhushan Power & Steel, Thelkoli, Odisha has been taken into consideration. The primary objective of the work is to analyse the system components separately to identify the parts responsible for having loss of exergy at large. The conclusion of the research can enable to configure suitable modifications to improve efficiency of the system components and to minimize the exergy loss of the power plant.**

Based on a study of exergy destruction, the boiler system is having a max. 64.04% of exergy loss. The exergy efficiency of the power plant is found 50.41%, which is low as compared to modern power plants. According to analysis it is found that boiler is the major source of irreversibility in the power plant, butexergy destruction rate in boiler can be reduced by introducing reheating system. It is a suitable technique to decrease boiler's irreversibility. The effect of reheating for improvement of overall performance is compared to the real condition of power plant in this research work. Without any change of fuel consumption, the effect of reheating to minimize exergy destruction has been also investigated. By introducing reheating system it is found that not only boiler's exergy destruction minimized but also overall plant efficiency and power generation has been increased.
Keywords: Exergy analysis; exergy efficiency; Exergy destruction; dead state; steam power plant.

<u>Nomenclature</u>

h	*Enthalpy (kj/kg)*
X	*Exergy (KW)*
M	*Mass flow rate*
P	*Pressure (bar)*
Q	*Heat transfer (kj)*
S	*Entropy (kJ/kg)*
T	*Temperature (k)*
I	*X destruction*
X	*Exergy*
ST	*Steam turbine*
In	*Inlet*
G	*Gas*
I	*Irreversibility*
Greek symbols	
η	*Exergy efficiency*
Ψ	*Specific exergy (kj/kg)*
S	*Steam*

INTRODUCTION

1.1 Introduction of power sector

Now-a-days, electricity is a basic need to human life. From personal to professional life, from home accessories to industrial machineries nothing can be imagined making aside the electricity. As such, power generation industry reflects a major role in the economic upliftment of the country. Presently, 80% approx. of total electricity consumed in the world is being produced from fossil fuels i.e. coal & petroleum products and only 20% approx. is produced from other sources like wind, water, hydraulic, solar, biogas, geothermal etc.

Now a day exergy analysis of power plant is of scientific interest for making efficient utilization of energy resources as they are constant in nature. The analysis of an energy conversion process is normally carried out by the first law of thermodynamics. But now a day, there is an increasing interest in the combined utilization of the first and second laws of thermodynamics, using both the law exergy and irreversibility can be calculated. By which one can evaluate the efficiency with which the maximum available energy is consumed. Exergy analysis method is a tool for clear distinction between the energy losses to the environment and internal irreversibility of the process.

1.2 Thermal power plant

Thermal power plants are the back bone of Indian power sector. In India 68.14 % of electricity is generated by the thermal power plant. A thermal power plant continuously convert the energy stored in fossil fuels (coal, oil, natural gas) into shaft work and ultimately into electricity. Thermal power plant converts heat energy of the working fluid into electrical energy. The working fluid is sometime in the liquid phase and sometime in the vapour phase during its cyclic operations.

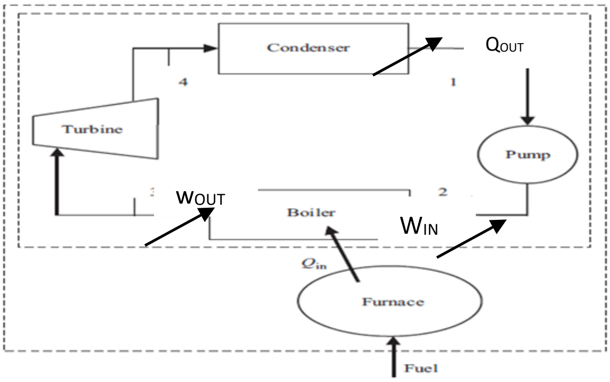

Fig: 1 Common power cycle of thermal power plant

1.2.1 Working Principle of thermal power plant:

The thermal power station is a power plant in which the prime mover is driven by steam. Water is heated in a boiler converts into steam and the steam passes through a nozzle which impact force on the turbine blade. This impact force produces turning moment to rotate the turbine shaft which drives an electrical generator to produce electricity. After expansion of stem in the steam turbine, it passes to the condenser where heat is taken away by the cooling water coming from the cooling tower or river bed. Makeup water is supplied to make the water level constant in the boiler. The condensed steam along with the makeup water is recycled to the boiler by a feed pump where it is again heated. The cycle is repeated continuously. This is known as a "Rankine cycle".

1.2.2 Reheating cycle

If higher steam pressures are used, in order to limit the quality of steam to 0.85 at the turbine exhaust reheating system is adopted. In that case all the steam after partial expansion in the high pressure turbine is brought return back to the boiler reheater, reheated by combustion gases and then feed back to the low pressure turbine for further expansion.

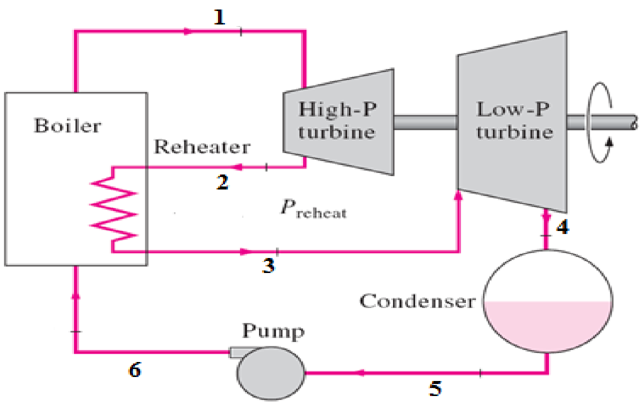

Fig: 2 Simple reheat cycle of thermal power plant

In the first step, steam expands in the high pressure turbine from the initial state and the steam is then reheated in the boiler and the remaining expansion is carried out in low pressure turbine. With the use of reheat cycle the network output of the plant and performance will increase of as the fuel consumption is same.

1.3 Plant description

Bhusan power and steel plant is located 300 m above the sea level at village thelkoli, 10 km away from Jharsuguda district head quarter, Odisha (India).The power plant has total installed power capacity of 300 MW in full load condition. It has been started to produce power in the last of nineties.The plant produces 300 MW (at full load) from three number turbine generators each 100 MW capacity. For running of these turbine generators there are five number of boiler. For turbine no I, two number boiler having capacity 210 ton per hour is used. For turbine no II, two number boiler having capacity 210 ton per hour is used. For turbine no III only one boiler having capacity 390 ton per hour is used. Till to date there is no reheating system used in this thermal power plant. The power plant used coal and sometimes charcoal as fuel.

The schematic flow diagram of actual power plant is shown in Fig. 1.3.1. Feed water heating is carried out in three stages i.e. low pressure heater, high pressure heater I and high pressure heater II. Steam is superheated to 793 K (T) and 96.108 (P) bar in the boiler and fed to the turbine. There are four number of turbine bleed. One number for lp heater, two number for hp heater and one number for dearator. The turbine exhaust streams are sent to condenser at 0.09 Bar and 42.9°C, the steam is condensed in the condenser and go to hot well. The makeup water enters to the hot well at temperature 54°C. The condensate sent to the dearator through lp heater by the condensate extraction pump. Then the water is recycled to boiler through hp heater-I and hp heater-II by the feed pump, where water is heated; this known as a 'Rankine cycle'. This power cycle starts over and over again. In Bhusan thermal power plant coal (sometimes charcoal) is used as the working fluid, which calorific value is 4011.625 Kcal/Kg, which are very low grade coal in quality.

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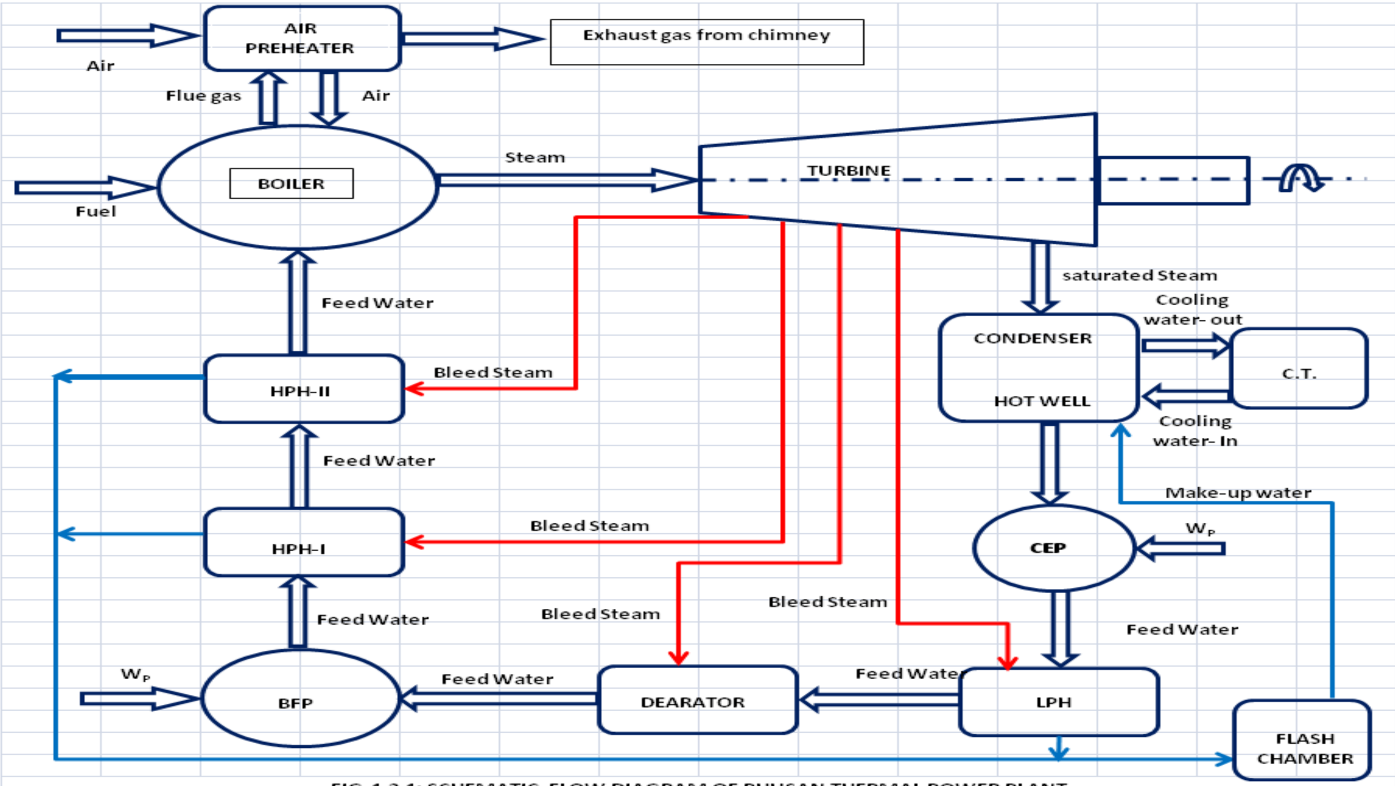

FIG-1.3.1: SCHEMATIC FLOW DIAGRAM OF BHUSAN THERMAL POWER PLANT

Operating Parameters Of The Thermal Power Plant:

Operating condition	value
Mass flow rate of coal	8.226 kg/sec
Mass flow rate f.w	65.28 kg/sec
Sup.steam temp.	793 K
Gross calorific value	4011.625 Kcal/kg
Boiler pressure	164.754 Bar
Steam pressure	96.108Bar
Mass flow rate of air	97 kg/sec
Ambient Temperature	300 K
Ambient Pressure	1.01325 Bar

2: EXERGY

2.1 Introduction

It is evident that the content of energy in the universe is constant. But very often, we come through different dialogues and articles on the topic that "How to conserve energy". Since time immemorial it is known that energy is constant in nature, what need to conserve the energy which is already conserved. The content required to be conserved is exergy which is the vital parameter and work potential of the energy. Exergy is irrecoverable i.e. once it is wasted can never be recovered. Simply, it means that when energy is used, the conversion of energy in a less powerful form i.e. exergy is used not the energy. Hence, energy is never exhausted.

Exergy defines the maximum capacity of a system to produce useful work as it proceeds from a specified state to a final state which is in equilibrium with its surroundings. Exergy cannot be conserved like energy as it is destructed in the system. Exergy destruction is the measure of irreversibility that is the source of performance loss. Therefore, exergy analysis enables us to identify the location, the magnitude and the source of thermodynamic inefficiencies in the overall system

The minimum exergy that has to be rejected to the sink by the second law is called unavailable energy (U.E.). Therefore,

Q_1 = U.E. + Exergy

W_{max} = Exergy = Q_1 - U.E.

Exergy analysis is a method for the evaluation of the performance of system devices or processes. It examines the exergy at different locations of a system through a series of energy conversion steps. Exergy analysis helps to evaluate exergetic efficiencies and to identify the system components having max. exergy loss. Broadly speaking, the exergy analysis provides a more authenticated and realistic view of the process or system analysis to improve the efficiencies of the power plant.

4: MATHEMATICAL FORMULATION

Exergy analysis is a method that uses both the principle of conservation of energy and mass along with the second law of thermodynamics. This analysis is carried in most of the power plant for enhancement of system or system component efficiency. The exergy analysis method is a useful tool for consuming energy-resource in a more efficient way. It helps the engineers/designers to identify locations and magnitudes of wastage, losses and to determine the meaningful efficiency of the system.

The exergy (Ψ) of heat transfer (Q) from the control surface at temperature (T) is determined from maximum rate of conversion of thermal energy to work(W_{max}) . This can be written by following equations:

Q = Unavailable Energy + Exergy (1)
W_{max} = Exergy = Q - Unavailable Energy (2)
$W_{max} = X = \sum Q\,(1-\frac{T_o}{T})$ (3)
And the specific exergy is given by
$\Psi = (h-h_o) - T_o(s-s_o)$ (4)
The total exergy rate associated with a fluid stream becomes $X = m \cdot \Psi$ (5)
Taking the value Ψ of from equation (4)

$$X = m\,[(h-h_o)-T_o(s-s_o)] \quad (6)$$

Change in enthalpy $\Delta h = h - h_o$ (7)
Enthalpy gradient for a constant pressure process is given by the equation $\Delta h = mc_p\Delta T$ (8)
Change in entropy is given by the equation
$\Delta s = s - s_o$ (9)

Change in entropy for a constant pressure process is given by the equation $\Delta s = mc_p \ln\frac{T}{T_o}$ (10)
Where h_o, T_o and s_o are the value of reference condition i.e. atmospheric condition.
Exergy of fuel is given by: X_{Fuel} = mass of fuel × Calorific value of fuel (11)
Calorific value of coal = [80.8 × C + (287 × H – O/8) + 22.5 × S – 6 × M] Kcal/kg

Where; C = carbon compositions in coal
H = Hydrogen compositions in coal
S = Sulphur compositions in coal
O = Oxygen compositions in coal
M = Moisture composition in coal

The above exergy balance is written in a general way. For the boiler operation, the heat input will be included when calculating the chemical exergy of coal. Exergy can increases because of heat (associated with a temperature factor) and work transferred across the system boundary. Exergy associated with the streams of matter entering or living the control volume. In real processes, exergy are destroyed due to irreversibility.

The second law of efficiency or exergetic efficiency is defined as- $\eta = {}^{\text{Exergy output}}/_{\text{Exergy input}}$

For a steady state operation, and choosing each component in control volume, the exergy destruction rate (I) and the exergy efficiency (η) is shown by: $I = W_{max} - W$ (12)

For boiler: $I_B = X_{fuel} + X_{in} - X_{out}$ (13)
$\eta_B = {}^{(X_{out} - X_{in})}/_{X_{fuel}}$ (14)
For turbine: $I_T = X_{in} - X_{out} - W_T$ (15)
$\eta_T = 1 - {}^{I_T}/_{X_{in} - X_{out}}$ (16)
For condenser or Hot well:
$I_C = X_{in} - X_{out} + X_{MW}$ (17)
Where X_{MW} is the exergy of Makeup water

$\eta_C = {}^{X_{out}}/_{X_{in} + X_{MW}}$ (18)
For pump: $I_P = X_{in} - X_{out} + W_P$ (19)
Where W_P is the work input to the pump.
$\eta_P = 1 - {}^{I_P}/_{W_P}$ (20)
For overall cycle:
$I_{Cycle} = \sum I_{all\ component}$ (21)
$\eta_{Cycle} = {}^{\text{NET OUT PUT}}/_{\text{INPUT}}$ $\eta_{Cycle} = {}^{W_{net\ out}}/_{X_{fuel}}$ (22)
$W_{Net} = W_T - W_P$ (23)
Steam rate = Capacity of power plant $= {}^{1}/_{W_{Net}}$ (kg/h) (24)
Heat Rate $= {}^{1}/_{\eta} = {}^{Q}/_{W_{Net}}$ (kg/h) (25)

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All above formulation play the key impact for the exergy analysis of bhusan thermal power plant.

5: EXERGY ANALYSIS OF BHUSAN THERMAL POWER PLANT:

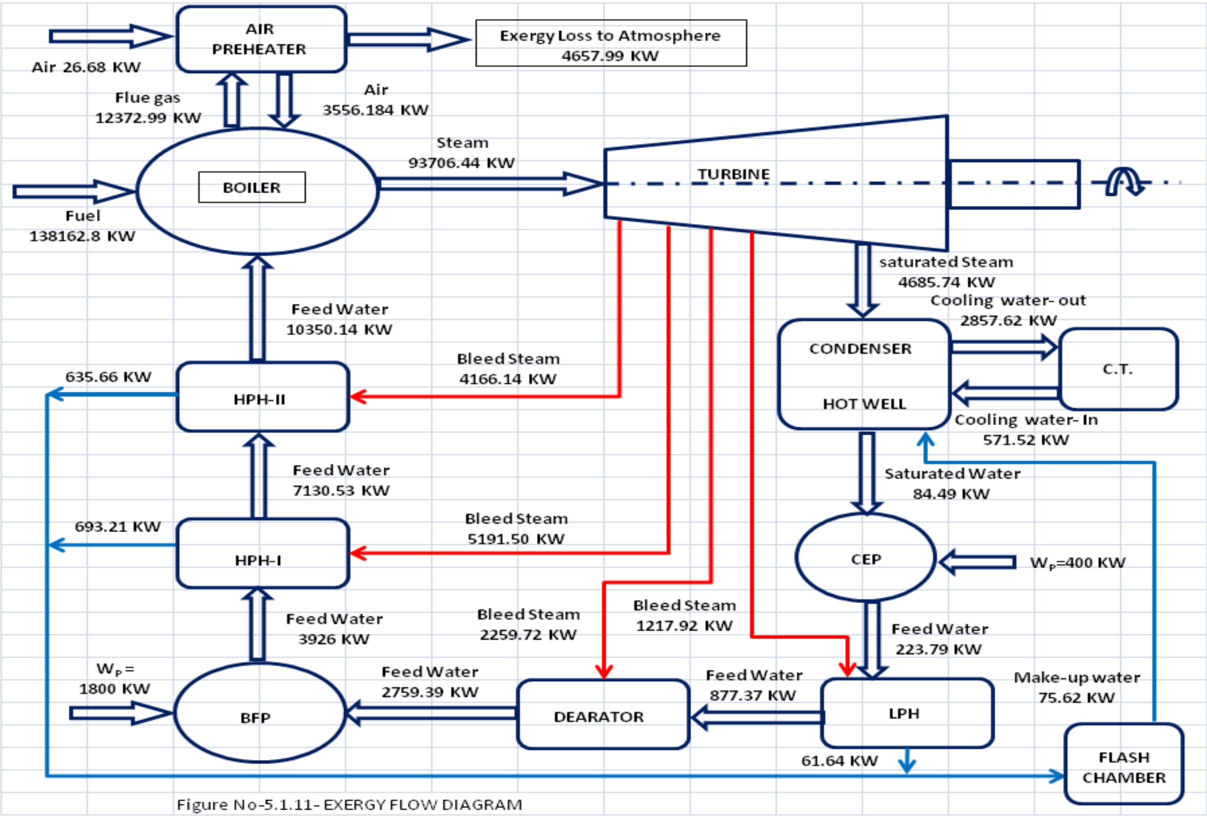

Figure No-5.1.11- EXERGY FLOW DIAGRAM

6: RESULTS AND DISCUSSION:

Thepower plant has been analyzed using the above relationsand formulation by considering that the environmentaltemperature and pressure are 300 K and 1.013 bar,respectively. Coal is the supply fuel of the powerplant, with the following components: Ash = 40%,Moisture = 8%, Hydrogen = 2.3%, Nitrogen = 0.7%,Sulphur = 0.30%, Oxygen = 6.60%, Carbon = 42%, GCV = 16795.87KJ.In this power plant major exergy loss was found in the boiler, where 64.04% of the total exergy loss was destroyed. Next to it was the turbine which represents 9.0% of total exergy destruction. The percent exergy destruction in the condenser was 3.33% while all heaters and pumps destroyed less than 2% except APH. Theexergy efficiency of the power plant was 50.41%.

Table 6.1 Exergy destruction and exergy efficiency of power plant componentswhen To = 300 K, Po = 1.013 bar.

Component	*Exergy destruction (KW)*	*Percentage of destruction*	*Efficiency (%)*
Boiler	*45989.74*	*64.04*	*69.76*
Turbine	*6535.43*	*9.10*	*93.03*
Condenser	*2390.77*	*3.33*	*55.17*
CEP	*260.69*	*0.36*	*46.19*
LPH	*502.70*	*0.70*	*65.13*
Dearator	*377.71*	*0.53*	*87.96*
BFP	*633.39*	*0.88*	*86.11*
HPH-I	*1293.76*	*1.80*	*85.81*
HPH-II	*310.87*	*0.43*	*97.25*
APH	*4185.49*	*5.83*	*66.25*
To atmosphere	*9334.86*	*13.0*	

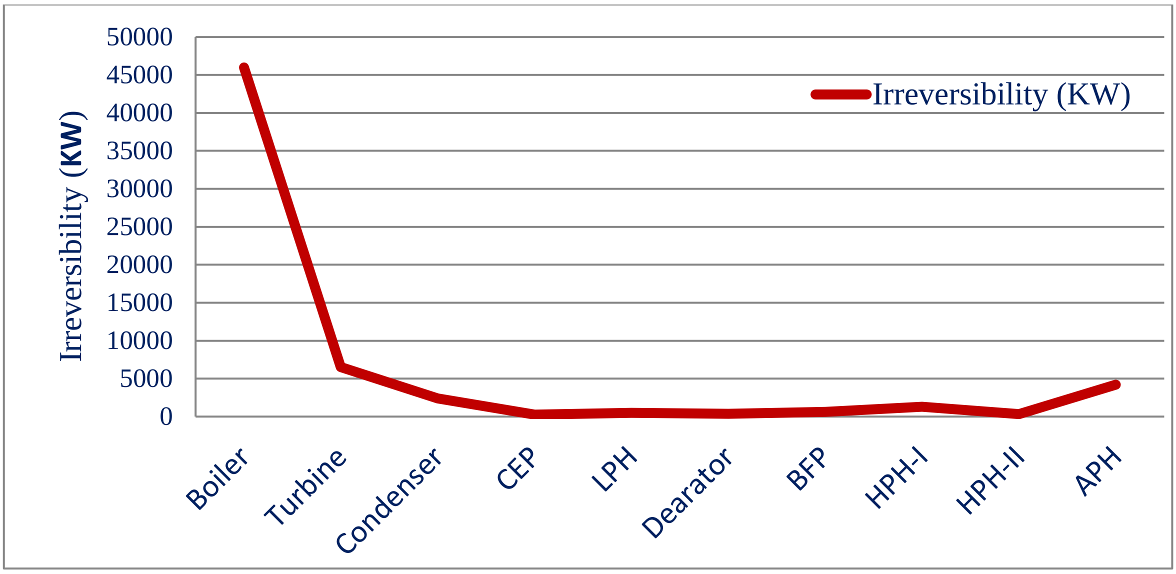

Fig: 6.1 Component wise exergy destruction

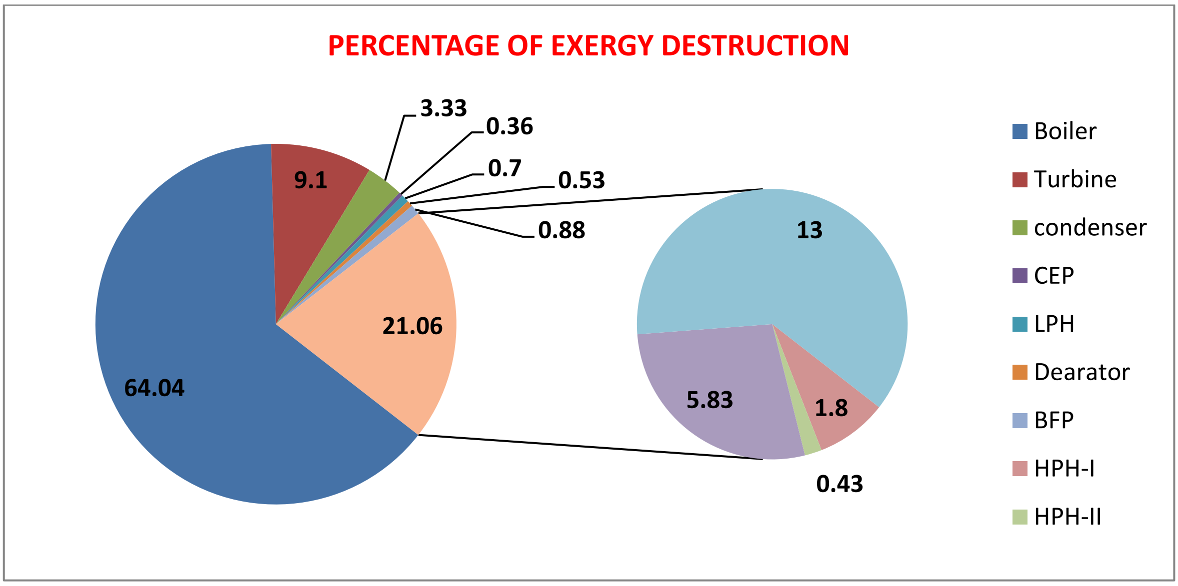

Fig: 6.2 Percentage of exergy destruction

From the exergy analysis, the overall plant energy losses are calculated. Fig. 6.1.2 shows the comparison of exergy losses between different components. It isprominent that the maximum exergy loss (64.04%) occurred in the boiler. Exergy destruction in the boiler was not based on the specificheat input to the steam; rather, it was based on the lowerheating value of the fuel to incorporate the losses occurring inthe furnace-boiler system due to energy lost with hot gases,incomplete combustion, etc.More than half of the total plant exergy losses occur in the boiler 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 boiler by means of reducing its huge energy losses, which is almost impracticable. This indicates that tremendous opportunities are available for enhancement of efficiency. However, part of this irreversibility cannot be avoided due to technical, physical, and economic constraints. Hence reheating cycle is suggested & analysis has been done. Details of analysis are as given below.

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Table 6.2 Exergy analysis of thermal power plant with reheating;

Component	Exergy destruction (KW)	Percentage of destruction	Efficiency (%)
Boiler	33056.47	49.44	85.12
Turbine	12802.85	19.15	92.76
Condenser	2771.63	4.15	57.47
CEP	257.61	0.39	47.05
LPH	507.39	0.76	65.24
Dearator	397.88	0.60	87.40
BFP	633.39	0.95	86.11
HPH-I	1540.56	2.30	83.34
HPH-II	345.66	0.52	96.92
APH	4185.49	6.26	66.25
To atmosphere	10356.14	15.49	

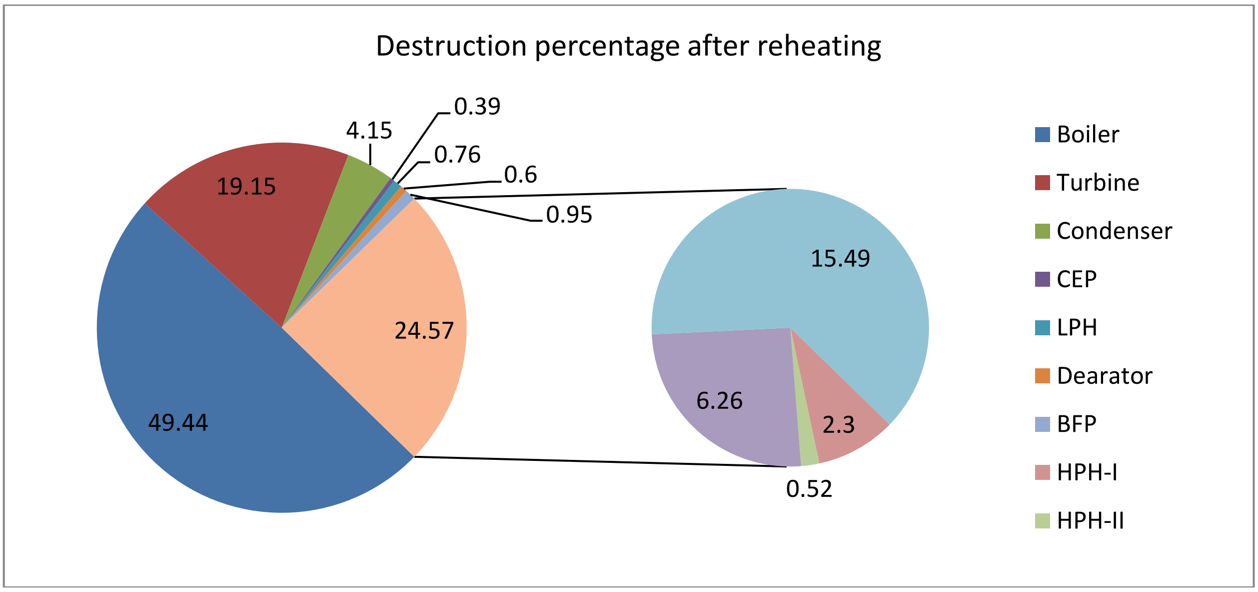

Fig: 6.3 Percentage of exergy destruction after Reheating.

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After reheating it is observed that the exergy destruction ultimately minimized without any other effect of fuel property or without any extra fuel consumption. It is the great opportunity to Bhusan thermal power plant for improving the overall performances of this thermal power plant.

According to exergy analysis, in boiler system before reheating the exergy destruction is found 45989.74 KW, which is reduced to 33056.47 KW after reheating in same plant without any extra fuel consumption. And in turbine before reheating the power generation is 69.65 MW, while after reheating the power production has been increased to 75.202 MW.

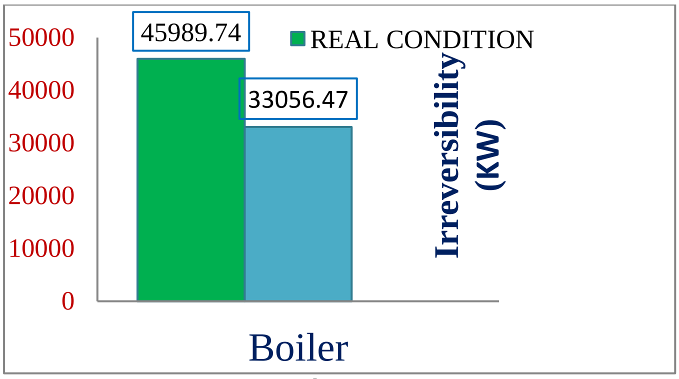

Fig: 6.4 Boiler comparisons

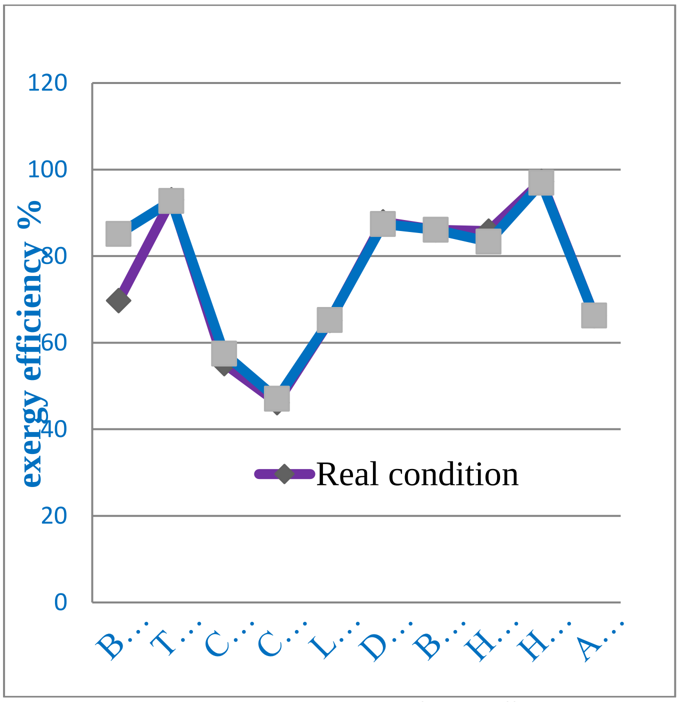

Fig: 6.5 Component wise comparison of exergy efficiency

Figure 6.5 showing that the component wise exergy efficiency charts.This chart determined that after reheating many components efficiency has been increased. For boiler efficiency increased 67.96 % to 85.12 % and overall plant efficiency increased from 50.41 % to 54.43 %. The overall efficiency of the turbine slightly decreased from 93.03 % to 92.76 % after reheating.The exergy efficiency of thepower system may be defined in several ways, however, the used definitionwill not only allow to irreversibility of heat transfer for thesteam in the boiler to be included, but also the exergy destructionassociated with fuel combustion and exergy lost with exhaust gasesfrom the furnace.

In Bhusan thermal power plant overall exergy destruction is 71815.4 (KW) while after reheating it can be minimized upto 66855.06 (KW) this is the great opportunity for improvement of overall performance of Bhusan thermal power plant.

7: CONCLUSION

An exergy analysis as well as the effect of introducing reheating system on the Bhusan thermal power plant, thelkoli, Odisha has been presented in this research work. In terms of exergy destruction, the major loss is found in the boiler system i.e64.04% of total exergy destruction has been occurred in the boiler system. Next to it was the turbine which represents 9.10% of exergy destruction. The exergy destruction in the condenser is 3.33% while all heaters and pumps destroyed less than 2% except air preheater, where exergy destruction is 5.83% .The calculated exergy efficiency of the power cycle is 50.41%, which is low as compared to modern power plants. In this power plant, boiler is the major source of exergy destruction. Chemicalreaction in the boiler combustion chamber is the most significant source of exergy destruction.

For reducing exergy destruction byintroducing reheating systemit is found that not only boiler's exergy destruction minimized but also overall plant efficiency and power generation has been increased.

In boiler actual exergy destruction is found45989.74KW but after introducing reheating system it is reduced to 33056.47KW i.e. the exergy loss of boiler is reduced from 64.04% to 49.44%. The overall exergy efficiency of the power plant has alsobeen increased from 50.41% to 54.43 %. The power generation has been increased from 69.65 MW to 75.202 MW.

In addition to the above other conclusions coming out from the research work are given below;

- Increasing of the boiler efficiency leads to a meaningful improvement of the overall performance of the plant,which is calculated by the exergy analysis.
- Exergy analysis is an effective methodfor the design and analysis of thermal power plants. It uses the conservation of mass and conservation of energy principles together with the second law of thermodynamics.
- Exergyanalysis shows that boiler in thermal power plants isthe significant source of Irreversibility.
- Exergy analysis method gives a logical solution for improving power generation opportunities in thermal power plants.
- The maximum exergy destruction is found in the boiler system, hence efforts should be concentrated for improving the boiler performance, which will lead to the largest improvement of the plant's efficiency and overall performance.

- Reheating of steam is the most common way for reducing the irreversibility of the boiler.
- Reheating is usually carried out by using the product of combustion in the boiler. Combustible gas after doing their main heating duty and before discharging into the atmosphere they reheat the steam.
- Reheating is the best technique for improvement of overall performance of the power plant. With the help of reheating we can reduce not only the irreversibility of boiler system but also overall plant efficiency i.e. power generation without any extra fuel consumption.

Exergy and percent of exergy destruction along with the second law efficiency are summarized in Table 6.2 for all components present in the power plant. It is seen that the exergy loss by the boiler is dominant over all other irreversibility in the cycle.This indicates that tremendous opportunities are available for improvement in the boiler system. However, part of this irreversibility cannot be avoided due to technical, physical, and economic constraints, so reheating was applied to Bhusan thermal power plant.

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