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Energy & Exergy Analysis of Thermal Power Plant at Design and Off Design Load

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Abstract: In this paper, the energy and exergy analysis of a thermal power plant is done at two different loads i.e. 100% and 70% load. The energy and exergy at inlet and outlet point of each component is calculated and specified with the help of data taken from the plant. The first and second law efficiency for each component of thermal power plant is calculated separately for design and off design load. The analysis shows that at design load maximum amount of exergy destruction occurs in the boiler, which is around 42% of the total exergy produced by the burning of coal and maximum energy loss occurs in the condenser which is 68.79%. The comparison of the performance of Plant is done at design and off design load and it is found out that plant performance is better at design load than its performance at off design load. The exergy destruction in boiler increases to 59% at off design load. Exergy efficiency of the boiler is significantly reduced at off design load than any other component of thermal power plant like turbine; boiler feed pump, heaters etc.

Keywords: Energy, Exergy, Exergy Destruction, Efficiency.

I. INTRODUCTION

The mostly used method for the analysis of energy conversion system is the first law of thermodynamics. The energy analysis based on first law of thermodynamics cannot provide the true measure of efficiency and thermodynamic losses. So there is increasing interest in the combined utilization of first and second law of thermodynamics. Exergy analysis based on second law of thermodynamics provides the clear distinction between energy loss to environment and internal irreversibilities in the process. It is a methodology for the evaluation of performance of devices and process and involving the exergy at different point in series of energy conversion steps. Exergy of a thermodynamic process shows efficiency or inefficiency of that process. Exergy provides us with a better understanding of processes for qualifying energy. Therefore, it would better to use exergy to locate, qualify and quantify energy destruction. For this reasons, modern approach to process analysis uses exergy analysis which provides more realistic view of a process and useful tool for engineering evaluation. Whenever the two system in different states, there is possibility of producing useful work and principle work can be developed as the two are allowed to come into equilibrium. When one of the two systems is a suitably idealized system called an environment and the other is some system of interest, exergy is the maximum theoretical useful work (shaft work or electrical work) obtainable as the systems interact to equilibrium, heat transfer occurring with the environment only.

Energy consumption is one of the most important indicator showing the development stages of companies and living standards of community. Population increment, urbanization, industrializing and technological development results directly in increase of energy consumptions. Thermal Power plants generate more than 80% of the total electricity produced in the world where as rest of the electricity is compensated from different sources like hydraulic, nuclear, wind, solar, geothermal, biomass etc. The economic growth of any country depends upon the cheap and abundant supply of electricity. Modern life is totally dependent on the electrical power in such a way that the per capita consumption of electricity is often taken as index of economic development prosperity and standard of living of a nation. It is therefore clear that if the country is to become prosperous and economically sound, more and more emphasis should be laid on the continuous growth of electrical power and efficiency performance analysis of energy and exergy efficiency.

II. LITERATURE REVIEW

Bejan et. al. 1996 [1] has outlined the fundamentals of the method of exergy analysis and entropy generation minimization, economic analysis and exergoeconomic analysis. This reviews the concept of irreversibility, entropy generation or exergy destruction. Examples illustrate the accounting for exergy flows and accumulation in closed system, open system heat transfer processes and power and refrigeration plants. Aljundi [2] has performed the exergy and energy analysis in Jordan. In his paper, each and every component of thermal power plant is analyzed separately and an energy and exergy loss in each component is quantified. The identification is done for the component having the lagest energy loss and exergy destruction. The largest energy loss is found to be condenser where 134MW is lost to the environment and only13MW is lost in boiler system. On the other hand, maximum exergy destruction is found to be in boiler and also has maximum percentage ratio of exergy destruction in boiler to total exergy destruction in plant which is about 77%. It is found that major source of irreversibility in plant is boiler. In boiler, major source of exergy destruction is chemical reaction in combustion chamber. In order to reduce the exergy destruction in combustion chamber preheating of combustion air is done and air fuel ratio is reduced.

Rashad et. al. 2009 [3] has performed the energy and exergy analysis steam power plant in Egypt. The primary objective of the paper is to analyze each and every component of the system separately and identify the components with highest energy losses and exergy destruction. The maximum energy loss was found in the condenser where 56.4%, 55.2% and 54.4% of the input energy was lost to the environment at 50%, 75%, and full load respectively. In addition, the calculated thermal efficiency of the cycle based on specific heat input to the steam was 41.9%, 41.7% and 43.9% at 50%, 75%, and full load respectively.

NOMENCLATURE

E_x = Exergy	**SUBSCRIPT**
E_n = Energy	ad =adiabadic
g = Acceleration due to Gravity	CH = Chemical
h = Enthalpy	d = Destruction
K.E = Kinetic Energy	e = Exit
m = mass flow rate of steam flow	f = Fuel
P.E = Potential Energy	gen = Generation
P = Pressure of Steam Flow	i = Inlet
s = Entropy	KN = Kinetic
T = Temperature of Steam Flow	l = Loss
U = Internal Energy	PT = Potential
u = Internal Energy	p = Product
V = velocity of Mass	PH = Physical
W = Work Done	surr = Surrounding
Z = Height of Mass	**SPECIAL SYMBOL**
	η = Efficiency

Adibhatla et. al. 2014 [4] has explained the energy and exergy analysis of thermal power plant at various load conditions under constant and pure sliding pressure. In this paper, power plant under consideration is of 660MW supercritical thermal plant and analysis is done at 100%, 80%, 60% load under constant and pure sliding pressure. The study reveals that boiler has highest rate of exergy destruction than any other component in the plant. The study also reveals that there is a significant reduction in the rate of exergy destruction at part load conditions for the turbine in case of sliding pressure operation in comparison to constant pressure operation. So the sliding pressure operation of the unit at part loads has several benefits. Hence sliding pressure operation is suitable for once through units and thus a better way of operating at part load conditions. Vuckovic et. al. 2014 [5] has performed the advanced exergy analysis and exergoeconomic performance evaluation of thermal processes in an existing industrial plant. In this paper, the advanced exergy analysis is used to identify performance of critical components and the potential for exergy efficiency improvement of a complex industrial energy supply plant. By the advance exergy analysis, overall system efficiency increased by 7.44% but this would require significant investment costs.

III. MATHEMATICAL FORMULATION

Energy is a basic concept of thermodynamics and one of the most significant aspects of engineering analysis. Energy can be stored within systems in different macroscopic forms: kinetic energy, gravitational potential energy, and internal energy.The change in energy between two states in terms of the work in an adiabatic process between these states is

$$(KE_2 - KE_1) + (PE_2 - PE_1) + (U_2 - U_1) = -W_{ad} \quad (1)$$

where 1 and 2 denote the initial and final states, respectively, and the minus sign before the work term is in accordance with the previously stated sign convention for work. The specific internal energy is symbolized by (u).

The specific energy (energy per unit mass) is given by equation (2).

$$\text{Specific energy} = u + V^2/2 + gZ \quad (2)$$

Where g is acceleration due to gravity, V is velocity of mass and Z is height of mass from reference positon. A property related to internal energy (u), pressure (p), and specific volume (v) is enthalpy (h), defined by

$$h = u + pv \quad (3)$$

In the form of enthalpy, the energy can be expressed

$$\text{Energy}(E_n) = m\,(h_1 - h_0) \quad (4)$$

Exergy is the maximum theoretical useful work obtained as the system interacts with the environment. In the absence of nuclear, magnetic, electrical, and surface tension effects, the total exergy of a system (**E_x**) can be divided into four components: physical exergy $E_{X(PH)}$, kinetic exergy $E_{x(KN)}$, potential exergy $E_{x(PT)}$, and chemical exergy $E_{x(CH)}$.

$$E_x = E_{x(PH)} + E_{x(KN)} + E_{x(PT)} + E_{x(CH)} \quad (5)$$

If the kinetic, potential and chemical exergy are considered to be negligible then exergy can be defined as by equation (6).

$$E_x = m[(h_1 - h_0) - T_0(s_1 - s_0)] \quad (6)$$

Exergy can be transferred to or from a system by heat, work, and mass.

As the energy can be transformed from or to a system by three forms as like that Exergy also transferred to or from the system by three means and these forms are:

Exergy transfer by heat(Q)

Work can be obtained from a heat source at temperature (T), which is above the environment temperature (T_0), by transferring heat (Q) to a heat engine and rejecting the waste heat to the environment. Hence, heat transfer is always accompanied by exergy transfer.

The maximum work that can be obtained from a heat source at temperature T is the work output from a Carnot heat engine which works between this heat source and the environment.

The Carnot efficiency of Carnot heat engine is,

$$\eta = 1 - \frac{To}{T} \quad (7)$$

Therefore, the exergy of heat Q is,

$$E_{x(heat)} = W_{net,out} = (1-T_0/T)Q (8)$$

When the temperature at the location where heat transfer occurs is not a constant, the exergy transfer accompanying heat transfer is determined by integration.

$$E_{x(heat)} = \int (1 - T0/T)\, \delta Q \quad (9)$$

Exergy Transfer by Work (W)

Exergy is the useful work potential. For boundary work, such as the expansion work of a piston-cylinder device, a portion of work is used to push the atmosphere air away and it cannot be utilized. Thus, the exergy transfer by the expansion work equals the difference between the expansion work and the surroundings work, that is,

$$E_{x(work)} = W - W_{surr} \quad (10)$$

Where $W_{surr} = P_0\ (V_2 - V_1)$ and P_0 is the atmospheric pressure.

Exergy Transfer by Mass (M)

Mass contains exergy as well as energy and entropy. The rate of exergy transfers to or from a system is proportional to the flow rate. When a mass (m) enters or leaves a system, exergy (m Ψ) enters or leaves a system as well, where Ψ is the flow exergy.

$$E_{x(mass)} = m\psi \ (11)$$

Or

$$E_{x(mass)} = m[(h - h_0) - T_0(s - s_0) + v^2/2 + g\,z] \quad (12)$$

Exergy Balance for Closed System

The exergy balance for a closed system is developed by combining the energy and entropy balances:

$$(U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) = \int_1^2 \delta Q - W \quad (13)$$

And entropy balance

$$S_2 - S_1 = \int_1^2 \frac{\delta Q}{T} + S_{gen} \quad (14)$$

Where W and Q represent, respectively, transfers of energy by work and heat between the system under study and its surroundings, T denotes the temperature on the boundary where energy transfer by heat occurs, and the term (S_{gen}) accounts for entropy generation owing to internal irreversibilities. Multiplying the entropy balance by the temperature (T_o) which is temperature of surroundingand subtracting the resulting expression from the energy balance gives

$$(U_2 - U_1) + (KE_2 - KE_1) + (PE_2 - PE_1) - T_0\,(S_2 - S_1) = \int_1^2 \delta\, Q - T_0 \int_1^2 \frac{\delta Q}{T} - W - T_0\, S_{gen}$$

Rearranging, the closed system exergy balance results:

$$E_{x2} - E_{x1} = \int_1^2 (1 - To/T)\, \delta Q - [W - P_0\,(V_2 - V_1)] - T_0 S_{gen} \quad (15)$$

Exergy Balance for Open System

Like mass, energy, and entropy, exergy is an extensive property, so it too can be transferred into or out of a control volume where streams of matter enter and exit. Exergy balance is given as:

$$\frac{dE_x}{dt} = \sum_j \left(1 - \frac{T_0}{T_j}\right) Q_j - \left(W_{cv} - P_0 \frac{dV_{cv}}{dt}\right) + \sum_i m_i e_i - \sum_e m_e\, e_e - E_{xd} \quad (16)$$

Where subscript 'i' and 'e' represents inlet and exit streams respectively, 'm' is the mass flow rate and 'P_0' is the atmospheric pressure.

Exergy Efficiency for Different Components of Plant

Let us consider a system at steady state where, in terms of exergy, the rates at which the fuel is supplied and the product is generated are E_{xf} and E_{xp} respectively. An exergy rate balance for the system reads

$$E_{xf} = E_{xp} + E_{xd} + E_{xl} \quad (17)$$

Whereas before E_{xd} and E_{xl} denote the rates of exergy destruction and exergy loss, respectively. The exergetic efficiency η_{ex} is the ratio between product and fuel:

$$\eta ex = \frac{E_{xp}}{E_{xf}} \quad (18)$$

The exergetic efficiency shows the percentage of the fuel exergy provided to a system that is found in the product exergy. Moreover, the difference between 100% and the actual value of the exergetic efficiency, expressed as a percent, is the percentage of the fuel exergy wasted in this system as exergy destruction and exergy loss.

$$\eta ex = 1 - \frac{E_{xl} + E_{xd}}{E_{xf}} \quad (19)$$

An important use of exergetic efficiencies is to assess the thermodynamic performance of a component, plant, or industry relative to the performance of similar components, plants, or industries. By this means the

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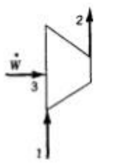
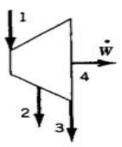
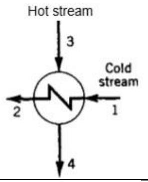
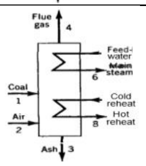
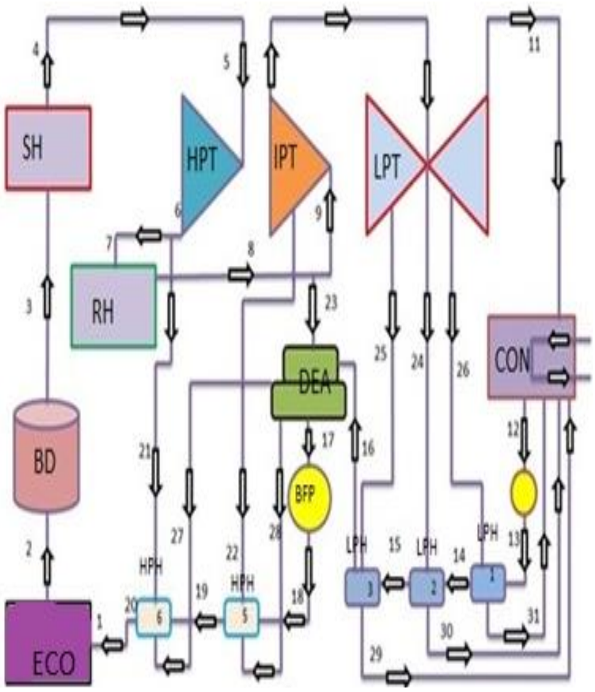
performance of a gas turbine, for instance, can be gauged relative to the typical present day performance level of gas turbines. The exergetic efficiency for different component of power plant is given following table.

Table1: Exergy Efficiency of Different Components of Plant

Component	Schematic	Fuel	Product
Pump, Compressor And Fan		W	$(E_{X2} - E_{X1})$
Turbine		$(E_{X1} - E_{X2} - E_{X3})$.	W
Heat Exchanger		$(E_{X3} - E_{X4})$,	$(E_{X2} - E_{X1})$
Boiler		$(E_{X1} + E_{X2}) - (E_{X3} + E_{X4})$	$(E_{x6} - E_{X5}) + (E_{X8} - E_{X7})$

IV. THERMAL POWER PLANT DESCRIPTION



ECO = Economiser

BD = Boiler Drum

SH = Super Heater

RH = Reheater

HPT = High Pressure Turbine

IPT = Intermediate Pressure Turbine

LPT = Low Pressure Turbine

DEA = Deaerator

CON = Condenser

BFP = Boiler Feed Pump

LPH = Low Pressure Heater

HPH = High Pressure Heater

Fig (1) Thermodynamic Model of the Plant

The Power Plant under consideration is Rajiv Gandhi Thermal Power Plant located in Hisar, Haryana. There are two units in plants and each has capacity of 600 MW. The work for implementation of 1200 MW Hisar Thermal Power Project was awarded during January, 2007. The total estimated cost of the project is Rs.4512 crore. The cost of Rs. 3.19 crore per MW for this project is the lowest in the Country. The thermodynamic model of the plant showing the steam flow is shown in figure (1)

V. ENERGY AND EXERGY ANALYSIS

Energy and Exergy analysis is performed at two load i.e. 100% and 70% load. The necessary steps to perform energy and exergy analysis are listed below:

1. First of all, the thermodynamic model of the plant is prepared showing the steam flow in the plant as shown in figure (1). The various channels connecting different elements are numbered as 1, 2 etc.
2. The data is taken from the plant related to the mass flow rate, pressure and temperature of steam flow at each point of thermodynamic model of the plant. This data is taken at two loads i.e. 100% and 70%. All the data taken is real time data taken at two loads.
3. With the help of Mollier Diagram and with the values of pressure and temperature at each point of thermodynamic model, the values of enthalpy and entropy can be find out at each point.
4. With the energy and exergy formula, the values of energy and exergy can be calculated at different point of the thermodynamic model of the plant.

The table 1 shows the energy and exergy analysis at 100% load whereas table 2 shows the energy and exergy analysis at 70% load. The tables also contain the value of mass flow rate, temperature and pressure of the steam flow at the various points of thermodynamic model of the plant.

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Table1: Energy and Exergy Analysis Data at Design Load

S.N	(m) (kg/s)	P (bar)	T (˚C)	h (kj/kg)	s (kJ/kg K)	Energy (KW)	Exergy (KW)
0	-----	1.0332	27	113.292	0.395	0.00	0.00
1	547.5	182.4	278	1221.74	3.012	6068800.09	177037.84
2	547.5	177.5	349	1651.51	3.743	842174..35	292265.35
3	547.5	170.8	378	2792.45	5.562	1466839.00	618159.25
4	547.5	165.2	537	3397.83	6.418	1798284.55	809006.80
5	547.5	161.42	531	3385.22	6.412	1791380.58	803088.33
6	515.83	40.30	336	3057.17	6.522	1518540.58	570393.46
7	506.93	39.30	335	3057.18	6.533	1492345.14	558884.24
8	506.93	36.67	535	3529.20	7.236	1731626.24	691253.80
9	488.93	34.29	533	3527.01	7.263	1669069.14	661677.76
11	435.62	0.247	75	2637.18	7.893	1099456.96	119573.33
12	446.66	28	44.7	189.623	0.633	34094.00	2202.48
13	446.66	32.63	46.6	197.953	0.6581	37814.68	2573.20
14	446.66	27.92	56.2	237.61	0.781	55527.87	3804.64
15	446.66	22.60	85	357.67	1.132	109153.87	10397.35
16	446.66	19.22	156	662.91	1.9101	245492.37	42485.40
17	446.66	10.19	183	758.792	2.129	288319.03	55966.498
18	446.66	192.01	188	807.474	2.191	310063.33	69402.92
19	446.66	188.21	213	917.456	2.424	383307.53	87305.95
20	446.66	182.4	278	1221.74	3.012	495103.40	144430.63
21	35.02	39.52	330	3043.73	6.508	102623.93	38400.76
22	22.02	21.37	455	3368.57	7.270	71681.22	26265.12
23	22.02	10.39	424	3316.69	7.525	70538.91	23438.13
24	8.233	5.58	325	3114.96	7.496	24707.56	7168.80
25	9.466	1.27	232	2937.80	7.853	26730.84	5551.61
26	1.466	0.632	160	2798.83	7.877	3936.07	645.49
27	35.02	39.52	328	3038.60	6.499	102422.29	38293.66
28	22.02	21.37	451	3358.43	7.256	71457.93	26134.17
29	8.233	10.39	323	3099.88	7.189	24588.579	7808.07
30	9.466	5.58	216	2887.29	7.076	26258.66	7285.96
31	1.466	0.632	142	2764.82	7.796	3887.140	632.180

Table2: Energy and Exergy Analysis Data at off Design Load

S.N	(m) (kg/s)	P (bar)	T (˚C)	h (kj/kg)	s (kJ/kg K)	Energy (KW)	Exergy (KW)
0	---	1.032	27	113.292	0.395	0.00	0.00
1	360	161.81	257	1119.406	2.828	362201.04	99437.04
2	360	157.88	333	1536.83	3.5623	512473.68	170405.28
3	360	154	383	2885.772	5.737	998092.8	421156.8
4	360	150	537	3414.99	6.479	1188611.28	531539.28
5	360	148.08	536	3414.39	6.484	1188395.28	530783.28
6	352.22	26.47	331	3079.55	6.739	1044775.39	374430.28
7	345.2	25.47	330	3079.67	6.757	1023993.68	365144.96
8	345.2	24.43	534	3538.99	7.432	1182550.95	453799.22
9	324.63	23.23	532	3535.709	7.451	1111019.23	423842.44
11	265.36	0.147	55	2600.393	8.022	659977.12	52806.90
12	277.66	29	43	182.61	0.61108	19246.83	1247.80
13	277.66	21.93	50	211.21	0.702	27187.91	1615.42
14	277.66	17.26	50	210.81	0.703	27076.84	1421.06
15	277.66	13.62	78	327.61	1.0507	59507.53	4889.03
16	277.66	11.29	113	474.77	1.4508	100367.98	12421.95
17	277.66	7.15	165	697.35	1.992	162169.54	29142.63
18	277.66	165.73	175	749.63	2.0708	176685.60	37094.82

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19	277.66	163.22	198	849.88	2.289	204521.02	46754.61
20	277.66	161.81	257	1119.406	2.828	279357.61	76693.57
21	26.05	28	330	3073.43	6.705	77111.59	27798.94
22	15.05	14.71	471	3410.644	7.497	49625.08	17559.55
23	5.05	7.15	373	3212.08	7.540	15648.87	4824.20
24	6.43	3.72	342	3154.06	7.747	19552.13	5370.13
25	7.52	0.686	243	2961.68	8.183	21419.87	3850.14
26	0.426	0.23	150.23	2782.55	8.304	1137.10	126.33
27	26.05	28	328	3068.69	6.697	76988.11	27737.98
28	15.05	14.71	469	3406.294	7.491	49559.61	17521.17
29	6.43	7.15	338	3138.69	7.423	19453.30	5896.29
30	7.52	3.72	232	2928.58	7.343	21170.96	5496.27
31	0.426	0.23	139.23	2761.34	8.253	1128.06	123.816

VI. PERFORMANCE ANALYSIS

From the energy and exergy analysis table generated at two loads, the first law and second law efficiency is calculated. Table 3 shows the first law efficiency calculated at 100% and 70% load.

Table3: First Law Efficiency at Two Loads

First Law Efficiency in (% age)		
Component	100% load	70% load
Boiler	87.87	60.49
Turbine	80.29	64.18
Condenser	31.21	58.09
Overall Plat	38.60	29.92

Figure (2) shows the plot for the first law or energy efficiency. The plant performance improves at full load as it is clear from the plot.

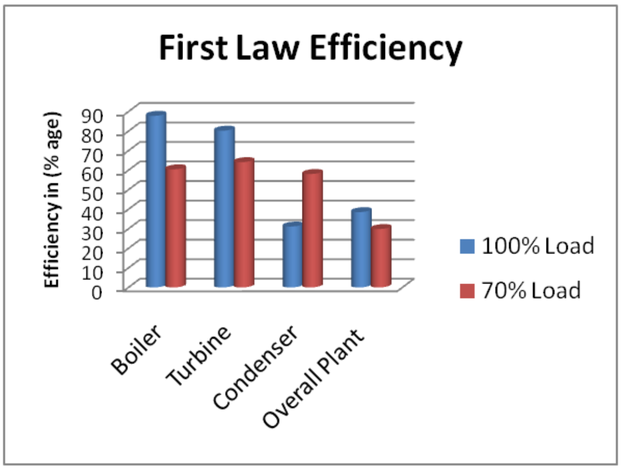

Fig (2) First Law Efficiency at Two Loads

Form the energy and exergy analysis table generated, the second law efficiency or exergy efficiency is calculated and results are shown in table (4) and are plotted in figure (3). Figure (4) shows the percentage exergy destruction in the various components of the plant.

It seems form the figure (4) that deaerator has more exergy destruction at off design load as compared to the boiler but this data is in percentage term.

Table4: Second Law Efficiency at Two Loads

Second Law Efficiency		
Component	100% Load	70% Load
Boiler	58.21	41.58
Turbine	90.6	87.3
Condenser	89.87	94.964
Deaerator	54.756	23.179
BFP	80.639	78.56
LPH-1	72.54	71.46
LPH-2	62.05	65.392
LPH-3	31.71	31.33
HPH-5	84.33	84.69
HPH-6	68.795	71.38

In absolute term, the boiler has maximum exergy destruction at design load and even in off design load.

It is clear from the figure (2) that at design load, the boiler and the turbine has more energy efficiency than at off design load. The boiler energy efficiency which was 87.87% at design load is decreased to 60.49% at off design load. The turbine has efficiency of 80.29% at full load and is decreased to 64.18% at part load. It means that plant should be run at maximum or full load for more energy efficiency. Similarly, overall plant energy efficiency is decreased at off design load as in case of turbine and boiler. The overall plant efficiency was 38% at design load and decreased to around 29% at part load.Boiler has exergy efficiency of 58.21% at design load and this efficiency decreases to 41.58% at off design load. Similarly for the turbine, the exergy efficiency decreases at part load. Previously it was 90% at design load and decreases to 87.3% at 70% load as shown in figure (3). In

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condenser, there is increase in energy and exergy efficiency at off design load.

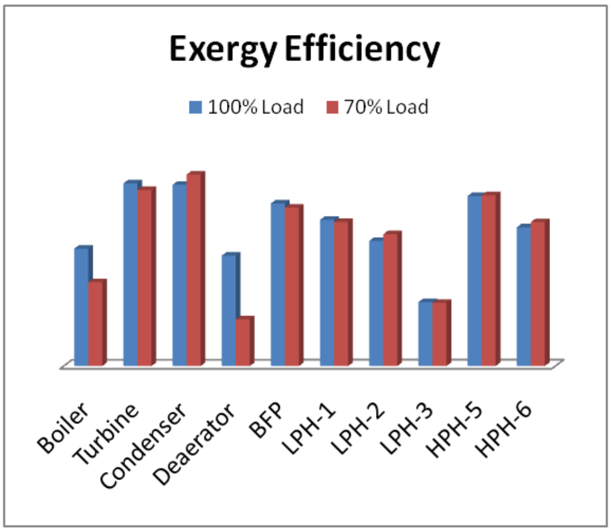

Fig (3) Second Law Efficiency at Two Loads

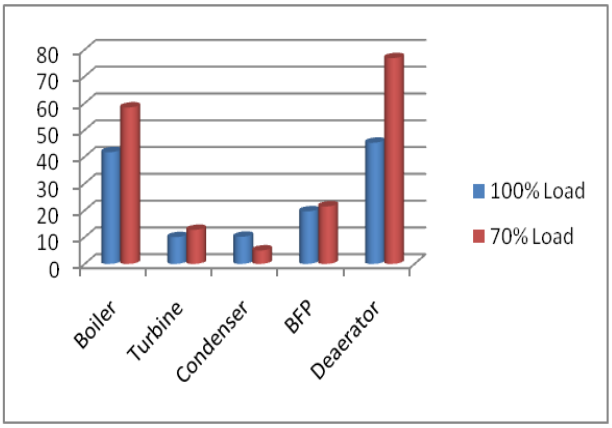

Fig (4) Percentage Exergy Destruction at Two Loads

VII. CONCLUSION

Performance Analysis suggests that plant should always berun at design load or full load for maximum exergetic or energetic efficiency of overall plant. As the plant load decreases, the efficiency is also decreasing. The condenser is the only component where with decrease in load, energy or exergy efficiency is increasing. The reason is that at off design load, exergy destruction or energy loss in remaining components increases, that energy will be released to the environment through condenser but the effectiveness and size of the condenser is same as that of full load, so there will be increase in exergy efficiency of efficiency of condenser at off design load.

The boiler has the highest amount of exergy destruction, so the great attention should be paid towards boiler in terms of design or technical change. The boiler is the source of the major irreversibility in the plant. Around 42% of exergy supplied is lost in the steam generator itself, so efforts should be made in this direction for positive results. The plant should always be run on the design load or maximum available load in order to decrease the amount of exergy destruction. At part load, the exergy and energy efficiency of the components and overall plant decreases significantly.

The major technical changes should be made in the boiler design in order to increase the exergy efficiency of the boiler after finding out the cause of lower exergy efficiency of the boiler. The future work must concern itself on how to improve the quality of the energy transferred to the steam in boiler.

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