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Exergy Modelling of a Coal Based 210 MW Thermal Power Plant working under varying Load Conditions

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Abstract: *In the present work, exergy analysis of a coal-based thermal power plant is done using the operating data of a 210MW thermal power plant under operation in eastern region of India. The entire power plant cycle is split up into ten thermal components for the analysis in order to analyze and compare the exergy destruction, % exergy destruction and second law efficiencies of the system and their components at full load as well as at part load conditions. The above analyses were carried out at 100%, 75% and 60% of operating load to investigate the performance of the total power cycle and their constituting components in order to obtain the sources and causes of irreversibility's as well as the variations in exergy efficiency under different operating conditions. It has been observed that the boiler causes the maximum exergy destruction at all loads under study. The contribution of the deaerator comes next followed by turbine and condenser while the contribution of the feed water heaters and pumps is the least among the selected components.*

Keywords: *Exergy Modelling**;** Exergy Analysis; Exergy Destruction; Performance* analysis; Thermal Power Plant.

Nomenclature

h	specific enthalpy [kJ/kg]
$\dot{m}$	mass flow rate [kg/sec]
$\dot{I}$	exergy destruction rate/irreversibility rate [MW]
P	pressure [MPa]
s	specific entropy [kJ/kg K]
t	temperature [^{o}C]
T	temperature [K]
W	power output of turbine/pump [MW]
X	turbine outlet vapour quality
e	specific exergy [kJ/kg]
E_x	total exergy [MW]
η_{II}	2nd law efficiency [%]
m_{fuel}	rate of coal flow [kg/sec]
e_{fuel}	lower heat value of Coal [kJ/kg]

Subscripts

Ref 0 Reference ambient condition

Abbreviation

CEP	condensate extraction pump
BFP	boiler feed pump
HPH	high pressure heater

LPH low pressure heater

HPT high pressure turbine

IPT intermediate pressure turbine

LPT low pressure turbine

1.0 Introduction

India's electricity sector consumes about 80% of the coal produced within the country. The installed power generation capacity of India till 31.08.2017 is 329 GW. Coal is found to be one of the major sources of power production when compared with other sources, since it constitutes a share of around 58% of the total installed capacity [Figure1]. Under coal based generating power plants, 200-250MW units contributes 25% share [Figure 2] having an average age of 25 years which requires immediate renovation and modernization for further efficient generation.

In the last several decades, exergy analysis has begun to be used for system optimization. Exergy analysis provides us a method to evaluate the degradation of energy during process, entropy generation and the loss of opportunity to do work and also it serves as an alternative approach for the improvement of power plant performance. The use of energy and exergy analysis of a steam power plant started with the evaluation of the losses in a 60 MW power station [1] and subsequently by means of the entropy balance diagram [2], second law analysis on regenerative steam turbine power cycle [3], studies of energy and exergy analyses for power generation systems [4] and to find out the contributions of different parts of the plant towards exergy destruction [5]. The energy and exergy analysis of a reheat regenerative vapour power cycle has been investigated and reported that the cycle energy and exergy efficiency increases with increase in pressure and temperature [6]. The energy and exergy analysis of Shobra El-Khima power plant of Cairo, Egypt have been studied to analyze the system components separately to find out the sites having largest energy and exergy losses at different load [7]. The Exergy analysis of the combined Brayton/Rankine power cycle of NTPC Ltd. Dadri has also been done and reported that more exergy losses occurred in the gas turbine combustion chamber [8]. Naga Varun et al. [9] have investigated exergy analysis for different components of a thermal power plant and reported that the maximum exergy destruction rate is observed in the low pressure turbine. Pattanayak et al. [10] investigated the exergy analysis of a coal fired 500 MW unit under design and off design condition and reported that the greatest exergy destruction occurs at the combustor followed by heat exchanger. Thermodynamic analysis of the thermal power plant was carried out by Anjali et al. [11] to enhance the efficiency and reliability of steam power plants. Mitra and Ghosh [12] studied the exergy and energy efficiencies of a coal fired 250 MW thermal power plant operating under different load conditions. Umrao et al. [13] carried out the work on actual performance of a coal based 210 MW power plant at variable load conditions and evaluated the specific fuel consumption as well as efficiency of power cycle components.Satish et al. [14] carried out energy and exergy analyses of a Vijayawada Thermal Power Plant (VTPS) in order to evaluate the energetic and exergetic efficiencies and irreversibility's of units. They reported that the exergy destruction is more in the low pressure turbine. Kavad et al. [15] has also presented the exergy analysis of a Thermal Power plant. Their results showed that, the boiler was the major source of irreversibility in the power plant amongst all other components but excluding the boiler followed by turbine. Second Law analyses of an Organic Rankine Cycle with superheating under different heat source temperature conditions have been investigated and reported a choice system for converting low grade heat to power [16].
A thermodynamic analysis of power generation system suggests that there are two approaches to improve the system performance: one, to improve the heat/ exergy input; the other, to enhance the heat-work conversion ability of the system [17]. Second law analysis for power generation has also been reported recently [18]. Second law analysis for regenerative power cycle has also been conducted under realistic conditions[19].

The brief review of literature mentioned above does not clearly evaluate the areas and locations of irreversibilities of the actual running thermal power plants under variable load conditions. Therefore, under present study an exergy analysis has been carried out by taking the operational parameters of a 210 MW thermal power plant unit situated in eastern part of India. The variation in 2nd law efficiency, exergy destruction and % exergy destruction at different operational load has been found for different thermal components as well as total power cycle and are compared.

2.0 Exergy Modelling for thermal Power Plant

A schematic diagram of the entire plant considered in the present study is shown in Figure 3. A continuous mass flow diagram for one unit of power plant modelled in this study includes the main components such as turbine, boiler, condensate extraction pump, boiler feed pump, condenser, deaerator, low and high pressure feed water heaters. Thermodynamic properties at each node of the power plant cycle were found. By these values the exergy at each node is evaluated considering the reference environmental condition and thermodynamic properties from Sonntag et al., [20].

On a single shaft three turbines i.e. HPT, IPT and LPT is mounted and directly coupled to the generator. In between IPT and LPT a single reheat is done. The exhaust of LPT gets accumulated in the hot well of the condenser as condensate. The condensate is taken away from hotwell by means of condensate extraction pumps and after passing through three low pressure heaters it goes to feed storage tank via deaerator. The extraction steam from different stages of LPT is utilized in LP heaters to raise the condensate temperature whereas the deaerator utilizes a stream of IPT exhaust as pegging steam. Boiler feed pumps takes suction from feed storage tank that pressurizes the feed water which further passes through two high pressure heaters and one economizer to raise temperature of feed water before entering to the boiler drum. The bled steams for HPH's are coming from IPT and CRH.

The data for operating parameters (pressure, temperature and mass flow rate) at full and part loads at each node of the power plant cycle is collected from the plant along with operating conditions are shown in Table 1 and 2 respectively for further calculation of exergy at each node in consideration with reference environmental condition is shown in Table 3.

The irreversibility rate or entropy generation decides the performance of any thermodynamic system processes. The entropy generation under any thermodynamic process depends on external and internal factors. Friction, unrestrained expansions and a heat transfer over a finite temperature difference causes internal irreversibilities whereas mechanical transfer of work causes external irreversibilities.

Under this study, the pressure drop inside thermal components and connected pipe lines for the power cycle is neglected. Further, it is assumed that each components attained uniform flow condition.
Then, for any controlled volume of the power cycle, the irreversibility rate maybe expressed as:

$$\dot{I} = T_0 \frac{ds_{total}}{dt} \quad (1)$$

or, $$\dot{I} = \dot{m}\, T_0 \left[\sum_{outlet} s - \sum_{inlet} s + \frac{ds_{system}}{dt} + \sum_k \frac{q_k}{T_k} \right] \quad (2)$$

Here, T_k =heat source temperature, q_k = heat transfer from heat source to working fluid and T_0 = the environmental temperature. The total entropy generation due to external or internal factors are taken into considerations in equation (2).
For steady condition, $\frac{ds_{system}}{dt}$ =0, and equation (2) gets modified to:

$$\dot{I} = \dot{m}\, T_0 \left[\sum_{outlet} s - \sum_{inlet} s + \sum_k \frac{q_k}{T_k} \right] \quad (3)$$

For a single component having single inlet and single outlet at steady state, equation (3) gets modified to:

$$i = \dot{m} T_O \left[\left(s_{out} - s_{in} \right) + \frac{q}{T} \right] \quad (4)$$

For, negligible kinetic and potential energy changes at steady state condition for any thermal component exergy balance maybe expressed as follows:
Specific exergy for any thermal component is given by

$$e = (h - h_0) - T_o(S - S_o) \quad (5)$$

Where h_o, s_o, T_o represents the ambient conditions or reference state point.
Now, Total exergy becomes:

$$E_x = \dot{m}\, [(h-h_o)-T_o(s-s_o)] \quad (6)$$

Whereas, the specific physical exergy of the stream was evaluated as

$$e_i = [(h_i-h_o) - T_o (s_i- s_o)] = [\Delta h-T_o\Delta s] \quad (7)$$

Total physical Exergy of the stream is given by

$$E_{xi} = \dot{m}\, e_i \quad (8)$$

For any control volume and any thermal component [Figure 4]
Exergy Destruction may be expressed as

$$\dot{I} = (E_{xi}) - [(E_{xj}) + (W)] \quad (9)$$

$$\%\text{Exergy Destruction} = \frac{ExergyDestruction}{TotalExergyDestructionOfThePowerCycle} X100 \quad (10)$$

Second Law efficiency for any controlled volume is evaluated as,

$$\eta_{II} = \frac{ActualWorkDone}{MaximumTheoreticalWork} \quad (11)$$

it may also be expressed as

$$\eta_{II} = \frac{ActualWorkDone}{ExergeInput - ExergyOutput} \quad (12)$$

The second Law efficiency may be expressed as,

$$\eta_{II} = \frac{Exergy\ Output}{Exergy\ Input} X100\% \quad (13)$$

3.0 Exergy Analysis

More-over, with the selection of each component of power cycle in Figure 3 as control volume the second law efficiency can be expressed and evaluated as follows:
(i) Boiler,

$$\eta_{II} = \frac{ExergyOut - ExergyIn}{ExergyFuel - ExergyFlue\,Gas} \text{x100 \%} \quad (14)$$

Exergy Input = $E_{11} + E_{12}$ + Exergy Fuel
Exergy Output = $E_1 + E_3$ + Exergy Flue gas
Where, (Exergy Fuel- Exergy Flue gas) = m_{fuel} x e_{fuel} x 0.70
m_{fuel} =Rate of coal flow , e_{fuel} = lower heat value of coal and 0.70 is exergy factor.

(ii) Turbine,

$$\eta_{II} = \frac{PowerOutput}{Poweroutput + ExergyDestruction} \text{x100\%} \quad (15)$$

Exergy Input = $E_5 + E_1 + E_3$, Exergy Output = $E_6 + E_8 + E_9 + E_{10} + E_2 + E_4 + E_7$

(iii) Condenser,

$$\eta_{II} = \frac{Exergy\ Output}{Exergy\ Input} X100\% \quad (16)$$

Exergy Input = $E_6 + E_{13} + E_{25}$, Exergy Output = $E_{14} + E_{15}$

(iv) Condensate Extraction Pump,

$$\eta_{II} = \frac{\text{Exergy Out} - \text{Exergy In}}{\text{Pump Input Power}} \text{x100} \quad (17)$$

Exergy In = E_{15} and Exergy Out = E_{16}
Pump Input power = m_{16} x $(h_{16}-h_{15})/0.80$
Isentropic efficiency of pump is assumed as 0.80

(v) Boiler Feed Pump,

$$\eta_{II} = \frac{\text{Exergy Out} - \text{Exergy In}}{\text{Pump Input Power}} \text{ x100} \quad (18)$$

Pump Input power = m_{18} x $(h_{18}-h_{17})/0.90$
Exergy In $=E_{17}$ and Exergy Out = E_{18}

(vi) Heaters,

$$\eta_{II} = \frac{Exergy\ Output}{Exergy\ Input} X100\% \quad (19)$$

Where, for
(a) HPH 6: $E_{in} = E_{19} + E_{22}$ and $E_{out} = E_{11} + E$
(b) HPH 5: $E_{in} = E_7 + E_{18} + E_{20}$ and $E_{out} = E_{21} + E_{22}$
(c) LPH 3: $E_{in} = E_8 + E_{27}$ and $E_{out} = E_{23} + E_{28}$
(d) LPH 2: $E_{in} = E_9 + E_{23} + E_{26}$ and $E_{out} = E_{24} + E_{27}$
(e) LPH 1: $E_{in} = E_{10} + E_{24} + E_{16}$ and $E_{out} = E_{25} + E_{26}$

(vii) Total Power Cycle,

$$\eta_{II} = \frac{NetPowerOutput}{NetPoweroutput + ExergyDestruction} \quad (20)$$

Exergy In = E_{13} + Exergy Fuel; Exergy Out = E_{14} + Exergy Flue gas
Net Power Output = Power Output - Aux. Power Input
At steady state condition, with negligible potential and kinetic energy changes, total exergy at each node and % exergy destruction of selected thermal components, as shown in Figure 3 are evaluated with basic equations 4 to 10. The exergy of the components at inlet and outlet points are calculated using equations 5, 6 and 7. The results are tabulated in Table 4, 5 and 6 for 100%, 75% and 60% load operation respectively. Calculation of Exergy destruction (Equation 9), % exergy destruction (Equation 10) and second law efficiency (Equation 14 to 20) for each component as well as total power cycle (Figure 3) and total exergy at each node as tabulated in Table 4, 5 and 6 operating on 100%, 75% and 60% load of 210 MW is carried out which is shown in Table 7.

4.0 Results and discussions

The exergy destruction, % exergy destruction and second law efficiency for any selected thermal components as well as total power cycle of an operational 210 MW thermal power plant based on coal at full load as well as part load conditions was compared and thermodynamically analyzed.

4.1 Exergy Analysis at 100%, 75% and 60% load conditions:

Figure 5, 6 and 7 shows the exergy destruction, percentage exergy destruction and exergy efficiency of main components respectively for the full load condition (210Mw) of the power plant. From the Figure 5, it is observed that the maximum exergy destruction occurs in the boiler and hence maximum percentage of exergy destruction will be in the boiler (Figure 6) as compared to other components of the power plant. It is apparent from Figure 7 that high pressure heater has the highest exergy efficiency followed by turbine and condensate extraction pump. Boiler has the lower exergy efficiency as compared to the condenser, while deaerator has the lowest exergy efficiency.

Figure 8, 9 and 10 shows the exergy destruction, percentage exergy destruction and exergy efficiency of main components respectively for the 75% load condition valued 157.50 Mw. It is apparent that the maximum exergy destruction occurs in the boiler and hence maximum percentage of exergy destruction will be in boiler as compared to the other components of power plant. High pressure heater has the highest exergy efficiency. Boiler has lower exergy efficiency as compared to turbine and condenser, while deaerator has the lowest exergy efficiency of all.

Figure 11, 12 and 13 shows the exergy destruction, percentage exergy destruction and exergy efficiency of main components respectively for 60% load condition valued 126 MW. It is evident that the maximum exergy destruction occurs in the boiler and hence maximum percentage of exergy destruction will be in the boiler compared to other components of the power plant. Pumps (BFP & CEP) have the highest exergy efficiencies. Boiler has the lower exergy efficiency as compared to the turbine and condenser, while the lowest exergy efficiency is observed in deaerator.

4.2 Comparative study of each component at different load condition

Exergy analysis has been carried out for full load as well as part load conditions of the thermal power plant. The results obtained for the exergy destruction, % exergy destruction and exergy efficiency of the main components of the thermal power plant at full load and part load conditions are tabulated in Table 7. Based on the comparative results obtained in Table 7, the variations of exergy destruction, % exergy destruction and exergy efficiency of the thermal power plant components with different operating load conditions of plant have been plotted which is shown in Figure 14 to Figure 19.

Figure 14 shows the variations of exergy destruction of the boiler, deaerator, and turbine whereas Figure 15 shows the variations of exergy destruction of condenser, CEP, BFP, HP Heaters and LP Heaters respectively at full load and part load conditions. It is apparent that, the exergy destruction increases with the increment in load and its value attains maximum at full load condition. Further, it is observed that, the exergy destruction of condenser, CEP, BFP and HP heaters almost increases linearly with increase in load having attaining their maximum at full load whereas for LP Heater its value first increases and then decreases with raising loads.

The second law efficiency variation with different operational load of studied power plant for boiler, condenser, turbine and HP heater is shown in Figure 16. It is clear from this figure that second law efficiency of HP Heater is maximum followed by turbine full load among at the selected plotted components. The 2nd law efficiency of condenser also increases with load whereas for boiler it decreases with load. The second law efficiency variation with different operating load of studied power plant for CEP, BFP, LP Heater and Deaerator is shown in figure 17. It is apparent that the second law efficiency for CEP and Deaerator is almost constant with increase in load where as it increases for LP Heater and decreases for BFP with increase in operating load.

The variations of % exergy destruction with different operating load conditions, in different components of studied thermal power plant are shown in Figure 18 and Figure 19. From those figures it is observed that the % exergy destruction in boiler is maximum followed by turbine and deaerator. Figure 18 shows the variations of % exergy destruction of the boiler, deaerator, and turbine whereas Figure 19 shows the variations of exergy destruction of condenser, CEP, BFP, HP Heaters and LP Heaters respectively of the studied thermal power plant at full load and part load conditions. It is apparent from Figure 18 that the % exergy destruction in boiler and turbine attain their minimum value at full load condition where as in case of deaerator, the % exergy destruction attains its maximum value at full load condition although the variations are very less. It is observed from Figure 19 that the % exergy destruction of condenser, CEP, LP Heater and HP Heaters decreases with increase in load whereas for BFP its value increases with raising loads.

4.3 Validation with the earlier published literature:

Sengupta et.al. 2007 [5] obtained a variation of second law efficiency of total power cycle and Turbine with different operating load of similar to present study thermal power plant. The results obtained under the present study for the same are compared with plots in MATLAB 16.0 and shown in Figures 20 and Figure 21. It is observed from those figures that the second law variation for total power cycle and turbine are nearly similar to that obtained by them. The minor difference observed is due to Sengupta et.al. [5] has neglected the exergy destruction inside the condenser component.

Further, Satish et.al 2016 [14] and Kavad et.al 2017 [15] have examined the second law efficiency during exergy analysis different components of 210 MW thermal power plant bearing different node parameters compared to present studied plant at full load. The comparative plot is shown in Figure 22. The variation of second law efficiency for HP Heater, LP Heater and Turbine of the present work shows in agreement with the results of [14] and [15] .The variation obtained for boiler component of present work is similar to [14] where as for condenser component it is in conformity with [15].

5.0 Conclusion

The above analyses were carried out at 100 % , 75 % and 60% of operating load of the studied 210 MW coal based thermal power plant to investigate the performance of the total power cycle and their constituting components. The following important conclusions are drawn:

1. Exergy destruction of Condenser, CEP, BFP and HP heaters increases almost linearly with the increase in load and attains their maximum value at full load condition whereas exergy destruction for LP heater first increases and then decreases with the raising loads. Boiler causes maximum exergy destruction at all loads followed by the components such as deaerator, turbine and condenser respectively.The exergy destruction in feed water heaters and pumps are found to be minimum among the selected components.

2. The % exergy destruction is highest in case of boiler among all the components followed by turbine and deaerator. Boiler and Turbine attain their minimum value while deaerator attain its maximum value respectively at full load conditions. Further, for components such as CEP, LP Heater and HP Heater %, the exergy destruction value decreases with increase in load while for BFP its value increases with raising loads.

3. Second law efficiency of HP Heater is highest among all the components at full load condition. The value of 2nd law efficiency increases with increase in load for Condenser, LP heater, whereas for boiler its value decreases with increase in load. The 2nd law efficiency for CEP and Deaerator is almost constant even with the increase in load. Furthermore, the efficiency of BFP shows a decreasing trend with the increase in operating load.

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Figure Caption

Tables

Table 1. Operational Parameter at different loads on 76mm Hg condenser pressure

	60% Load			**75% Load**			**100% Load**		
Nodes	**Press.**	**Temp.**	$\dot{m}$	**Press.**	**Temp.**	$\dot{m}$	**Press.**	**Temp.**	$\dot{m}$
1	14.72	537	102.9	14.72	537	127.0	14.72	537	173.0
2	2.35	313	102.9	2.85	318	127.0	3.825	342	173.0
3	2.06	537	94.1	2.55	537	115.3	3.43	537	155.4
4	0.39	310	88.7	0.49	310	108.5	0.685	307	145.7
5	0.39	310	84.1	0.49	310	102.5	0.685	307	136.9
6	0.01	X=0.95	76.2	0.01	X=0.95	91.8	0.0101	X=0.92	120.2
7	0.98	426	5.4	1.18	426	6.8	1.57	424	9.6
8	0.137	200	4.0	0.167	195	5.1	0.295	192	7.3
9	0.05	105	4.0	0.06	105	5.3	0.0825	102	7.9
10	0.0147	X=0.96	0.1	0.016	X=0.95	0.4	0.021	X=0.95	1.2
11	15.7	220	103.2	15.9	230	127.3	16.5	245	173.3
12	2.35	313	94.1	2.85	318	115.3	3.825	342	155.4
13	0.22	32	7324.7	0.22	32	7324.7	0.22	32	7324.7
14	0.22	37.65	7324.7	0.22	38.81	7324.7	0.22	40.68	7324.7
15	0.0101	46	84.9	0.0101	46	103.3	0.0101	46	137.9
16	1.96	46	84.9	1.86	46	103.3	1.57	46	137.9
17	0.588	149	103.2	0.59	149	127.3	0.59	149	173.3
18	15.9	150	103.2	16	151	127.3	16.7	162	173.3
19	2.35	313	8.9	2.85	319	11.7	3.825	343	17.6
20	1.177	198	8.9	1.37	200	11.7	1.765	220	17.6
21	0.863	167	14.2	0.88	170	18.5	0.98	174	27.3
22	15.7	170	103.2	16	180	127.3	16.6	200	173.3
23	0.0588	92	4.0	0.068	90	5.1	0.09	88	7.3
24	0.0186	73	7.9	0.02	72	10.3	0.03	73	15.2
25	0.0157	52	8.0	0.017	51	10.8	0.0195	50	16.4
26	0.98	70	84.9	0.88	70	103.3	0.785	70	137.9
27	0.0588	95	84.9	0.49	96	103.3	0.395	95	137.9
28	0.147	125	84.9	0.137	124	103.3	0.128	125	137.9
29	0.412	310	4.6	0.49	309	6.0	0.67	307	8.8

Units: Pressure in MPa, Temperature in ^{0}C, Mass flow rate in kg/sec.

Table-2: Operating conditions at different loads on 76mm Hg condenser pressure

Operating conditions	Unit	60% Load	75% Load	100% Load
Generation	**MW**	126	157.5	210
Coal Flow	**Ton/Hr**	71	85.8	112
Total Air Flow	**Ton/Hr**	527	586	769
Auxiliary Power	**MW**	12.6	14.175	18.9
Main Steam pressure	**Mpa**	14.72	14.72	14.72
Main Steam Temperature	**^oC**	537	537	537
Main Steam Mass flow rate	**Ton/Hr**	370.595	457.241	622.804

Table- 3 : Reference environmental conditions

Ambient parameters	Value	Unit
Pressure	1.013	bar
Temperature	298	K
Enthalpy	104.9	kJ/kg
Entropy	0.3673	kJ/kg-K

Table-4: Total Exergy calculation at each Node for 100% load

Node	Press (Mpa)	Temp. (^0C)	Mass flow rate,kg/sec	Specific Enthalpy(h) (kJ/kg)	Specific Entropy(s) (kJ/kg.K)	Specific Exergy(e) (kJ/kg)	Total Exergy(E), (MW)
1	14.72	537	173.0	3416	6.488	1487.131	257.275
2	3.825	342	173.0	3077	6.576	1121.907	194.091
3	3.43	537	155.4	3536	7.273	1373.201	213.368
4	0.685	307	145.7	3074	7.334	893.023	130.157
5	0.685	307	136.9	3074	7.334	893.023	122.269
6	0.0101	X=0.92	120.2	2394	7.547	149.549	17.980
7	1.57	424	9.6	3307	7.323	1129.301	10.877
8	0.295	192	7.3	2849	7.285	682.625	5.004
9	0.0825	102	7.9	2682	7.466	461.687	3.635
10	0.021	X=0.95	1.2	2494	7.539	251.933	0.307
11	16.5	245	173.3	1063	2.719	257.293	44.583
12	3.825	342	155.4	3077	6.576	1121.907	174.322
13	0.22	32	7324.7	134.3	0.4643	0.494	3.618
14	0.22	40.68	7324.7	170.6	0.5814	1.898	13.904
15	0.0101	46	137.9	192.6	0.6517	2.949	0.407
16	1.57	46	137.9	194	0.651	4.557	0.629
17	0.59	149	173.3	627.9	1.831	86.817	15.043
18	16.7	162	173.3	693.7	1.944	118.943	20.610
19	3.825	343	17.6	3079	6.58	1122.715	19.784
20	1.765	220	17.6	2835	6.466	912.687	16.083
21	0.98	174	27.3	736.8	2.081	121.217	3.304
22	16.6	200	173.3	858.9	2.308	175.671	30.440
23	0.09	88	7.3	368.5	1.169	24.693	0.181
24	0.03	73	15.2	2633	7.79	316.135	4.810
25	0.0195	50	16.4	209.3	0.7037	4.153	0.068
26	0.785	70	137.9	293.6	0.9544	13.744	1.896

27	0.395	95	137.9	398.2	1.25	30.255	4.173
28	0.128	125	137.9	2724	7.373	531.401	73.295
29	0.67	307	8.8	3074	7.344	890.043	7.860
Coal Flow =31.11 kg/sec, LHV of coal = 24610 kJ/kg							535.931
For BFP : Pump Input power = $m_{18}x(h_{18}-h_{17})/0.90$							12.668
For CEP : Pump Input power = $m_{16}x(h_{16}-h_{15})/0.80$							0.2414

Table-5: Total Exergy calculation at each Node for 75% load

Node	**Press (Mpa)**	**Temp. (^{0}C)**	**Mass flow rate, kg/sec**	**Specific Enthalpy(h) (kJ/kg)**	**Specific Entropy(s) (kJ/kg.K)**	**Specific Exergy(e) (kJ/kg)**	**Total Exergy(E), (MW)**
1	14.72	537	127.0	3416	6.488	1487.131	188.883
2	2.85	318	127.0	3043	6.645	1067.345	135.565
3	2.55	537	115.3	3544	7.418	1337.991	154.260
4	0.49	310	108.5	3085	7.505	853.065	92.525
5	0.49	310	102.5	3085	7.505	853.065	87.438
6	0.01	X=0.95	91.8	2465	7.775	152.605	14.005
7	1.18	426	6.8	3317	7.467	1096.389	7.489
8	0.167	195	5.1	2862	7.571	610.397	3.105
9	0.06	105	5.3	2691	7.634	420.623	2.213
10	0.016	X=0.95	0.4	2483	7.625	215.305	0.091
11	15.9	230	127.3	993.2	2.585	227.425	28.948
12	2.85	318	115.3	3043	6.645	1067.345	123.057
13	0.22	32	7324.7	134.3	0.4643	0.494	3.618
14	0.22	38.81	7324.7	162.8	0.5565	1.518	11.122
15	0.0101	46	103.3	192.6	0.6517	2.949	0.305
16	1.86	46	103.3	194.2	0.6509	4.787	0.495
17	0.59	149	127.3	627.9	1.831	86.817	11.051
18	16	151	127.3	646.2	1.835	103.925	13.228
19	2.85	319	11.7	3045	6.649	1068.153	12.518
20	1.37	200	11.7	2805	6.511	869.277	10.187
21	0.88	170	18.5	719.2	2.042	115.239	2.138
22	16	180	127.3	771	2.12	143.795	18.303
23	0.068	90	5.1	2660	7.494	431.343	2.194
24	0.02	72	10.3	2633	7.976	260.707	2.698
25	0.017	51	10.8	213.5	0.7166	4.509	0.049
26	0.88	70	103.3	293.7	0.9543	13.874	1.434
27	0.49	96	103.3	402.5	1.261	31.277	3.232
28	0.137	124	103.3	2721	7.334	540.023	55.805
29	0.49	309	6.0	3083	7.502	851.959	5.080
Coal Flow =23.83 kg/sec, LHV of coal = 24610 kJ/kg							410.519
For BFP : Pump Input power = $m_{18}x(h_{18}-h_{17})/0.90$							2.588
For CEP : Pump Input power = $m_{16}x(h_{16}-h_{15})/0.80$							0.2067

Table-6: Total Exergy calculation at each Node for 60% load

Node	Press (Mpa)	Temp. (^{0}C)	Mass flow rate,kg/sec	Specific Enthalpy(h) (kJ/kg)	Specific Entropy(s) (kJ/kg.K)	Specific Exergy(e) (kJ/kg)	Total Exergy(E), (MW)
1	14.72	537	102.9	3416	6.488	1487.131	153.090
2	2.35	313	102.9	3044	6.731	1042.717	107.341
3	2.06	537	94.1	3549	7.521	1312.297	123.453
4	0.39	310	88.7	3088	7.614	823.583	73.047
5	0.39	310	84.1	3088	7.614	823.583	69.292
6	0.01	X=0.95	76.2	2465	7.775	152.605	11.626
7	0.98	426	5.4	3320	7.555	1073.165	5.773
8	0.137	200	4.0	2874	7.686	588.127	2.339
9	0.05	105	4.0	2692	7.721	395.697	1.563
10	0.0147	X=0.9642	0.1	2513	7.755	206.565	0.016
11	15.7	220	103.2	947.8	2.494	209.143	21.588
12	2.35	313	94.1	3044	6.731	1042.717	98.092
13	0.22	32	7324.7	134.3	0.4643	0.494	3.618
14	0.22	37.65	7324.7	157.9	0.5409	1.267	9.282
15	0.0101	46	84.9	192.6	0.6517	2.949	0.250
16	1.96	46	84.9	194.3	0.6508	4.917	0.417
17	0.588	149	103.2	627.9	1.831	86.817	8.961
18	15.9	150	103.2	641.8	1.825	102.505	10.581
19	2.35	313	8.9	3044	6.731	1042.717	9.248
20	1.177	198	8.9	2812	6.59	852.735	7.563
21	0.863	167	14.2	706.1	2.012	111.079	1.583
22	15.7	170	103.2	727.5	2.023	129.201	13.336
23	0.0588	92	4.0	2666	7.575	413.205	1.643
24	0.0186	73	7.9	2635	8.015	251.085	1.990
25	0.0157	52	8.0	217.7	0.7295	4.864	0.039
26	0.98	70	84.9	293.7	0.9542	13.904	1.180
27	0.0588	95	84.9	2672	7.591	414.437	35.178
28	0.147	125	84.9	2722	7.305	549.665	46.656
29	0.412	310	4.6	3087	7.588	830.331	3.786
Coal Flow =19.72 kg/sec, LHV of coal = 24610 kJ/kg							339.754
For BFP : Pump Input power = $m_{18}x(h_{18}-h_{17})/0.90$							1.65
For CEP : Pump Input power = $m_{16}x(h_{16}-h_{15})/0.80$							0.1804

Table-7: Comparative results showing exergy destruction, % exergy destruction and 2nd law efficiency at different loads.

Components	Exergy destruction(MW)			% Exergy destruction			2nd Law efficiency (%)		
	100% load	**75% load**	**60% load.**	**100% load**	**75% load**	**60% load.**	**100% load**	**75% load**	**60% load.**
Boiler	284.19	219.38	182.89	86.674	87.99	87.12	53.03	53.44	53.83
Turbine	20.86	18.09	18.13	6.363	7.25	8.64	90.96	89.69	87.42
Condenser	7.35	6.245	5.75	2.242	2.5	2.74	65.67	64.65	62.37
CEP	0.04	0.0167	0.01	0.011	0.0066	0.01	91.92	91.92	92.57
BFP	6.44	1.411	0.03	1.963	0.656	0.01	43.94	84.11	98.18
LPH 1&2	0.51	1.713	1.2	0.156	0.68	0.57	89.26	65.69	50.3
HPH	3.38	2.148	2.43	1.032	0.86	1.16	93.39	93.53	90.5
Deaerator	69.42	51.972	43.06	21.171	20.84	20.51	17.81	17.53	17.22
LPH 3	-64.3	-51.66	-43.53	-					-
Grand Total Of Cycle	327.89	249.31	209.94						
Total Power Cycle	334.35	259.69	220.69				36.35	35.56	33.94

Figures

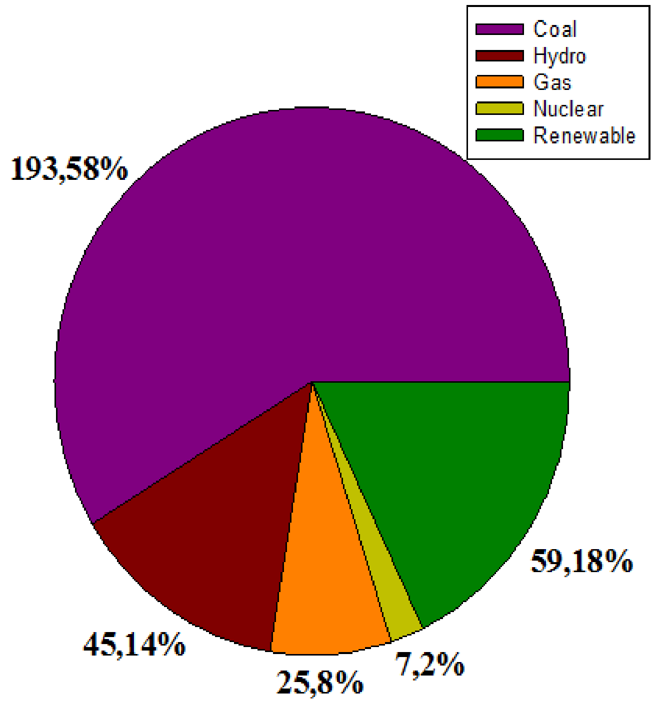

Figure 1: All India Installed Capacity (GW) as on 31.08.2017

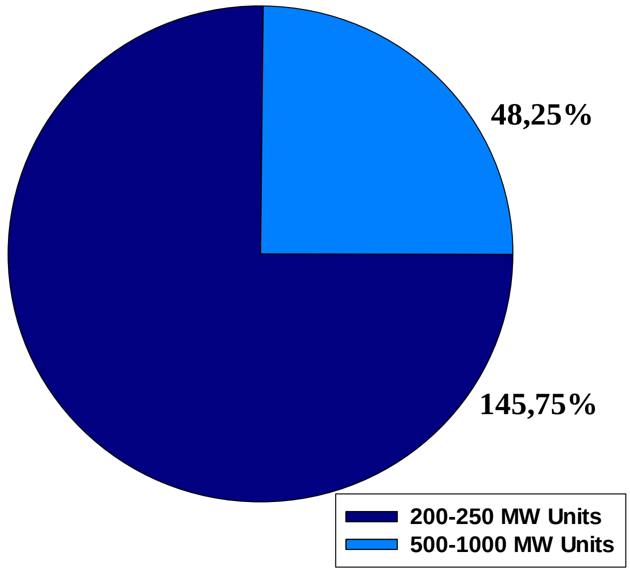

Figure 2: Installed Coal Units (GW) as on 31.08.2017

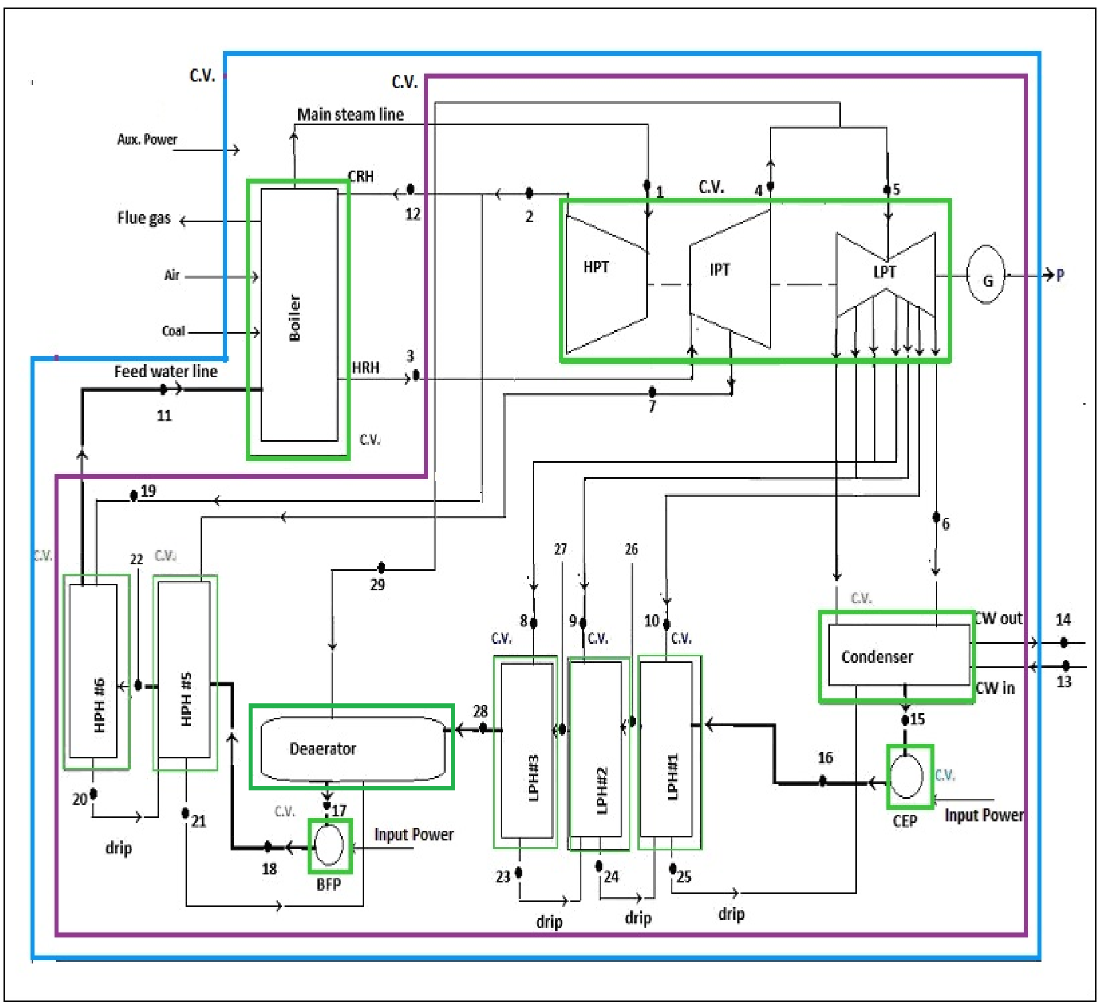

Figure 3: Schematic diagram of 210 MW Unit with nodes choosing each component as control volume.

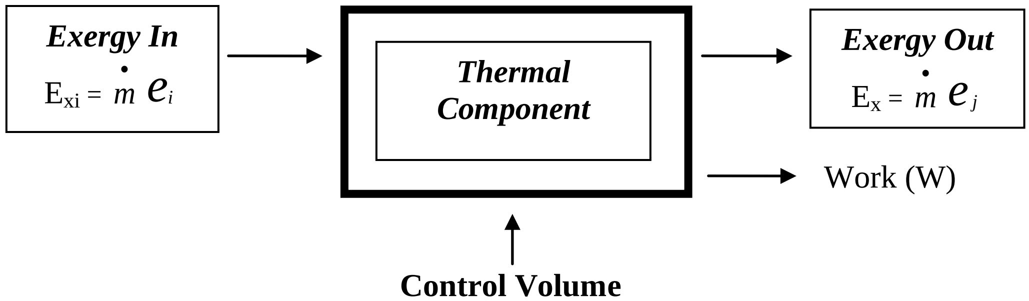

Figure 4: Exergy Model of Thermal component

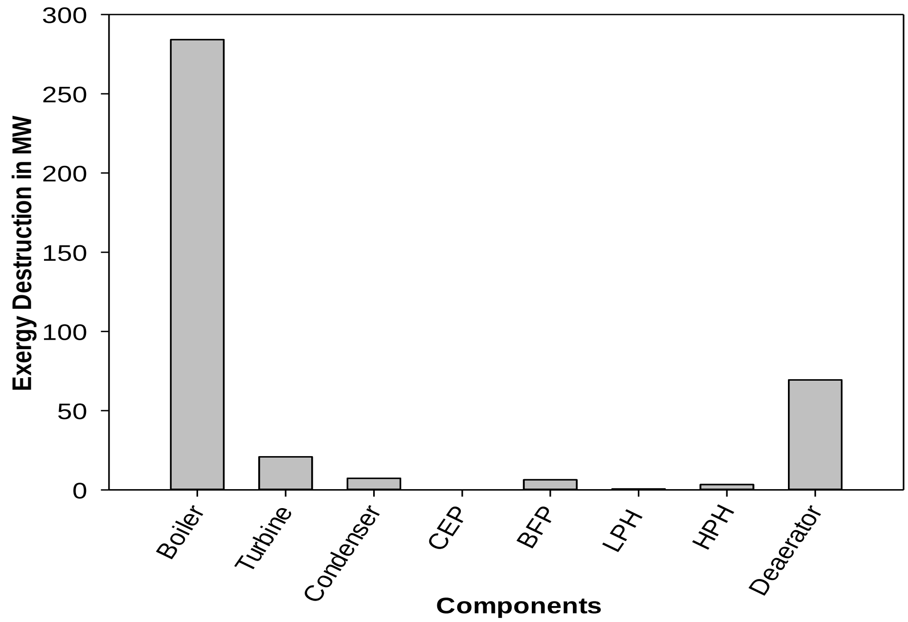

Figure 5: Power cycle components versus Exergy destruction (MW) at 100% load

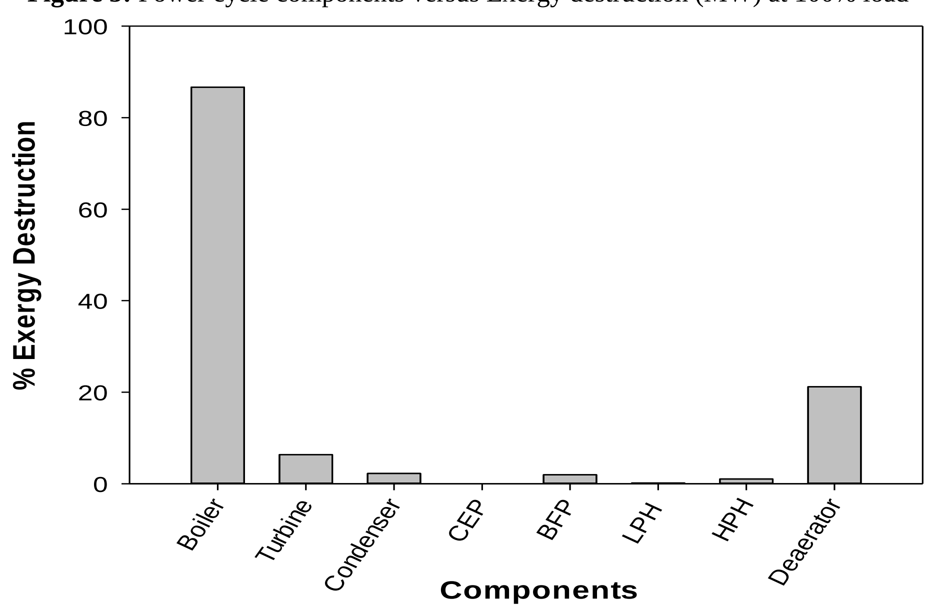

Figure 6: Power cycle components versus % Exergy destruction at 100% load

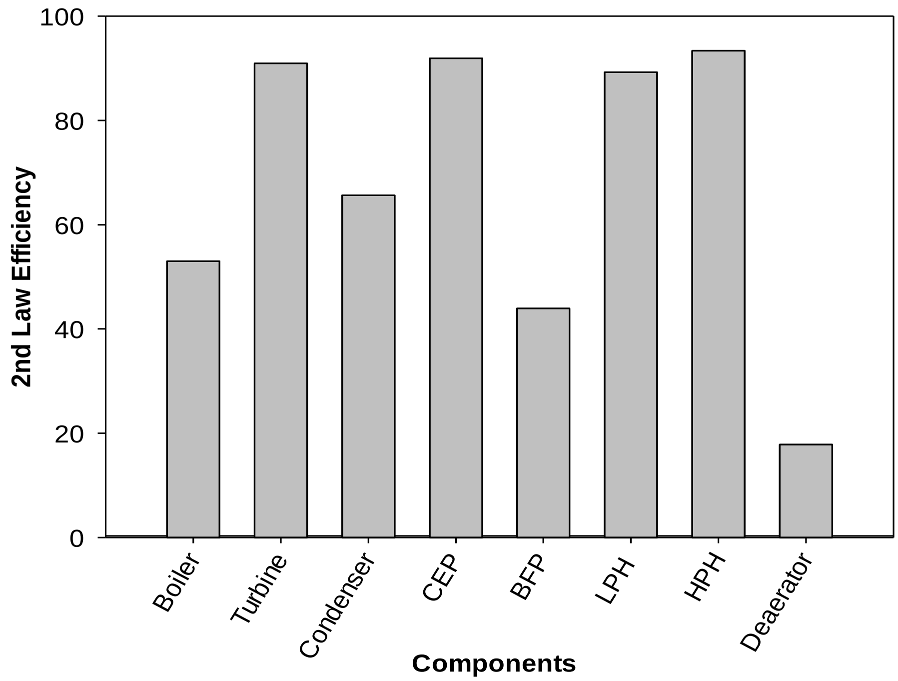

Figure 7: Power cycle component versus 2^{nd} Law Efficiency (%) at 100% load

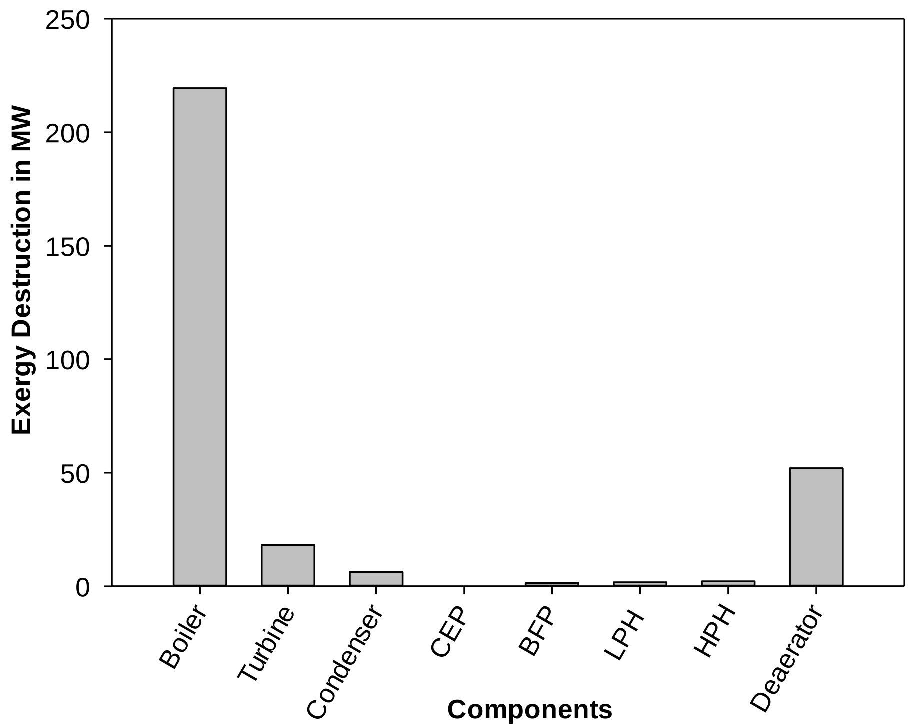

Figure 8: Power cycle components versus Exergy destruction (MW) at 75% load

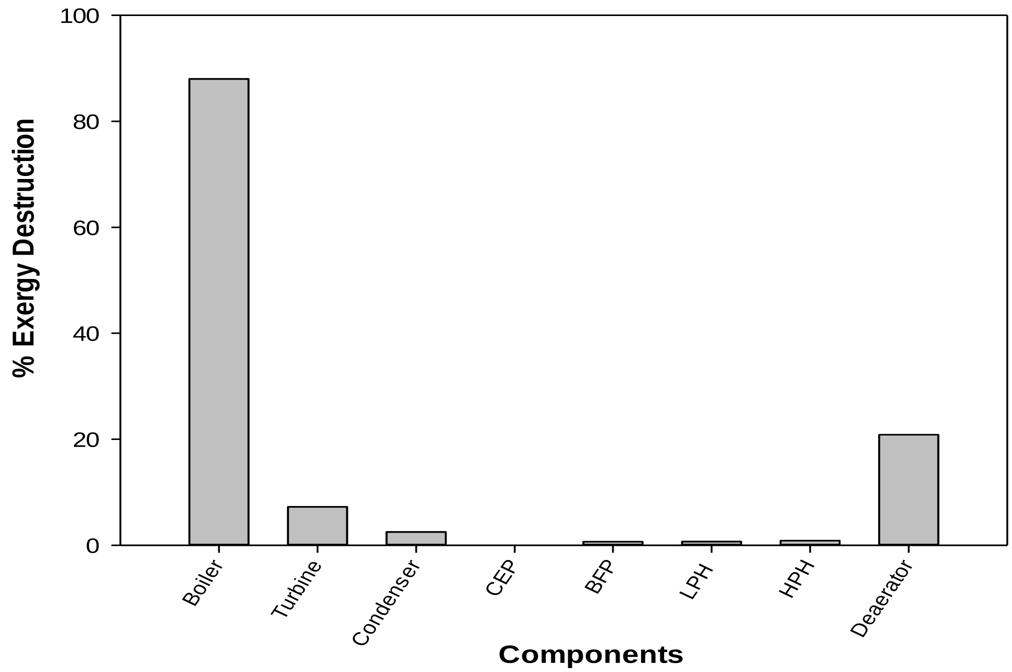

Figure 9: Power cycle components versus % Exergy destruction at 75% load

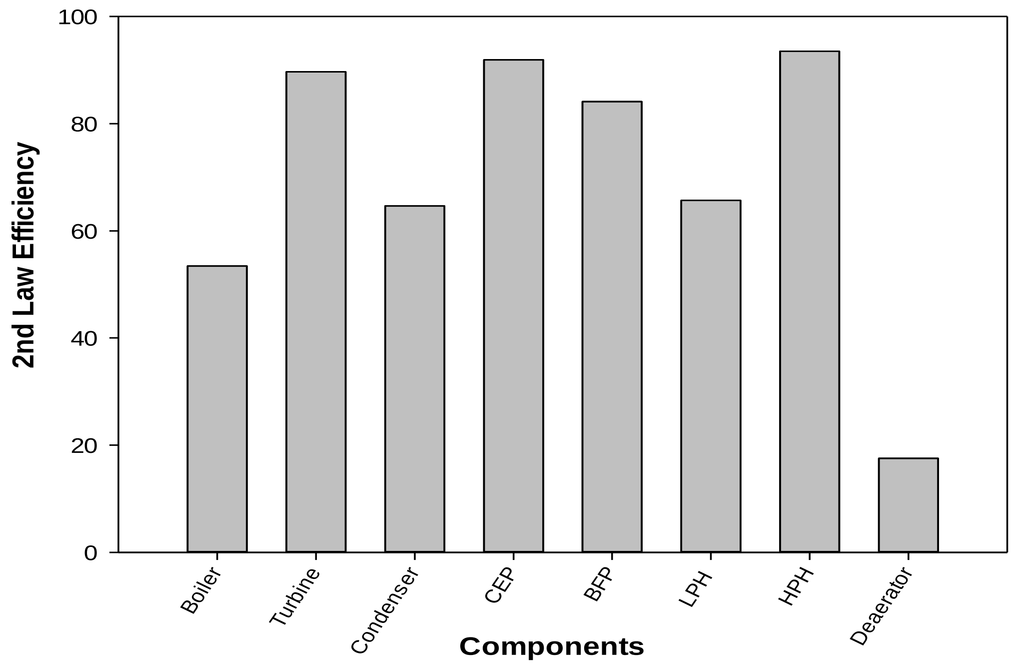

Figure 10: Power cycle component versus 2nd Law Efficiency (%) at 75% load

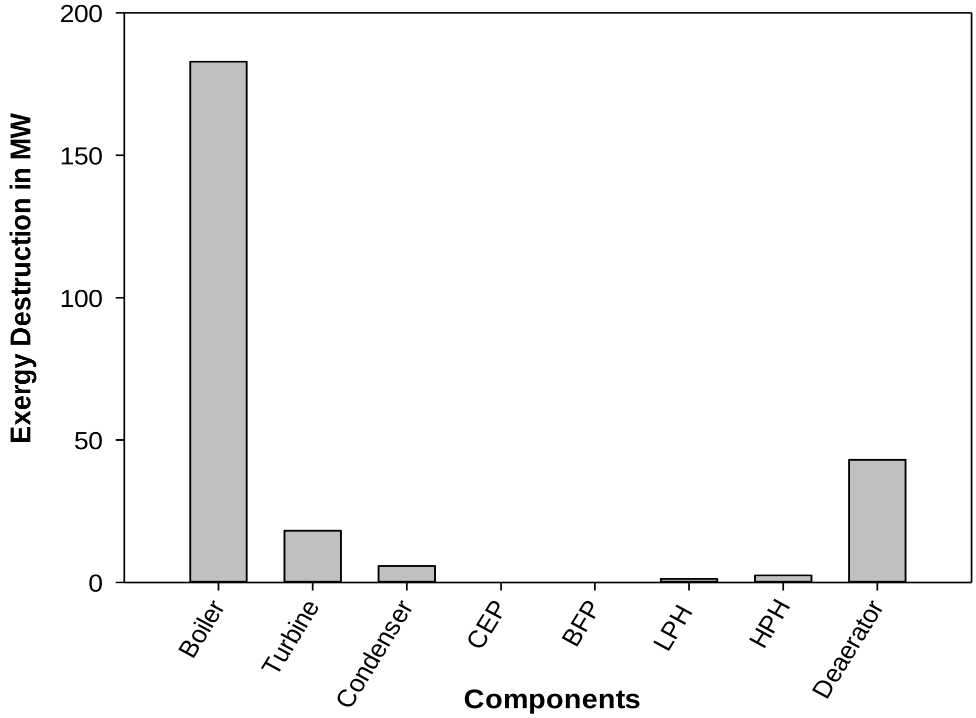

Figure 11: Power cycle component versus Exergy destruction (MW) at 60% load

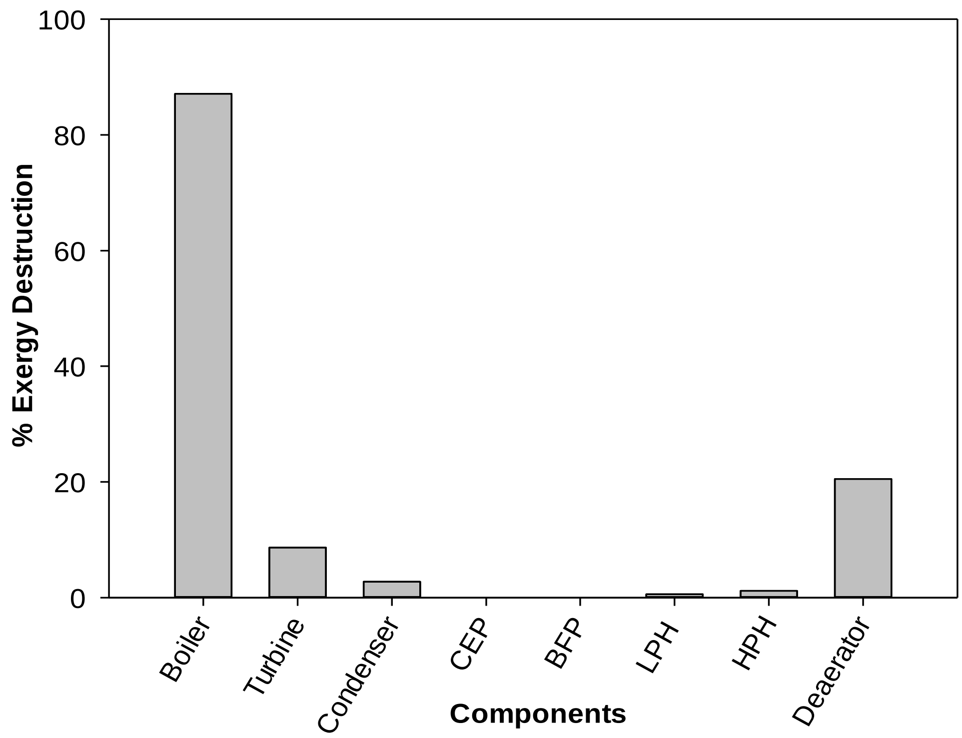

Figure 12: Power cycle components versus % Exergy destruction at 60% load

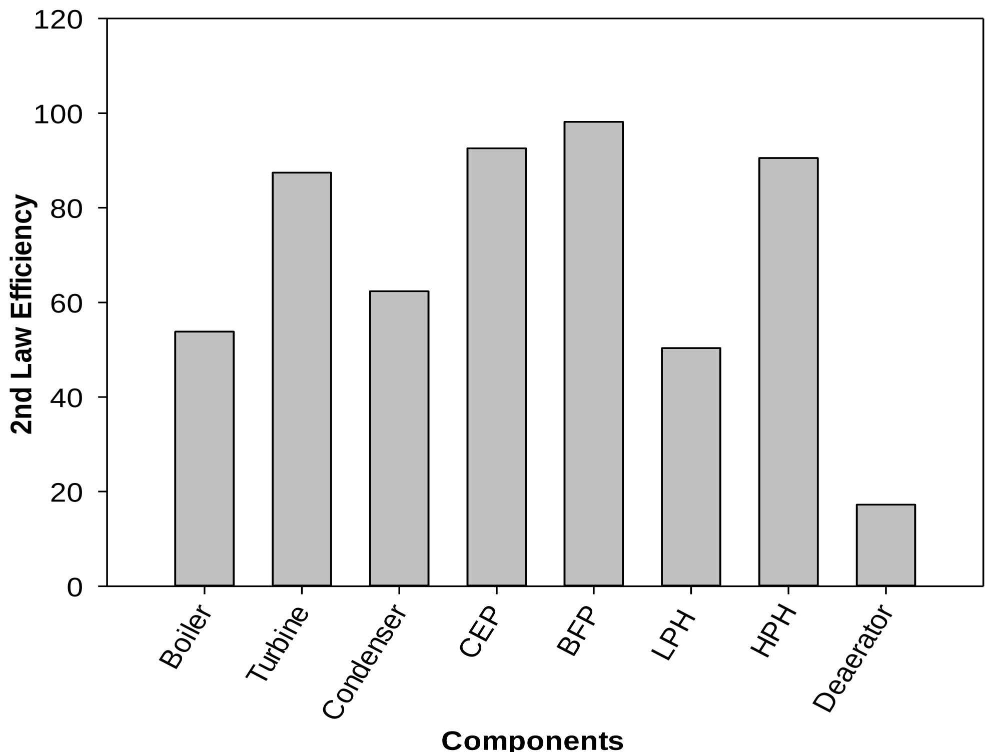

Figure 13: Power cycle component versus 2nd Law Efficiency(%) at 60% load

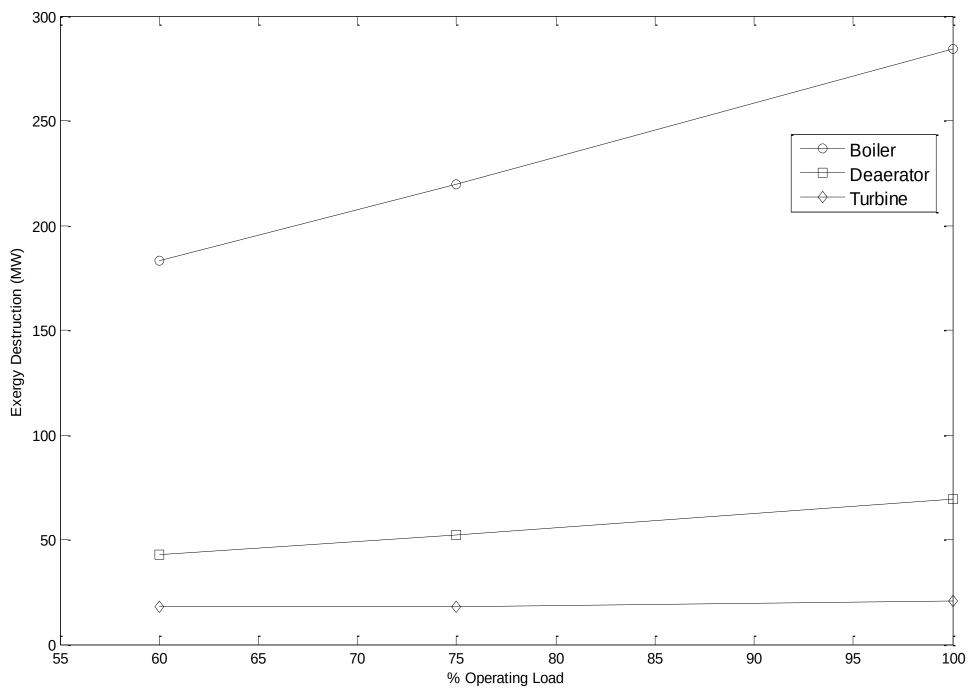

Figure 14: Variation of Exergy Destruction at different loads

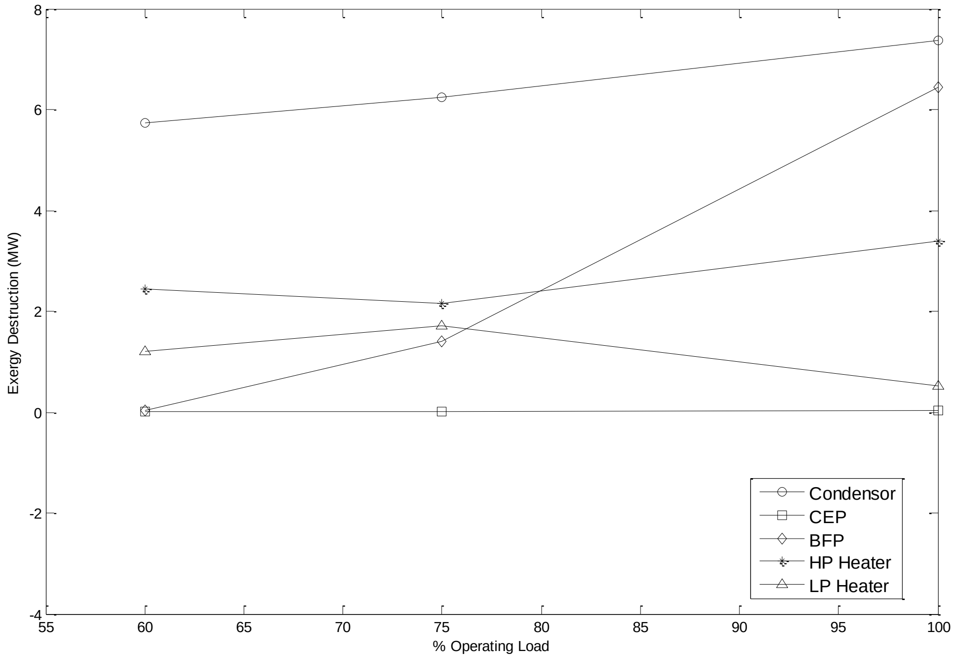

Figure 15: Variation of Exergy Destruction at different loads

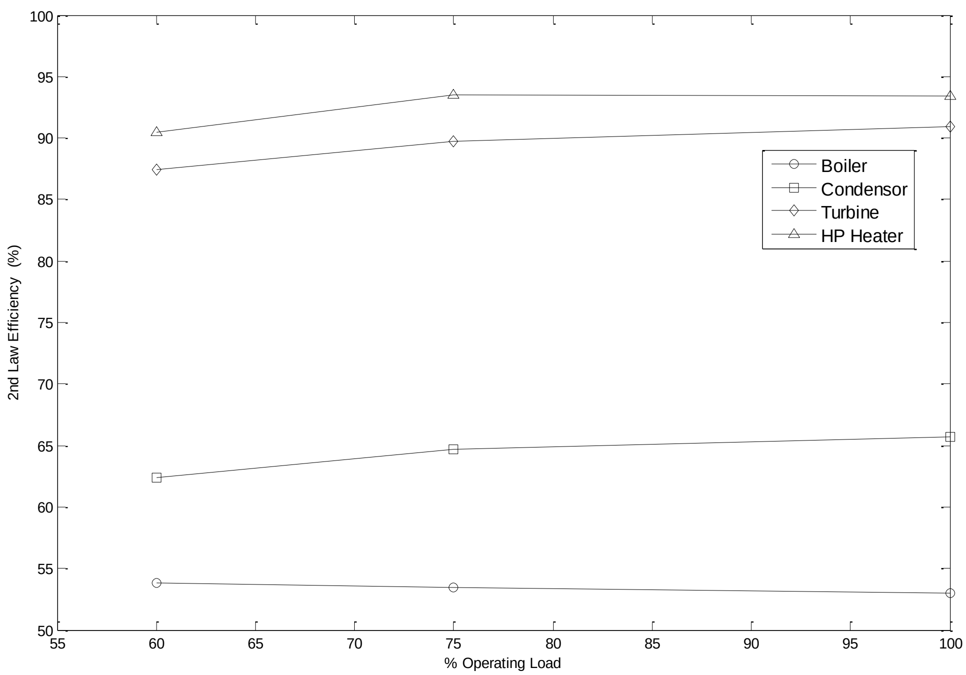

Figure 16: Variation of 2^{nd} Law Efficiency at different loads

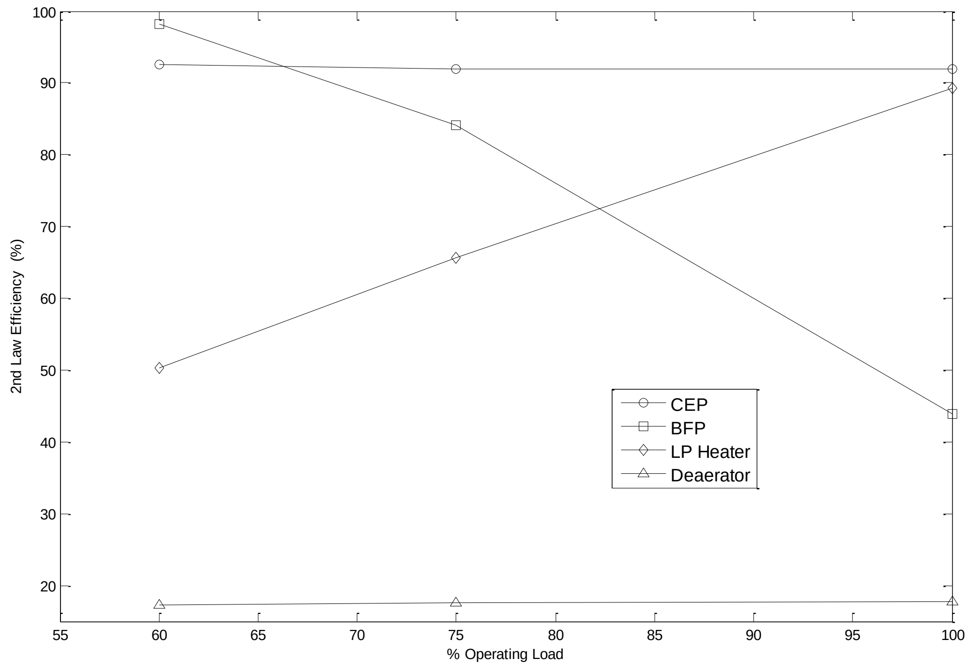

Figure 17: Variation of 2nd Law Efficiency at different loads

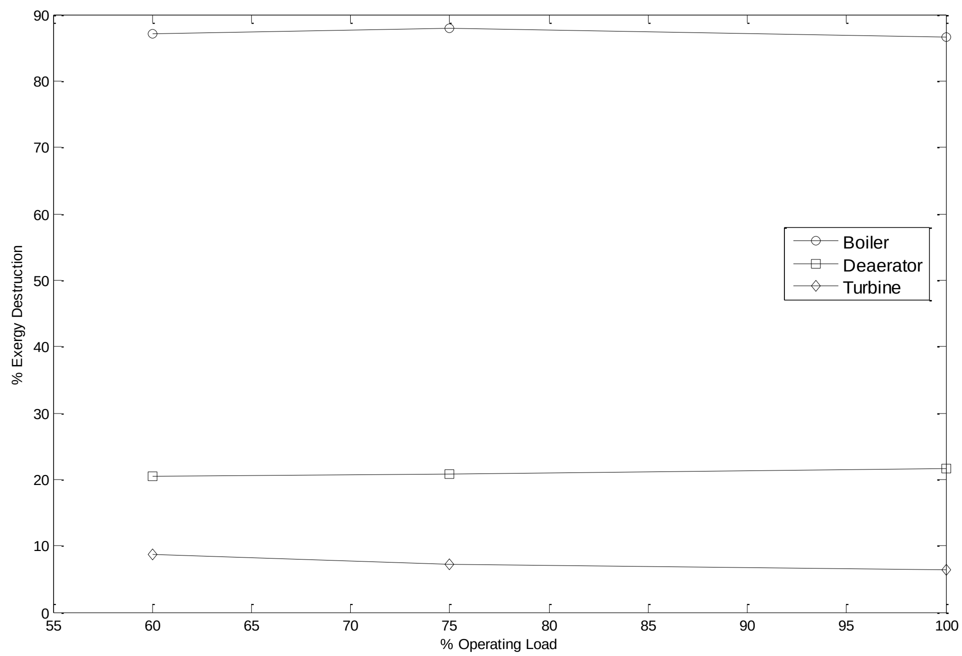

Figure 18: Variation of % Exergy Destruction at different loads

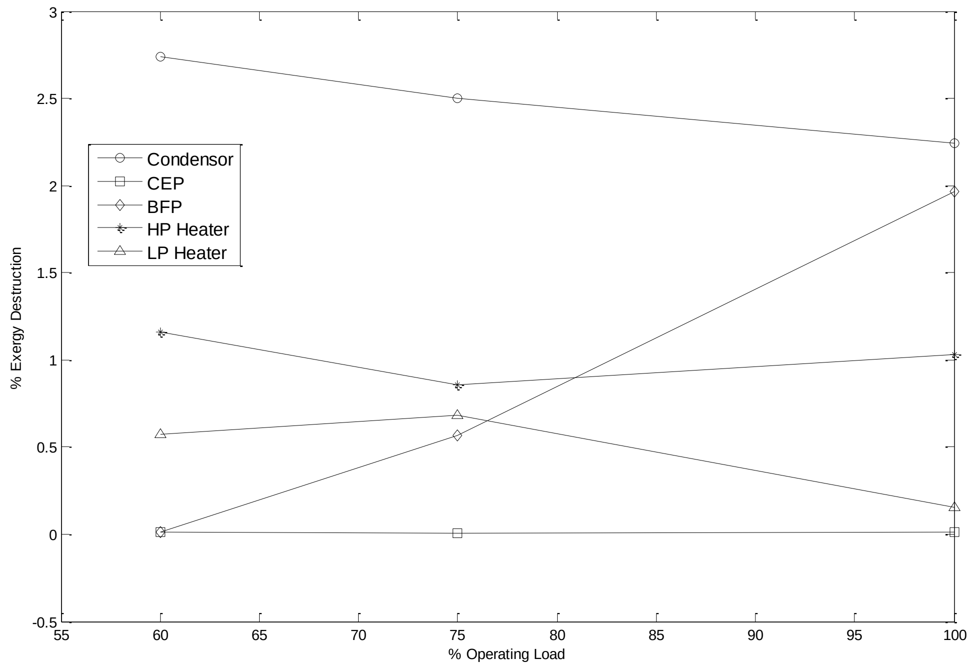

Figure 19: Variation of % Exergy Destruction at different loads

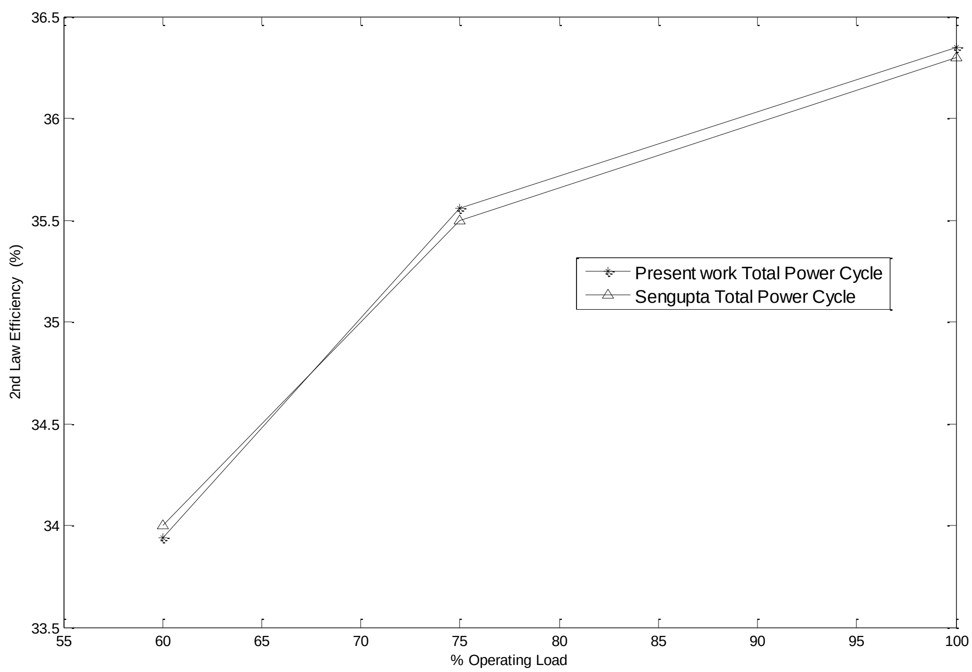

Figure 20: Comparison of 2nd Law efficiency (Total Power Cycle) with % Load of Sengupta et.al.2007

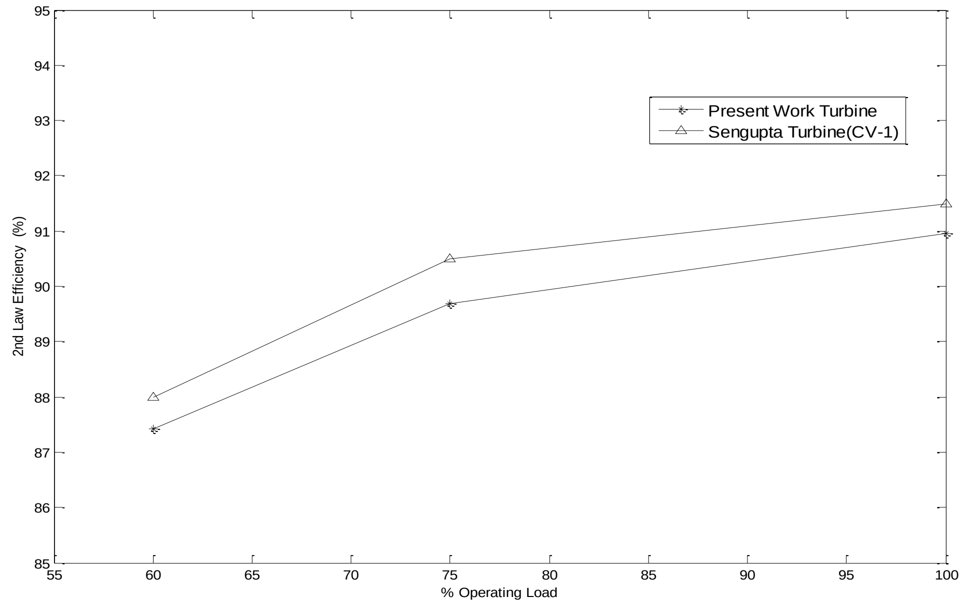

Figure 21: Comparison of 2nd Law efficiency (Turbine/CV-1) with % Load of Sengupta et.al.2007

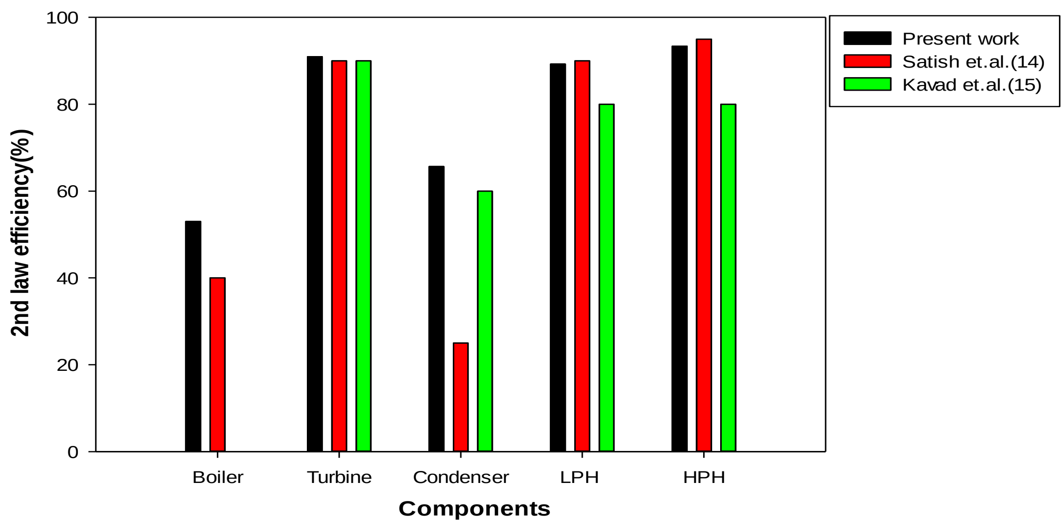

Figure 22: Comparison of 2nd Law efficiency of present work at 100 % load with Satish et.al 2016 and Kavad et.al 2017