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An Exergy Analysis of a 250 MW Thermal Power Plant

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Abstract
In this work, an exergy analysis of a 250 MW power plant is carried out. A thermal performance analysis is also done using the MATLAB calculation tool. The exergy destruction phenomenon and the exergetic efficiency are calculated for the various components of the 250 MW coal fired sub-critical power plant. The calculated overall plant exergy efficiency is evaluated to be 34.75%. Besides, from the results obtained, it can be concluded that the exergy destruction takes place in the steam generator 490.76 MW (93.07%), followed by the other components. A comparative study of the heat loss ratio with respect to varying plant load is performed, out of which, the condenser contributes to a major heat loss ratio. The outcomes of this research work will be beneficial for the future researchers.

Keywords: *Thermal performance, Thermal power plant, Exergy efficiency, Boiler.*

1. Introduction

In order to resolve the various energy related issues, a number of researchers have paid attention towards new searches for various energy resources in a continuing manner. The researchers have focused their research works on the energy efficiency enhancement in coal-based power plants [1-10]. These new alternative energy resources are expensive and are full of challenges for their implementation in the developing countries [11]. The world has always remained serious regarding a more efficient use of energy and its saving [12]. In many countries, the development is running so fast that the steam power plant cycles are going to vanish because of their low efficiency and so much environment pollution. Also availability of the fossil resources is going down in nearby future [13]. The world's electricity demand is mainly dependent upon fossil fuels in majority, although the solar and wind powers are also contributing some of their shares at a rapid rate. Thus efforts are being made to convert the aged sub-critical power plants into the efficient ones. A number of private companies have also entered the energy sector and have mainly concentrated on super-critical power plant commissioning because of their higher efficiencies. At the present time, coal-fired power plants are using a clean coal technology to reduce emissions and so have increased the plant efficiency. Exergy is a helpful tool to make a distinction between internal irreversibility and energy losses [14]. Energy resources and exergy efficiency can be optimized using the non-traditional optimization techniques. The exergy efficiency of a plant also depends on a fraction of excess air in it [15, 16]. Many researchers have made efforts to increase the exergy efficiency of the thermal system by introducing nano-fluids in the working fluid [17], proposing involvement of artificial neural network to build an efficient predictive model [18]. The novel approach of using photovoltaic modules for electricity generation has been investigated by the researchers in the recent years [19, 20]. Exergoeconomic analysis on adding a new feed water heater in a plant cycle has been investigated in Iran [21]. A study to analyse the energy, exergy, and environment performance of a combined cycle power plant at various loads has also been discussed [22, 23]. Some researchers have used the exergy analysis in case of heat pump to study the exergy destruction for domestic water heating applications [24]. Many more exergy analyses have been performed by various researchers around the world in different applications such as cement factories and hybrid-based power plants [25-27]. It is clear that a profitable capital investment always proves good in the nation economic growth and prosperity [28]. Thus the thermal performance of a sub-critical plant is proposed in this work.

2. A Power plant under study

Figure 1 depicts the functioning of a 250 MW power plant.

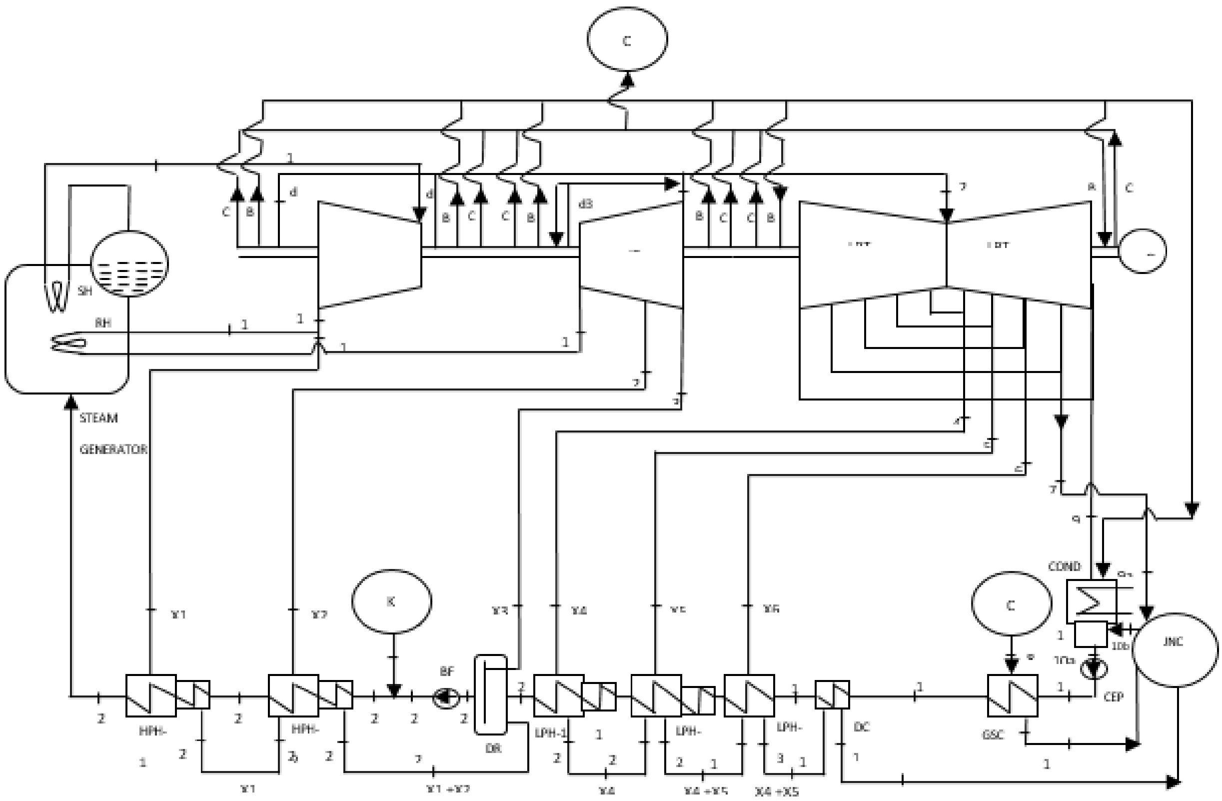

Figure 1. A 250 MW thermal power plant.

3. Exergy analysis modeling

The exergy balance equation is as follows:

$$\dot{X}_{in} + \dot{X}_{Q} = \dot{X}_{out} + \dot{X}_{W} + \dot{X}_{D} + \dot{X}_{L} \quad (1)$$

where the subscripts '*in*' and '*out*' refer to the inlet and outlet flows.

$$\dot{X}_{Q} = (1 - \frac{\dot{T}_o}{T_i})\dot{Q}_i \quad (2)$$

$$\dot{X}_{W} = \dot{W} \quad (3)$$

The exergy losses for a single component is zero [29].

$$\dot{X}_{L} = 0 \quad (4)$$

The sum of exergies can be represented by an equation [30], as given below:

$$\dot{X} = \dot{X}_{ph} + \dot{X}_{kn} + \dot{X}_{pt} + \dot{X}_{ch} \quad (5)$$

In table 1, the components of used fuel in the plant are represented.

The flue gas exergy can be evaluated using equation (8).

Some expressions for this exergy are also presented (see tables 2&3).

Table 1. Mass fractions of the coal elements.

Coal elements	Notation	Mass fraction
C	c	0.386
H	h	0.0263
O_2	o	0.909
S	s	0.0145
N_2	n	0.0104

***Data deduced from plant records.**

Table 2. Exergy function [13, 31].

Description	Expression	Equation
For a pure substance	$\dot{X} = \dot{m}\left[(h-h_o) - T_o(s-s_o)\right]$	(6)
For a solid fuel (semi-empirical correlation)	$\dot{X} = [(NCV)^o + 2442w]\phi_{dry} + 9417(s/100)$ $where, \phi_{dry} = 1.0437 + 0.1882\frac{h}{c} + 0.0610\frac{o}{c} + 0.0404\frac{n}{c}$	(7)
For a gas phase (flue gas)	$\dot{X} = \dot{m}\left[(h-h_o) - T_o(s-s_o) + \sum X_k^{'} \cdot e_k^{CH} + \bar{R}.T_o.\sum X_k^{'}.\ln X_k^{'}\right]$	(8)

Table 3. Exergy destruction and efficiency equations [32].

Component	Exergy destruction	Eqn.	Exergy efficiency	Eqn.
Pump	$\dot{X}_{D,P} = \dot{W}_P + \sum \dot{X}_{in,P} - \sum \dot{X}_{out,P}$	(9)	$\lambda_{ex,P} = (\dot{X}_{out,P} - \dot{X}_{in,P}) / \dot{W}_P$	(12)
Condenser	$\dot{X}_{D,C} = \sum \dot{X}_{in,C} - \sum \dot{X}_{out,C}$	(10)	$\lambda_{ex,C} = \dot{X}_{out,C} / \dot{X}_{in,C}$	(13)
Steam generator	$\dot{X}_{D,B} = \dot{X}_F + \sum \dot{X}_{in,B} - \sum \dot{X}_{out,B}$	(11)	$\lambda_{ex,B} = (\dot{X}_{out,B} - \dot{X}_{in,B}) / \dot{X}_F$	(14)
Steam turbine	$\dot{X}_{D,T} = \sum \dot{X}_{in,T} - \sum \dot{X}_{out,T} - \dot{W}_T$	(15)	$\lambda_{ex,T} = \dot{W}_T / (\dot{X}_{in,T} - \dot{X}_{out,T})$	(18)
Heater	$\dot{X}_{D,H} = \sum \dot{X}_{in,H} - \sum \dot{X}_{out,H}$	(16)	$\lambda_{ex,H} = \dot{X}_{out,H} / \dot{X}_{in,H}$	(19)
Cycle	$\dot{X}_{cycle} = \sum \dot{X}_{all_{components}}$	(17)	$\lambda_{ex,total} = \dot{W}_{netout} / \dot{X}_F$	(20)

4. Results and discussion

In this work, a 250 MW subcritical power plant was analyzed using the above relations. The exergy flow rates were tabulated in table 4. A comparison of heat loss ratio of the plant components at different load conditions is shown in table 5. The exergy destruction rate of the boiler was found to be 490.76 MW, followed by the other components. The exergy destructions of the steam turbine were observed to be 6.98, 3.40, and 10.98 MW, which were 1.32%, 0.64%, and 2.08% of the total cycle exergy destruction respectively. The exergy destruction was found to be 4.61 MW (0.87% of the total plant exergy destruction). The exergy analysis is shown by a log plot for various components in the 250 MW capacity plant; refer to Figures. 2(a)-2(c). The plant overall exergy efficiency was calculated to be 34.75%. A Comparison was also made in table 6 at different load conditions. It is clear from figure 2(a) that the exergy destruction rate value decreases in trend. The components such as steam generator, low pressure turbine, and boiler feed pump should be studied in the design perspective in order to reduce the exergy destruction. Also the percent exergy destruction gives the idea of replacement of the components involved in the steam generation process with the components having a low exergy destruction rate; see figure 2(b). The boiler feed pump is to be considered for replacement. The reported minimum boiler and condenser exergetic efficiencies were 32.90 and 54.760, as shown in figure 2(c).

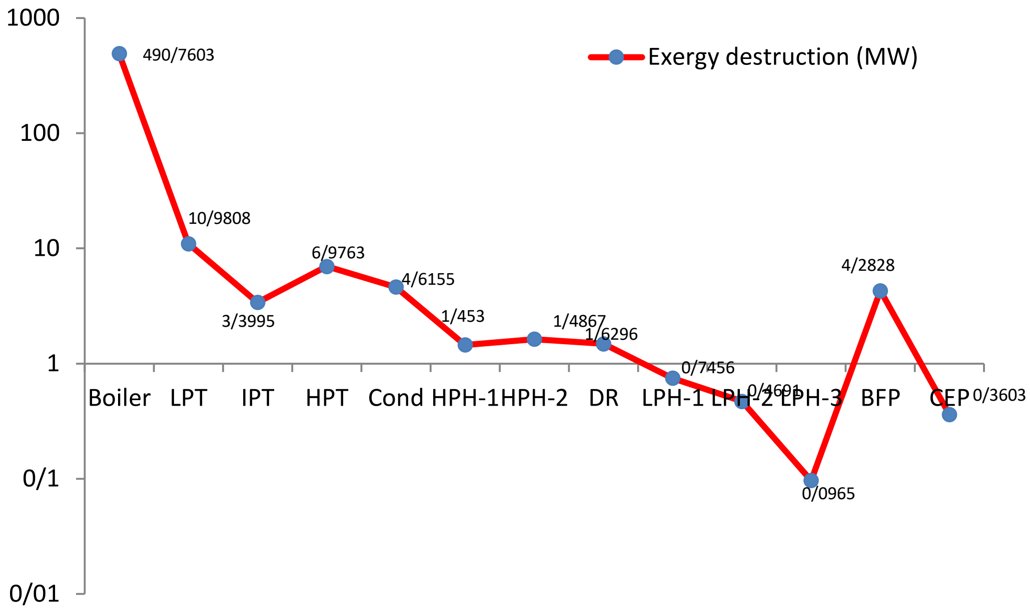

Figure 2(a). Exergy destruction (MW) log plot for various components of the 250 MW capacity plant.

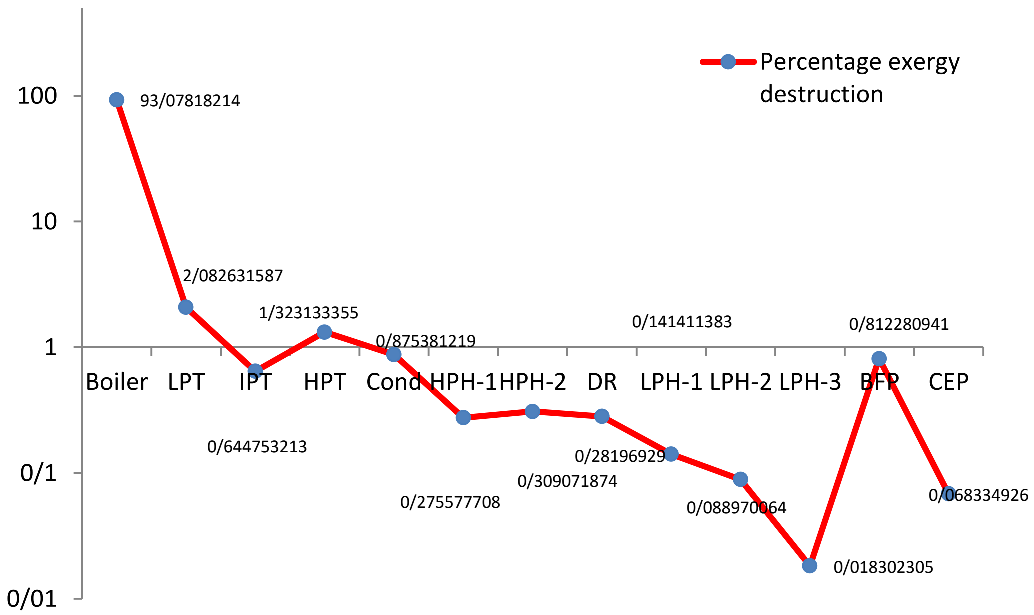

Figure 2(b). Percent exergy destruction log plot for various components of the 250 MW capacity plant.

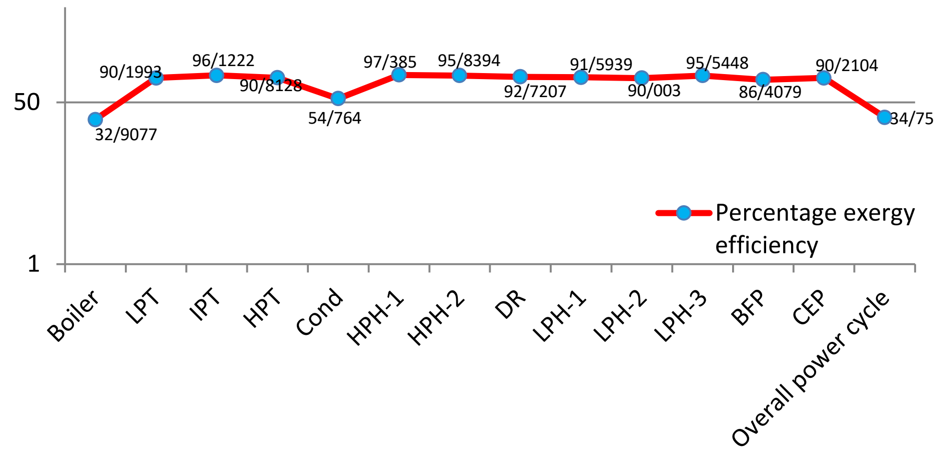

Figure 2(c). Percent exergy efficiency log plot for various components in the 250 MW capacity plant.

In order to find the exergy at a specific stream, values of enthalpy, entropy, pressure, and temperature were recognized using an energy analysis. Each component was separated by an input and output stream. The stream exergy values were calculated and tabulated in table 4. The exergy analysis identifies the process that is inefficient. It can be noticed in table 4 that exergy of stream follows a decreasing trend from the outlet of boiler and continues to decrease up to a high pressure heater. The highest values for exergy indicate that energy can be extracted from stream till it reaches an equilibrium state with its surrounding. The amount of heat loss in the process at different plant loads is shown in table 5. The condenser was found to be the high heat loss component, where approximately 78% of the energy is lost to the circulating water for all load conditions. A significant change was seen in the turbine section for varying load conditions. At 90% and below load conditions, the heat loss for turbine reduces as compared with a 100% load. Also heat loss reduces at the heater section for a negligible level at a load less than 90%. The exergy destruction values of various components at varying load conditions are tabulated in table 6. The steam generator was found to be the maximum exergy destruction component irrespective of varying load conditions. The exergy destruction values decrease for the intermediate and low pressure turbines, while for a high pressure turbine, the exergy destruction value increases with respect to varying load conditions. The exergetic efficiency reduces by 0.85% as the load changes from 100% to 80%.

Table 4. Exergy analysis of a 250 MW plant.

Stream	$\dot{X}$ (MW)	Stream	$\dot{X}$ (MW)	Stream	$\dot{X}$ (MW)	Stream	$\dot{X}$ (MW)
1a	299.7207	7	0.004084	17	2.6	27	14.5
1b	223.7854	8	-	18	3.6	28	193.0
1c	202.5463	9	16.79907	19	42.6	29	475.5
1d	247.5071	10a	0.286623	20	2.2	$Water_{in}$	130.4
1	21.23444	10b	-	21	61.7	$Water_{out}$	487.6
2	12.85156	11	0.646563	22	111.8		
3	9.303881	12	0.524274	23	18.0		
4	4.829757	13	0.003197	24	116.8		
5	2.647424	14	0.618552	25	116.8		
6	1.363987	15	0.068279	26	150.3		

Table 5. Comparison of heat loss ratios at different load conditions.

	Heat loss, MW Plant load			Heat loss, % Plant load		
Plant components	100%	90%	80%	100%	90%	80%
Condenser	322.2838	296.8234	271.1854	78.38445	78.22182	78.54611
Steam generator	83.304	79.7556	71.5014	20.26083	21.01798	20.70966
Turbine	5.096	2.8442	2.5565	1.239427	0.749532	0.740464
Heaters	0.474	0.0405	0.013	0.115284	0.010673	0.003765
Power Cycle	411.1578	379.4637	345.2563	100	100	100

Table 6. Comparison of exergy destruction at different load conditions.

	Exergy destruction, MW Plant load			Percent exergy efficiency, %Plant load		
Plant components	100%	90%	80%	100%	90%	80%
Steam generator	490.7603	446.5875	401.7089	32.9077	32.9589	33.0931
LPT	10.9808	9.2996	8.3701	90.1993	90.6801	90.5126
IPT	3.3995	3.057	2.7428	96.1222	96.1514	96.1493
HPT	6.9763	8.7803	10.2428	90.8128	87.6018	84.3525
Cond	4.6155	3.9906	3.3901	54.764	88.399	63.0765
HPH-1	1.453	1.3039	0.7737	97.385	97.2871	98.1076
HPH-2	1.6296	1.4884	6.2909	95.8394	95.6123	81.451
DR	1.4867	1.398	1.1836	92.7207	92.0212	92.0297
LPH-1	0.7456	0.6349	0.5329	91.5939	91.6451	91.7227
LPH-2	0.4691	0.5066	0.4091	90.003	87.5309	87.9185
LPH-3	0.0965	0.4156	0.2996	95.5448	81.6206	83.733
BFP	4.2828	3.9075	1.8131	86.4079	86.8918	45.8857
CEP	0.3603	0.3275	0.269	90.2104	73.33113	57.9668
Overall power cycle	527.256	481.6974	438.0266	34.75	34.37	33.9

5. Conclusion

An exergy analysis of a 250 MW coal fired power plant situated in North India has been presented in this work. The exergy analysis was carried out for the system components separately and the exergy destruction of various components in the plant was evaluated. A large portion of exergy destruction takes place in the steam generator so the possibility of efficiency improvement was found to be in the steam generator. The exergy destruction of a high pressure turbine shows a significant increase, while an intermediate pressure turbine and a low pressure turbine show decreases with respect to varying load conditions. The exergy efficiency of the condenser showed a remarkable maximum value of 88.399% at 90% of plant load as compared with 100% and 80% of plant load. It can be concluded that the existing drum of the steam generator requires some necessary modification for reduction of its exergy destructions for an improvement in the plant performance. Also due to low quality, the exergy loss in the condenser was found to be thermodynamically insignificant. The overall exergy efficiency of the plant was calculated to be 34.75%.

Nomenclature

BFP	Boiler feed pump
CEP	Condensate extraction pump
COND	Condenser
DR	Dearator
DC	Drain cooler
GCVcoal	Gross calorific value of coal
H	Enthalpy (kJ/kg)
HPT	High pressure turbine
HPH	High pressure feed water heater
IPT	Intermediate pressure turbine
i	Interest rate
IPT	Intermediate pressure turbine
JNCT	Condensate collector
LPT	Low pressure turbine
LPH	Low pressure feed water heater
LHV	Lower heating value of coal (kJ/kg)
MW	Capacity of plant
MWe	Electric power output
$\dot{m}_f$	Coal consumption rate (Ton/h)
$\dot{m}_{uv}$	Unit mass flow rate of water (Ton/h)
NCVcoal	Gross calorific value of coal
P	Pressure in bar
S	Entropy ((kJ/kg K)
up_{hr}	Annual operating hours of the plant
$\dot{W}_P$	Work done by pump
$\dot{W}_T$	Power output of turbine
x_i	Mass flow rate of steam at the 'ith' state
$\dot{X}$	Exergy function

Greek letters

η_P	Pump efficiency
λ_{ex}	Exergy efficiency

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