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Research Article

Application of exergy analysis in understanding the performance of a coal-fired steam power plant (120 mw) with single reheat and regenerative configuration

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ABSTRACT

In the present paper, a rigorous analysis of a sub-critical steam power plant (120 MW) with reheating and regenerative configuration is presented, using energy and exergy analysis. The total work output from the power plant is 121.80 MW, which is close to the real value of 120 MW. The calculated energy efficiency of the steam power plant is 34.7%, while its exergy efficiency is 32%. In addition to it, energy analysis introduces the condenser as a major source of heat loss, on other hand, exergy analysis introduces the boiler as a major source of exergy destruction. Further to understand the effect of main steam temperature, reheating temperature and condenser pressure on the power plant, a parametric study is being conducted.

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INTRODUCTION

In recent years, coal-based steam power plant (SPP) is being eliminated from the energy generation matrix in a phase-wise manner, and it is because of its low efficiency and high environmental degradation [1]. Hence, many research activities are being promoted in the area of renewables [2]. Of course, it cannot be denied the fact that renewable source of energy has the potential to impede climate change. However, the issue of its capability to meet the growing demand for energy specially in the form of power is still in the research stage [3]. Further, data released by IEA regarding power production referring to 2015 shows that the contribution of renewable account for 23.1% in the energy generation matrix, while fossil-fuel based thermal power plant accounts for 76.9% (oil 4.1%; nuclear 10.6%; natural gas 22.9%; coal 39.3%) [4]. Hence, it can be inferred, that still the majority of electricity production

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comes from SPP, and in the coming decades also, it will dominate the graph. Further wide availability of coal, ease of transportation, and suitability for baseload make SPP a suitable choice [5].

Seeing the importance of SPP in global energy matrix, efforts are being taken to improve the performance of SPP through thermodynamic analysis. The most common method adopted to assess the performance of SPP is through energy analysis. However, due to scarcity of natural resources, a rigorous analysis where not only the quantity of energy is judged, rather issues like quality also becomes important, and this "quality of energy" is well gauged by exergy analysis. It represents the true potential of an energy system assessing not only the effective utilization of energy, but also its degradation by different processes. Hence, there is an increasing need for considering both energy and exergy analysis for the performance assessment [6]. Many authors have applied exergy for different energy system. Ibrahim et al. [7] investigated about gas turbine, and concluded combustion chamber to be a major source of exergy destruction among all components. Topal et al. [8] investigated circulating fluidized bed with olive pits co-firing and concluded that with co-firing, there is an increase in exergy efficiency by 0.51% and a decrease in dust emission. Another author, Kamate et al. [9] investigated about backpressure steam turbine, condensing steam turbine and boiler installed in a sugar factor, and concluded that backpressure steam turbine requires least improvement potential, while boiler requires highest improvement potential. Apart from all these, exergy analysis has been applied in context of combined cycle power plant [10], diesel based cogeneration [11], trigeneration [12], Kalina cycle [13], absorption systems [14], transportation [15] and coal based SPP [16]. Few other authors are also cited in context of SPP.

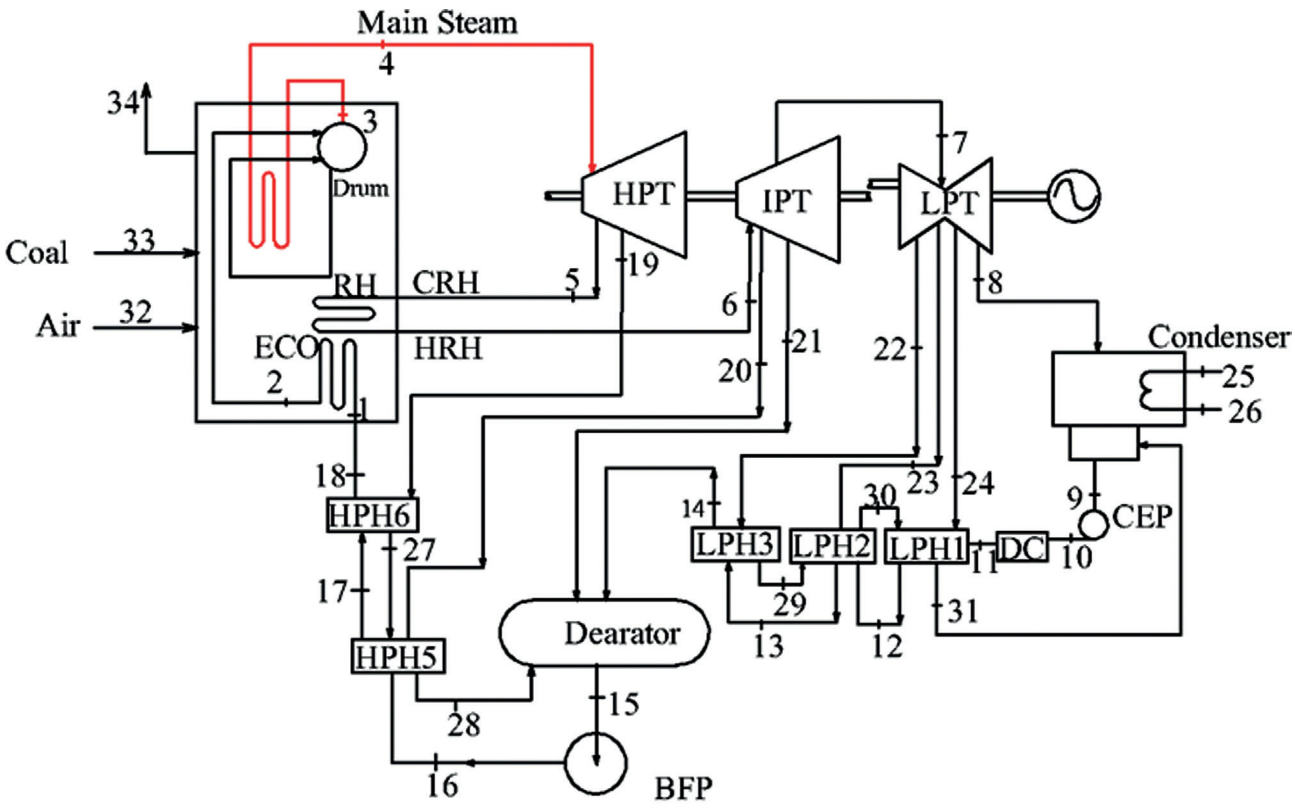
Regulagadda et al. [17] assessed 32 MW coal-fired power plant and introduces boiler as a major contributor for exergy destruction. Fadhil et al. [18] also assessed exergy analysis of a 120 MW coal-fired power plant, and introduces boiler as the main source of exergy destruction, and this result was supported by Erdem et al. [19]. Further, the pattern of exergy destruction shown by various components in SPP does not change irrespective of load [20], ambient temperature [21] and fuel used [22]. Hence, in order to improve the performance assessment, some methods are suggested by various researchers. In this context, Rashidi et al. [23] carried out performance assessment of SPP and concluded that performance is dependent on the condenser pressure and boiler exit temperature. Further, Li et al. [24] suggested to operate the plant at full load. Similarly, Hou et al. [25] assessed the performance of SPP using ASPEN, and suggested to increasing the combustion chamber temperature which ultimately increases the temperature of main steam, causing a rise in the power output from turbine. Similarly, Xiong et al. [26] investigated the application of oxy-combustion SPP instead of the conventional one, and appreciated the application oxy-combustion boiler. Recently, many authors are suggesting the incorporation of solar for reheating. Alotaibi et al. [27] incorporate solar by removing low pressure turbine extractions, and showed increment of power by 9.8 MW. Further, many researchers have suggested the incorporation of other cycles with SPP. In this regard, Khankari et al. [28] incorporated kalian cycle to recapture from the condenser of 500 MW thermal power plant, and produced electricity.

It need not be exaggerated that though the available analyses can give some broad guidelines about the performance of a power plant however the performance is dependent on its configurations and operating parameters. It may further be noted that so far energy and exergy analysis for utility based power plants have been considered, captive power plants (CPP) have rarely been considered. A CPP is typical industrial facilities which provides a localized source of power to the entire complex. Hence, seeing this aspect we cannot neglect the fact that CPP are very important for the large industrial establishment, particularly where energy security and flexibility is an important factor [29]. Further, assessing losses in energy system through energy and exergy analysis, helps in reducing the fossil fuel consumption, which indirectly helps in reducing economic cost, water footprint etc. As far as the author knows, so far no efforts have been made for the performance analysis of any SPP, configured into CPP mode. The present work aims at a thorough assessment of the plant and tries to explore the scope of further improvement in plant performance.

Power Plant Description

This plant (Unit 4) is situated in the Jojobera (Jamshedpur, India), and it is owned by Tata power. Figure 1 presents the schematic diagram of SPP with 120 MW capacity, with coal as fuel. Technical specifications of unit 4 are presented in Table 1. It is modelled as improved Rankine cycle with reheating and regenerative feed water heating, with two high pressure heaters (HPH6 and HPH5), three low pressure heaters (LPH3, LPH2 and LPH1) and one open feed water heater called deaerator.

However, without the description of coal handling plant, it would be very improper to start the system description. Coal, when received from collieries through train, is unloaded by wagon tippler technology. It is then transported to dead storage site through belt conveyor system. After that coal is prepared for combustion through crushers. After that the crushing, coal is transported to coal storage area through belt conveyor and kept as an inventory, and it is injected into the boiler furnace (33) along with preheated air (32), to convert feed water to superheated steam. The feed water after converting into superheated steam is allowed to expand in HPT



HPT-High pressure turbine; IPT-Intermediate pressure turbine; LPT-Low pressure turine; LPH- Low pressure heater; HPH- High pressure heater; CRH- Cold reheat; HRH- High reheat; BFP-Boiler feed pump; DC- Drain cooler; CEP- condensate extraction pump

Figure 1. Schematic representation of a coal fired steam power plant with 120 MW capacity.

(4), and there after one part of steam is sent through CRH for reheating (5), and another part of steam (19) is sent to HPH 6 for feed water heating. CRH after reheating in boiler is converted to HRH, and allowed to expand in IPT (6), where after expansion in IPT, one part is sent towards HPH5 (20), and other one towards deaerator (21). Further, the stream coming towards LPT (7) from IPT is allowed to expand in LPT, after which it gets divided into four streams, and sent towards LPH3 (22), LPH2 (23) and LPH1 (24) and condenser (8), respectively. The steam after producing useful work in all three turbines i.e. HPT, IPT and LPT is routed to condenser, where it is condensed by cooling water. After that, the condensate is sent by CEP towards LPH1 through DC. From the last LPH1, the condensate is routed to the deaerator (14), via LPH2 and LPH3 respectively. After getting preheated in the deaerator, BFP supplies this condensate from deaerator to HPH5 (16) and HPH6 (17) respectively. After HPH6, the condensate enters the boiler section through economizer (18), thereby entering boiler section. Hence, following the route the cycle is completed. It should be noted that all the number in parenthesis represents the reference points, which is used for designation in SPP, and it is represented in Table 2.

Table 1. Operating conditions of Unit 4

Operating conditions	Value	Units
Power produced	120	MW
Fuel input	24.9	kg/sec
Lower heating value	14070	kJ/kg
Main line steam flow rate	122.11	kg/sec
Main line steam pressure	129	kPa
Main line steam temperature	544	°C
Feed water temperature	233	°C
Stack gas temperature	124	°C
Air flow rate	122	kg/sec
Stack gas flow rate	147	kg/sec

METHODOLOGY

Energy analysis

To carry thermodynamic modelling of each component, the thermophysical properties of the working fluid must be known. Thermodynamic properties of fluid have been obtained from the EES [30] while for gas mixtures the law of average has been used knowing the mole fraction of each component [31]. Appendix A presents the property of the various working fluids. Further, for carrying out analysis of SPP, following assumptions have been made, and they are listed below: -

- The system operates under steady-state conditions.
- Combustion is assumed to be complete.
- The reference condition for the ambient is considered as P_0 = 101.235 kPa and T_0 = 303 K.
- The fuel coal has following composition: C (33.1%), H_2 (2.95%), Sulphur (0.65%), O_2 (12.298%), N_2 (0.6%), Ash (50.679%), H_2O (43%) with a *LHV* of 14070 kJ/kg. These values are provided by Tata power

Table 2. Nomenclature of various points present in SPP (Figure 1)

Reference points	Nomenclature
1	The inlet of feed water to economizer
2	The outlet of feed water from economizer
3	The outlet of steam from boiler
4	The main steam line towards HPT
5	Cold reheat steam from HPT
6	High reheat steam towards IPT
7	The outlet of IPT towards LPT
8	The outlet of LPT towards condenser
9	The outlet of condensate from condenser towards CEP
10	The outlet of condensate from CEP
11	The outlet of condensate from DC
12	The outlet of condensate from LPH1
13	The outlet of condensate from LPH2
14	The outlet of condensate from LPH3
15	The outlet of feed water from deaerator
16	The outlet of feed water from BFP towards HPH5
17	The outlet of feed water towards HPH6
18	The outlet of steam from HPH6 towards economiser
19	The outlet of steam from HPT towards HPH6
20	The outlet of steam from IPT towards HPH5
21	The outlet of steam from IPT towards Deaerator
22	The outlet of steam from LPT towards LPH3
23	The outlet of steam from LPT towards LPH2
24	The outlet of steam from LPT towards LPH1
25	Cold water input into condenser
26	Hot water output from condenser
27	Drip from HPH6
28	Drip from HPH5
29	Drip from LPH3
30	Drip from LPH2
31	Drip from LPH1
32	Air input to boiler
33	Coal feed as input to boiler
34	Stack

Boiler

In the boiler, the chemical energy of coal is used to change the feed water into superheated steam. For heat loss, Eq. (1) is used [32]

$$\dot{m}_{33}LHV + \dot{m}_{32}h_{32} = \dot{m}_{34}h_{34} + \dot{m}_1(h_4 - h_1) + \dot{m}_6(h_6 - h_5) + \dot{Q}l_b \quad (1)$$

$$\eta_{1,boiler} = \frac{\dot{m}_1(h_4 - h_1) + \dot{m}_5(h_6 - h_5)}{\dot{m}_{33}LHV} \quad (2)$$

In Eq. (1), $\dot{m}_{33}$ represents the mass of coal. Further $\dot{m}_{32}$, $\dot{m}_{34}$, $\dot{m}_1$, $\dot{m}_6$ represents the mass flow rate of air, flue gas, water through economizer and HRH. Similarly h_{32}, h_{34}, h_1, h_6 represents corresponding enthalpy of air, flue gas, water inlet through economizer and hot reheat. Further, Eq. (2) presents the formulation of boiler efficiency, where *LHV* represents lower heating value of fuel.

Before assessing the performance of entire steam cycle, it is very important to find out the mass of steam extracted from HPT, IPT and LPT. To determine these flow rate through various extraction points, Eq. (3) is used, and this equation is valid for $\dot{m}_{19}$ only, i.e. HPH6. In this regard, Figure 2 presents the schematic diagram of HPH6. The mass flow rate from BFP is already know to us i.e. 102.2 kg/sec. Further pressure and temperature of all point is known to us. Hence, applying basic mass equation for HPH6, we have Eq. (3). Similarly, procedure is followed for other extraction. Table 3 presents the mass of steam extracted from different turbines. In Eq. (3), $\dot{m}_{19}$, $\dot{m}_{17}$, $\dot{m}_{27}$ and $\dot{m}_{18}$ denotes mass flow of extracted steam, feed water, drip and economizer. Further h_{19}, h_{17}, h_{27} and h_{18} denotes corresponding enthalpy.

$$\dot{m}_{19}h_{19} + \dot{m}_{17}h_{17} = \dot{m}_{27}h_{27} + \dot{m}_{18}h_{18} \quad (3)$$

Turbine

The power generated in this plant depends on the work produced by HPT, IPT and LPT. The term $\dot{W}_{HPT}$, $\dot{W}_{IPT}$ and

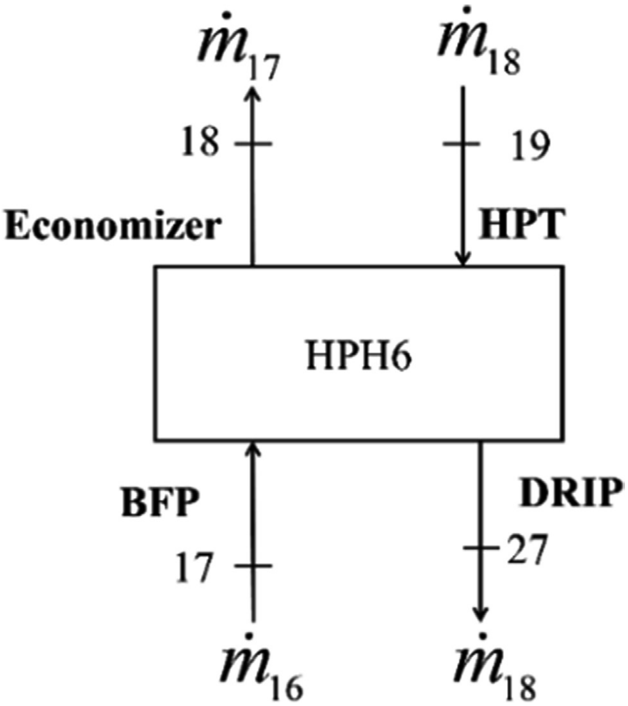


Figure 2. Schematic representation of HPH6.

$\dot{W}_{LPT}$ represent the power output from HPT, IPT and LPT respectively. The equations for deriving work from each turbine is presented from Eq. (3a) – (5c).

HPT

$$\dot{W}_{HPT} = \dot{m}_4(h_4 - h_{19}) + (\dot{m}_4 - \dot{m}_{19})(h_{19} - h_5) \quad (3a)$$

$$\dot{W}_{HPT,isen} = \dot{m}_4(h_4 - h_{19s}) + (\dot{m}_4 - \dot{m}_{19})(h_{19s} - h_{5s}) \quad (3b)$$

$$\dot{Q}l_{HPT} = \dot{W}_{isen,HPT} - \dot{W}_{HPT} \quad (3c)$$

In Eq. (3a), $\dot{m}_4$ represents the mas flow rate of steam to HPT turbine. Further the nomenclature of $\dot{m}_{19}$ is presented in Table 3. Similarly h_4 and h_{19} represents its corresponding enthalpy value.

IPT

$$\dot{W}_{IPT} = \dot{m}_6(h_6 - h_{20}) + (\dot{m}_6 - \dot{m}_{20})(h_{20} - h_{21}) + (\dot{m}_6 - \dot{m}_{20} - \dot{m}_{21})(h_{21} - h_7) \quad (4a)$$

$$\dot{W}_{IPT,isen} = \dot{m}_6(h_6 - h_{20s}) + (\dot{m}_6 - \dot{m}_{20})(h_{20s} - h_{21s}) + (\dot{m}_6 - \dot{m}_{20} - \dot{m}_{21})(h_{21s} - h_{7s}) \quad (4b)$$

$$\dot{Q}l_{IPT} = \dot{W}_{isen,IPT} - \dot{W}_{IPT} \quad (4c)$$

Table 3. Mass of extracted steam from different turbines

Mass of steam extracted	Values (kg/sec)
Mass of steam extracted from HPT ($\dot{m}_{19}$)	9.8
Mass of steam extracted from IPT ($\dot{m}_{20}$)	4.5
Mass of steam extracted from IPT/LPT ($\dot{m}_{21}$)	7.2
Mass of steam extracted from LPT ($\dot{m}_{22}$)	3.5
Mass of steam extracted from LPT ($\dot{m}_{23}$)	3.8
Mass of steam extracted from LPT ($\dot{m}_{24}$)	2.2

In Eq. (4a), $\dot{m}_6$ represents the flow rate of steam through HRH to IPT turbine and nomenclature of $\dot{m}_{20}$ is explained in Table 3. Similarly h_6 and h_{20} represents the corresponding enthalpy.

LPT

$$\dot{W}_{LPT} = \dot{m}_7(h_7 - h_{22}) + (\dot{m}_7 - \dot{m}_{22})(h_{22} - h_{23}) + (\dot{m}_7 - \dot{m}_{22} - \dot{m}_{23})(h_{23} - h_{24}) + (\dot{m}_7 - \dot{m}_{22} - \dot{m}_{23} - \dot{m}_{24})(h_{24} - h_8) \quad (5a)$$

$$\dot{W}_{LPT,isen} = \dot{m}_7(h_7 - h_{22s}) + (\dot{m}_7 - \dot{m}_{22})(h_{22s} - h_{23s}) + (\dot{m}_7 - \dot{m}_{22} - \dot{m}_{23})(h_{23s} - h_{24s}) + (\dot{m}_7 - \dot{m}_{22} - \dot{m}_{23} - \dot{m}_{24})(h_{24s} - h_{8s}) \quad (5b)$$

$$\dot{Q}l_{LPT} = \dot{W}_{isen,LPT} - \dot{W}_{LPT} \quad (5c)$$

In Eq. (5a), $\dot{m}_7$ and $\dot{m}_8$ represents the flow rate of steam through LPT turbine and condenser. Further the nomenclature of $\dot{m}_{22}$, $\dot{m}_{23}$ and $\dot{m}_{24}$ is explained in Table 3. Similarly h_7, h_{22}, h_{23}, h_{24} and h_8 represents the corresponding enthalpy.

Pump

The energy equation for condensate extraction pump (CEP) and boiler feed pump (BFP) is presented by Eq. (6a) and Eq. (7a).

CEP

$$\dot{W}_{CEP} = (P_{10} - P_9)\nu_9 \quad (6a)$$

In Eq. (6a), P_{10} represents pressure at the outlet of CEP, whereas P_9 represents the pressure at the inlet of CEP.

BFP

$$\dot{W}_{BFP} = (P_{16} - P_{15})\nu_{15} \quad (7a)$$

In Eq. (7a), P_{16} represents pressure at the outlet of BFP, whereas P_{15} represents the pressure at the inlet of BFP.

Condenser

The condenser is provided with cooling water to transform low-pressure steam to condensed liquid. Respective equation [32] to calculate heat loss from the condenser is given Eq. (8)

$$\dot{m}_8 h_8 + \dot{m}_{25} h_{25} + \dot{m}_{31} h_{31} + \dot{Q}l_{cond} = \dot{m}_9 h_9 + \dot{m}_{26} h_{26} \quad (8)$$

In the present equation, $\dot{m}_8$ and $\dot{m}_9$ denotes the mass of steam at the inlet and outlet of the condenser, whereas $\dot{m}_{25}$ and $\dot{m}_{26}$ denotes the mass of cold water. Further, $\dot{m}_{31}$ represents the mass flow rate of water fed to condenser through LPH1. Similarly, h_8 and h_9 denotes the enthalpy of steam at inlet of condenser and outlet of condenser h_{25} and h_{26} represents the corresponding enthalpy of the cooling water.

Drain cooler

Drain cooler is a heat exchanger, which is used to preheat the condensate from CEP, and related equation for drain cooler is presented by Eq. (8a).

$$\dot{m}_{10} h_{10} + \dot{Q}l_{DC} = \dot{m}_{11} h_{11} \quad (8a)$$

Feed water heaters

Energy analysis of a closed feed water heater is presented by Eq. (9a). The Eq. (9a) is applicable for HPH6, however the analysis and calculation part of all heaters i.e. HPH5, LPH3, LPH2 and LPH1 remains same. Further, deaerator is an example of an open feed water heater. The energy equations related to the deaerator is presented by Eq. (10a).

HPH6

$$\dot{m}_{17} h_{17} + \dot{m}_{19} h_{19} = \dot{m}_{27} h_{27} + \dot{m}_{18} h_{18} + \dot{Q}l_{HPH6} \quad (9a)$$

Deaerator

$$\dot{m}_{28} h_{28} + \dot{m}_{21} h_{21} + \dot{m}_{14} h_{14} = m_{15} h_{15} + \dot{Q}l_{dea} \quad (10a)$$

Exergy Analysis

Exergy [6] is a property of the system-environment combination, and it represents the work potential of a given amount of energy for a given environmental condition. For the present performance assessment, potential and kinetic exergy related to the exergy is neglected: only physical and chemical exergies are considered for calculations. The first and second laws of thermodynamics, when applied to a thermodynamic system at a steady state, result in the following equations:

$$\dot{E}x_{x,heat} + \sum_i \dot{m}_i e_{x,i} = \sum_e \dot{m}_e e_{x,e} + \dot{E}x_{x,w} + \dot{I}_{dest} \quad (11a)$$

$$\dot{E}x_{x,heat} = \sum_i \left(1 - \frac{T_0}{T}\right) \times \dot{Q}_i \quad (11b)$$

$$\dot{E}x_w = \dot{W} \quad (11c)$$

$$\dot{E}_x = \dot{E}_{x,physical} + \dot{E}_{x,chemical} \quad (11d)$$

$$e_x = e_{x,physical} + e_{x,chemical} \quad (11e)$$

In Eq. (11a), $\dot{E}x_{heat}$ is exergy flow due to heat generated, i and e represent inlet and exit conditions of the system respectively, whereas $\dot{E}x_w$ shows the exergy flow generated with work done by system. In the case of water and steam, the exergy is carried out by Eq. (12) where h_0 and s_0 are enthalpy and entropy values at dead state condition.

$$e_{x,physical} = (h - h_0) - T_0 (s - s_0) \quad (12)$$

Further, for calculating the chemical exergy of dry solid fossil fuels such as coal, Eq. (13a) to be used [33],

$$f = \frac{e_0}{LHV_{fuel}} \quad (13a)$$

Where $f = 1.0437 + 0.1882\left(\frac{h}{c}\right) + 0.0610\left(\frac{o}{c}\right) + 0.0404\left(\frac{n}{c}\right)$

and c, h, o and n are mass fraction of carbon, hydrogen, oxygen and nitrogen, respectively. The value of f is 1.06.

Chemical exergy of flue gases

In the system analysed, the chemical exergies of combustion products have important roles, and it is calculated by Eq. (13b) [34].

$$e_{x,chemical} = \sum_{i=1}^{n} x_i e_{x,chemical,i} + RT_0 \sum_{i=1}^{n} x_i \ln(x_i) \quad (13b)$$

Where x_i represents the mole fraction of each component of the gaseous fuel, and $e_{x,chemical,i}$ is the specific chemical exergy of each component. The value of specific exergy of each component is taken from [35]. Table 4 presents the chemical exergy of flue gas. The mass fraction is obtained from combustion equation with 17% of excess air.

Energy and Exergy Efficiency of Steam Power Plant

The energy efficiency of SPP is obtained by Eq. (14a), and it is based on the LHV of fuel and net power obtained [36].

$$h_I = \frac{\dot{W}_{net}}{\dot{m}_{33} LHV} \quad (14a)$$

Further, the exergy efficiency of SPP can be represented by Eq. (14b) respectively.

Table 4. Chemical exergy of flue gas at ambient pressure

Composition	Mass fraction (x_i)	Specific exergy $e_{x,chemical,i}$	$x_i e_{x,chemical,i}$	$RT_0\sum_{i=1}^{n} x_i \ln(x_i)$
CO_2	0.204	442.72	90.31	–28.45
H_2O	0.044	527.77	23.22	–12.05
N_2	0.65	25.71	16.71	–24.57
O_2	0.0100	124.06	1.24	–4.4
			131.48	–87.64
The chemical exergy of flue gas			43.85 kJ/kg	

Table 5. Expressions of exergies of the fuel ($\dot{E}x_F$) and exergies of products ($\dot{E}x_p$) for all components of SPP.

Components	($\dot{E}x_F$)	($\dot{E}x_p$)
Boiler	$m_1\dot{E}x_1 + m_{32}\dot{E}x_{32} + m_{33}\dot{E}x_{33} + m_5\dot{E}x_5$	$\dot{m}_6\dot{E}x_6 + m_{34}\dot{E}x_{34} + m_4\dot{E}x_4$
HPT	$\dot{m}_4(\dot{E}x_4 - \dot{E}x_{19}) + (\dot{m}_4 - \dot{m}_{19})(\dot{E}x_{19} - \dot{E}x_5)$	$\dot{W}_{HPT}$
IPT	$\dot{m}_6(\dot{E}x_6 - \dot{E}x_{20}) +$ $(\dot{m}_6 - \dot{m}_{20})(\dot{E}x_{20} - \dot{E}x_{21})$	$\dot{W}_{IPT}$
LPT	$(\dot{m}_7)(\dot{E}x_7 - \dot{E}x_{22}) +$ $(\dot{m}_7 - \dot{m}_{22})(\dot{E}x_{22} - \dot{E}x_{23}) +$ $(\dot{m}_7 - \dot{m}_{22} - \dot{m}_{23})(\dot{E}x_{23} - \dot{E}x_{24}) +$ $(\dot{m}_7 - \dot{m}_{22} - \dot{m}_{23} - \dot{m}_{24})(\dot{E}x_{24} - \dot{E}x_8)$	$\dot{W}_{LPT}$
Cond.	$\dot{m}_8(\dot{E}x_8 - \dot{E}x_9) + \dot{m}_{31}Ex_{31}$	$\dot{m}_{cw}(\dot{E}x_{26} - \dot{E}x_{25})$
CEP	$\dot{W}_{CEP}$	$m_9(\dot{E}x_{10} - \dot{E}x_9)$
BFP	$\dot{W}_{BFP}$	$m_{14}(\dot{E}x_{16} - \dot{E}x_{15})$
LPH1	$\dot{m}_{24}\dot{E}x_{24} + \dot{m}_{30}\dot{E}x_{30} - \dot{m}_{31}\dot{E}x_{31}$	$(\dot{m}_{11})(\dot{E}x_{12} - \dot{E}x_{11})$
LPH2	$\dot{m}_{23}\dot{E}x_{23} + \dot{m}_{29}\dot{E}x_{29} - \dot{m}_{30}\dot{E}x_{30}$	$(\dot{m}_{13})(\dot{E}x_{13} - \dot{E}x_{12})$
LPH3	$\dot{m}_{22}\dot{E}x_{22} - \dot{m}_{29}\dot{E}x_{29}$	$\dot{m}_{14}(\dot{E}x_{14} - \dot{E}x_{13})$
Deaerator	$\dot{m}_{14}\dot{E}x_{14} + \dot{m}_{21}\dot{E}x_{21} + \dot{m}_{28}\dot{E}x_{28}$	$\dot{m}_{15}\dot{E}x_{15}$
HPH5	$\dot{E}x_{20} + \dot{E}x_{27} - \dot{E}x_{28}$	$\dot{E}x_{17} - \dot{E}x_{16}$
HPH6	$\dot{E}x_{19} - \dot{E}x_{27}$	$\dot{E}x_{18} - \dot{E}x_{17}$

Table 6. Heat balance sheet of SPP

Input Parameter	MW	%	Output Parameters	MW	%
Fuel	351 MW		Turbine	121.80 MW	34.8%
			Heat accounted	213.12 MW	60.8%
			Pump	1.70 MW	0.5%
			Stack	12.90 MW	3.7%
	351 MW	100%		350 MW	100%

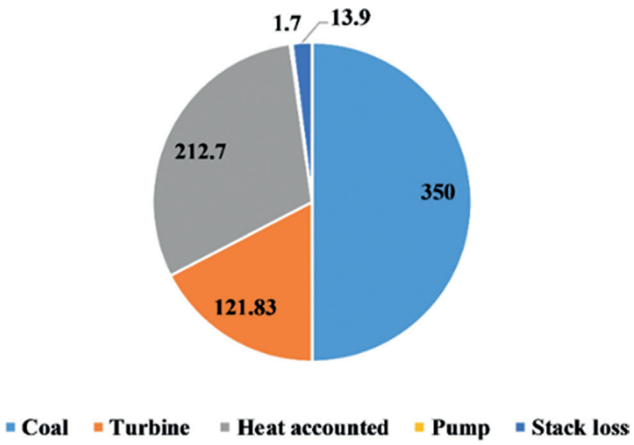


Figure 3. Representation of energy production and consumption in SPP through pie chart.

$$h_{II} = \frac{\dot{W}_{Net}}{\dot{E}x_{33} + \dot{E}x_{air}} \tag{14b}$$

Where $\dot{E}x_{33}$ represents exergy of coal and $\dot{E}x_{air}$ represents exergy of air. The chemical exergy of coal is obtained by Eq. (14c)

$$\dot{E}x_{33} = \dot{m}_{33} \times \phi \times LHV \tag{14c}$$

The value of ϕ is 1.06, as presented in Eq. (14c). To define exergy destruction and exergetic efficiency, the concept of exergy of fuel ($\dot{E}x_F$) and exergy of product ($\dot{E}x_P$) of various components has been introduced [11], and it is represented in Table 5. From Table 5, one could also calculate the required improvement potential (*IP*) of the energy system [37], which is given by Eq. (14f).

$$\dot{I}P = (1-\eta_{II})(\dot{E}x_F - \dot{E}x_P) \tag{14f}$$

RESULTS

The performance assessment of SPP is being analyzed using various equations applied for each componenets. Using the approach mentioned in Eq. (14a), the overall efficiency comes around 34.7%, with fuel input as 351 MW, and power output of 36.78 MW by HPT, 42.58 MW by IPT, 42.52 MW by LPT. The cycle efficiency of SPP is 41%. Table 6 presents the heat balance sheet of SPP. It can be seen that, out of the total amount of energy provided, 34.7% is used for work output, 60.8% is heat loss accounted. Table 6 is well represented by pie-chart, as shown in Figure 3.

The term "heat accounted" are those heat losses, which has been assessed by applying first law of thermodynamics. In this regard, Table 7 presents the list the heat losses from various equipment's of SPP.

Similarly using the approach mentioned in Eq. (14b), the exergy efficiency of coal-based steam power plant comes out to be 32%, with total exergy input as 372 MW and power output as 121.80 MW. It could be well understood that trend between energy efficiency (34.7%) and exergy efficiency (32%) is somewhat similar in nature, and it could be probably because of only one output i.e. electricity. Further, applying the concept mentioned in Table 5, exergy destruction and exergy efficiency of each and every componenet is presented in Table 8.

Table 8 presents the comparison of exergy destruction and exergy efficiency of various components of SPP. It could be seen that exergy analysis introduces boiler as a major source of exergy destruction, and it is because of the temperature difference between generated steam and combustible gas [18]. There are some methods like reduction in temperature difference between steam generation and flue gas, adopting preheating arrangement through flue gas which could be incorporated to reduce exergy losses in the boiler [38]. From Table 8, it could be observed that exergy loss in terms of turbine comes after the boiler, the value is HPT (3.6 MW), IPT (2.8 MW) and LPT (10.87 MW). The main factor contributing for exergy losses are throttling, heat loss, steam leakage and internal irreversibilities. Of course controlling all these parameters will reduce the exergy destruction, thereby increasing the performance of steam power plant. Figure 4 presents the comparison of energy loss and exergy destruction of main components of SPP. It could be well understood from the figure that boiler has largest share of exergy destruction, while condenser has major share in heat loss. There are some ways that could

Table 7. Energy losses from various equipment is of SPP.

Equipment	Heat loss (MW)	Efficiency (%)
Condenser	97.9	–
Boiler	76	82.63
HPT	7.2	83.61
IPT	5.2	88
LPT	11.2	79
Deaerator	6.2	–
Heaters	0.27	–
Drain cooler	7.7	–
BFP	0.58	61
CEP	0.018	86
Total cycle heat loss	212.268	34.7%

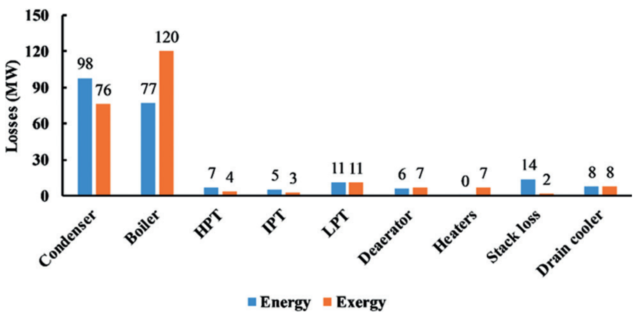


Figure 4. Comparison of energy and exergy loss in steam power plant.

be used to increase the performance of energy systems are increasing the temperature of main steam or by reducing the condenser pressure, however economic and metallurgical parameters should be considered [39].

Figure 5 presents the effect of main steam line temperature on the performance of SPP. The steam at higher temperature has higher enthalpy, and it requires more volume to expand. Hence, when it is allowed to expand in HPT, the higher expansion results in increased performance of the HPT, which ultimately results in the increased unit load of power plant. With an increase in 10 °C of main steam temperature, approximately 3 MW of power increases. Similar trend is shown by Figure 6, where by increasing the temperature of reheat steam the work output by IPT increases, keeping other parameters constant. This increase in work output of IPT leads to increase in the work output of entire power plant.

Figure 7 presents the impact of condenser pressure on the performance of steam turbine. We know this fact, if steam is allowed to expand more, it produces power. However, when there is increment in the condenser pressure, it ultimately leads to increases in the enthalpy of steam.

Table 8. Comparison of energy loss and exergy destruction of the different sub-systems in SPP.

Component	Exergy destruction (MW)	Exergetic Efficiency (%)
Boiler	121.8	38%
Condensers	45	70%
HPT	3.6	90%
IPT	2.8	93%
LPT	10.87	80%
Deaerator	6.98	84%
Drain cooler	7.6	
LP and HP heaters	7.8	–
BFP	0.089	90%
Cycle	205	32%

Table 9. Improvement potential of various sub-systems in SPP.

Components	$\dot{E}x_F$ (MW)	$\dot{E}x_P$ (MW)	h_{II}	$\dot{I}P$
Boiler	739	619.45	0.38	74.121
HPT	40.43	36.78	0.9	0.365
IPT	45.38	42.58	0.93	0.196
LPT	53.35	42.5	0.8	2.17

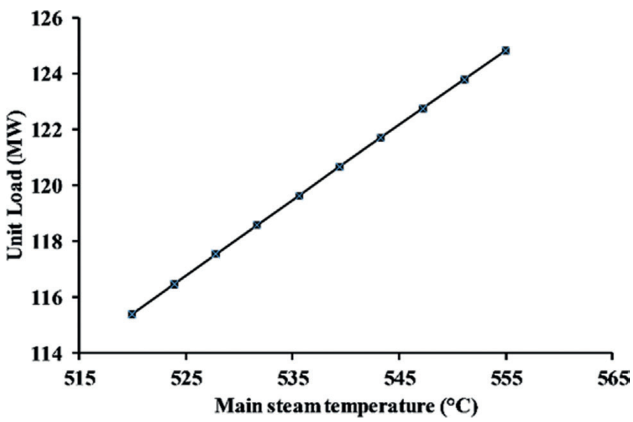


Figure 5. Effect of main steam temperature on the performance of SPP.

Due to increased enthalpy of steam there is reduction in the expansion of steam in LPT, which ultimately reduces the net power output. With increase in condenser pressure by 0.01 bar, approximately 0.12 MW of power is reduced. This reduction in power reduces the exergy efficiency, and it is well depicted by Figure 8.

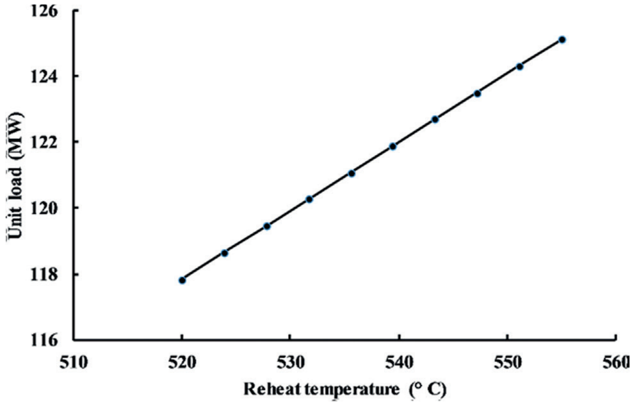


Figure 6. Effect of reheat steam temperature on the performance of SPP.

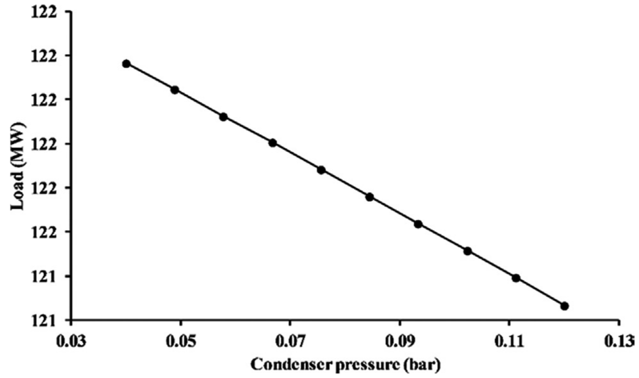


Figure 7. Effect of condenser pressure (bar) on the unit load of SPP.

Apart from this, Table 9 presents the improvement potential of various sub-systems of coal based SPP using Eq. (14f). From Table 9, we could infer that boiler requires highest improvement potential. Application of variable speed drive could be one of the effective way of reducing losses in boiler [40].

CONCLUSION AND RECOMMENDATIONS

In the present paper, performance assessment of SPP configured with reheating and regenerative configuration is carried out, and it might be able to help in understanding the most inefficient component, requiring highest improvement potential. For carrying out this assessment, real time data were collected from the control unit of power plant under full load condition. The main equipment on which stress has been given includes the boiler, turbine, condenser, deaerator and pump. Some of the important conclusion that can be drawn are as follows: -

- Energy efficiency of SPP comes out to be 34.7 %, and introduces condenser as a major source of heat loss.
- Exergy efficiency of SPP comes out to be 32%, and introduces boiler as a major source of exergy destruction, followed by steam turbine. Therefore, combustion process should be optimized by creating suitable fuel and air mixing operations, preheating air with waste heat, utilizing solar power as air preheater during daylight hours etc.
- In turbine, particularly Low pressure turbine (10.87 MW) has highest exergy destruction among HPT (3.6 MW) and IPT (2.8 MW).
- The performance of SPP can be increased by increasing main steam temperature and reheating temperature.

Apart from all these, some more practical steps could be introduced on improving power plant efficiency, seeing the economic and social aspect. As we could observe from

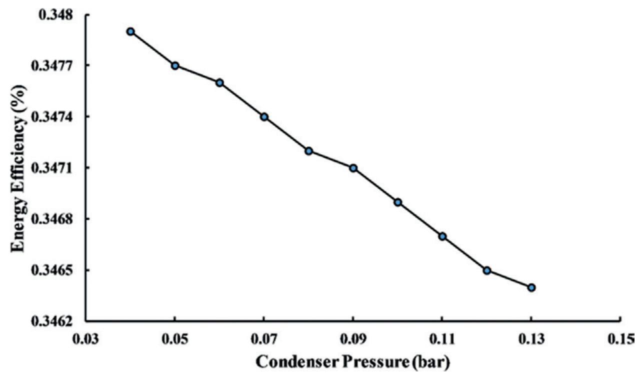


Figure 8. Effect of condenser pressure (bar) on the exergy efficiency of SPP.

Figure 7 and Figure 8, that the condenser pressure has a significant role in the performance assessment of SPP. Hence, removing the obstructions around the cooling towers, installing walls directing the airflow are few strategies that could be incorporated to increase efficiency [41]. Other suggestions included are as follows: -

- Repowering of SPP, which means changing the configuration of present plant by incorporating gas turbine units [42].
- Several other methods like hot wind box repowering, feed water heating etc. could also be implemented, keeping eyes of various parameters like original investment, payback time, social acceptance part.

NOMENCLATURE

c_p	Specific heat at constant pressure [kJ/kgK]
$e_{x,chemical,}$	Specific exergy of fuel [kJ/kg]
$\dot{E}x$	Exergy rate [kW]
e_x	Specific exergy [kJ/kg]

$\dot{I}_{dest}$	Exergy destruction rate [kW]
$\dot{m}$	Mass flow rate [kg/sec]
P	Pressure [kPa]
$\dot{Q}l$	Heat loss [kW]
s	Specific entropy [kJ/kgK]
T	Temperature [°C, K]
$\dot{W}$	Power [kW]
h	Specific enthalpy [kJ/kg]
x_i	mole fraction of each component

Greek letters

h_I	Thermal efficiency of steam power plant
h_{II}	Second law efficiency

Subscripts

a	air
o	dead state
c	Mass of coal

Abbreviations

BFP	boiler feed pump
CPP	captive power plant
CRH	cold reheat
CEP	condensate extraction pump
Cond.	Condenser
SPP	steam power plant
DC	Drain cooler
F/W	feed water
GSC	gland steam cooler
HPH	high pressure heater
HRH	high reheat
LPH	low pressure heater
LHV	lower heating value
HPT	high pressure turbine
IPT	intermediate pressure turbine
LPT	low pressure turbine
LDO	light diesel oil
TPH	Ton per hour

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AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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APPENDIX A:

Thermodynamic properties of points in cycle (refer to Fig. 1).

Node	*P* (bar)	*T* (°C)	$\dot{m}$ (kg/s)	*h*(kJ/kg)	*s*(kJ/kgK)	$\dot{E}x$ (MW)
1	147.0	233.0	102.2	1006.0	2.6	72.77
2	144.5	294.0	102.2	1305.0	3.1	37.8
3	144.9	349.9	102.2	2723.0	5.4	111.5
4	132.7	536.8	102.2	3432.0	6.5	319.48
5	38.2	339.2	93.6	3089.0	6.5	258.58
6	35.3	539.5	93.6	3539.0	7.3	300
7	5.13	307.01	79.5	3078	7.4	2.24
8	0.12	50.8	79.5	2306	7.2	110.4
9	0.12	50.8	79.5	209	7.1	16.61
10	19.0	50.0	79.5	210.9	0.7	0.3
11	12.6	75.6	79.5	317.6	1.0	1.5
12	17.5	70	80.7	294.4	0.95	115.8
13	17.51	95.42	80.7	401	1.5	116.8
14	17.52	121.73	80.7	512.2	1.2	118.7
15	6.3	151	102.2	636.7	1.8	1.504
16	156.8	151	102.2	646.1	1.8	1.518
17	147	182	102.2	779	2.1	159.2
18	147	236.5	102.2	1024	2.6	168.5
19	29.83	339	9.8	3089	6.7	24.48
20	11.72	407.7	4.5	3278	7.4	11.06
21	5.53	298	9.3	2898.5	7.7	2.2
22	1.93	227.93	3.5	2926	7.6	7.1
23	0.54	140	3.1	2760	7.8	5.5
24	0.47	80.13	0.4	2643	0.4	1.7
25	1.92	34.1	1250	143	0.6	1777.5
26	1.47	44.6	1250	186.9	2.2	1723.75
27	29.83	189	9.8	804	1.2	15.25
28	11.72	163.85	14	692.7	1.9	21.73
29	1.93	101.72	3.5	426.4	1.3	7.32
30	0.54	77	6.6	320.4	1.04	5
31	0.40	54.75	6.3	229.2	0.76	9
32	1.1	322.54	122.1	602.8	6.3	36.33
33			24.9			371
34	1.0	127.9	147	394.3	5.9	13.16