Energy and Exergy Analysis of 210 MW Jamshoro Thermal Power Plant

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ABSTRACT

In this paper, thermodynamic analysis of 210 MW dual-fire, subcritical, reheat steam power plant, situated near Jamshoro, Pakistan has been performed. Firstly, the plant is modeled by EES (Engineering Equation Solver) software. Moreover; a parametric study is performed to assess the impacts of various operating parameters on the performance. The net power output, energy efficiency and exergy efficiency are considered as performance parameters of the plant whereas, condenser pressure, main steam pressure and main steam temperature are nominated as operating parameters. According to the results, the net power output, energy efficiency and exergy efficiency are determined as 186.5 MW, 31.37% and 30.41% respectively, under design operating conditions. The condenser contributed a major share in the total energy loss i.e. 280 MW (68.7%) followed by boiler with 89 MW (21.8%). The major exergy destructing area is found in the boiler with 350 MW (82.11%) of the total exergy destruction followed by turbine with 43.1 MW (10.12%) and condenser 12 MW (5.74 %). According to the parametric study, variation in operating parameters had great influence on the plant performance.

Key Words: Energy, Exergy, Efficiency, Steam Power Plant, Parametric Study.

1. INTRODUCTION

The world's electricity needs are mainly satisfied by fossil fuels. Though, the development of renewable energy sources like solar and wind power has been growing remarkably, the reliance on fossil fuel is expected to continue for many years [1]. The electricity generation industry of Pakistan is also depending on the fossil fuels, as more than 67% of electricity is generated from oil and gas in both public and private sectors wherein, oil and gas contributed 55.96 and 43.94%, respectively, in thermal power generation during 2012-2013 [2]. The thermal power plants in Pakistan have operated at very low efficiencies due to aging and excessive energy losses [3].

The energy systems are generally investigated on the basis of the first law of thermodynamics, however; during the recent decades, the importance of exergy analysis, which is based on the second law of thermodynamics, has gained greater attention [4-19]. Its widespread acceptance is due to the effectiveness in assessment, optimization, design and improvement of the energy systems. The importance of the issue emerged as the awareness rose for world's limited resources. Therefore, many researchers have contributed towards exergetic analysis of energy systems in general and thermal power plant in particular [4]. Yang, et. al. [5] investigated 660

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MW ultra-supercritical SPP (Steam Power Plant) in China who have shown that, heavier exergy destruction is caused by exhaust flue gases with 73.51% of the total boiler subsystem. The exergy analysis of different thermal power plants concluded that, boiler is a key exergy destructing area where, the major proportion of the total exergy destruction has been recorded [6-12]. Many researchers have linked exergy to the cost analysis of the thermal power plants [13]. Gogoi and Talukdar [14] conducted the parametric analysis to investigate the impacts of boiler pressure and fuel flow rate on the performance of a thermal power plant. According to the results, the fuel flow rate and boiler pressure have the significant effects on the performance of the power cycle. Memon, et. al. [15] executed the thermodynamic based research study on open cycle gas turbine power plant. The parametric analysis is conducted to observe the impacts of variation in selected operating parameters like, compressor inlet temperature, turbine inlet temperature and pressure ratio on the overall cycle performance and CO_2 emission. In addition, multiple polynomial regression modeling and optimization is also performed to correlate the operating and performance parameters. Manesh, et. al. [16] have performed the exergoeconomic and exergoenvironmental evolution of 315 MW SPP with a total site utility system. Rashid and Maihy [17] performed the energy and exergy analysis of Shobra El-Khima power plant in Cairo, Egypt. It is found that; turbine is the component where major exergy destruction has been occurring (around 28% at different loads). The maximum energy loss has been recorded in condenser (55% at different loads). Sengupata, et. al. [18] conducted the exergy analysis to a coal based 210MW SPP with design parameters and focused on its exergetic performances under different loads.

In this work, a comprehensive thermodynamic analysis is performed on a 210 MW SPP. A detailed parametric study is performed to observe the impacts of condenser pressure, main steam pressure and main steam temperature on the performance parameters, namely, net power output, energy efficiency and exergy efficiency of the plant. A Model of the plant has been developed in the EES software. The basic function provided by EES is the numerical solution for different type of equations.

Additionally, EES provides a platform for parametric studies, data plotting, and optimization, regression and uncertainty analyses. The data base of this software includes number of functions for mathematical, thermo-physical, heat transfer and fluid flow properties.

2. PLANT DESCRIPTION

The schematic of SPP under study is shown in Fig. 1. The plant is situated at Jamshoro, 170 km northeast of Karachi. The total capacity of the plant is 880 MW, consisting of four power units. The installed capacity of unit # 1 is 250 MW with, an oil fired, pressurized furnace, boiler whereas, unit # 2, 3 and 4 are dual fired (oil and gas). In this study, however, Unit#2 has been considered. At 200 MW plant load, with ECR (Economic Continuous Rating) condition, 583250 Nm^3/hr and 48400 kg/h flow of air and furnace oil respectively enters the furnace for combustion. For cooling tower makeup and demineralization water, 600 ton/hour water is pumped from Indus River. Two regenerative air heaters are provided for waste heat recovery of flue gas. Feed water regeneration process is carried out in high pressure heateres (HPH1, HPH2, HPH3, DC and SC), low pressure heaters (LPH1, LPH2, LPH3 and LPH4) and contact heat exchanger (deaerator) stages. Steam enters into the HPT as superheated vapor and exhausted to re-heater to increase the steam temperature back to 538^0C which enters the IPT and leaves LPT as saturated vapor to be condensed in the condenser at constant pressure.

3. MODELING AND ASSUMPTIONS

In this section, thermodynamic model equations to assess the performance of various plant components and overall plant are defined. These model equations are basically from the fundamental laws namely mass conservation, energy conservation and exergy balance of energy systems. These equations are used to modelthe plant and then simulated under normal operating conditions of the plant to determine different performance parameters as a base case, and then parametric study is performed. For the base case, values of different operating parameters are referred from the model equations are applied to different plant components subject to the assumptions defined in Table 1.

3.1 Steam Turbine

The total power output from the steam turbines are given as:

$$\dot{W}_T = \dot{W}_{HPT} + \dot{W}_{IPT} + \dot{W}_{LPH} \quad (1)$$

From the energy balance as applied to HPT yields the power output as given below:

$$\dot{W}_{HPT} = \dot{m}_{20}\left(h_{20} - h_{21}\right) + \left(\dot{m}_{20} - \dot{m}_{21}\right) - \left(h_{21} - h_{23}\right) \quad (2)$$

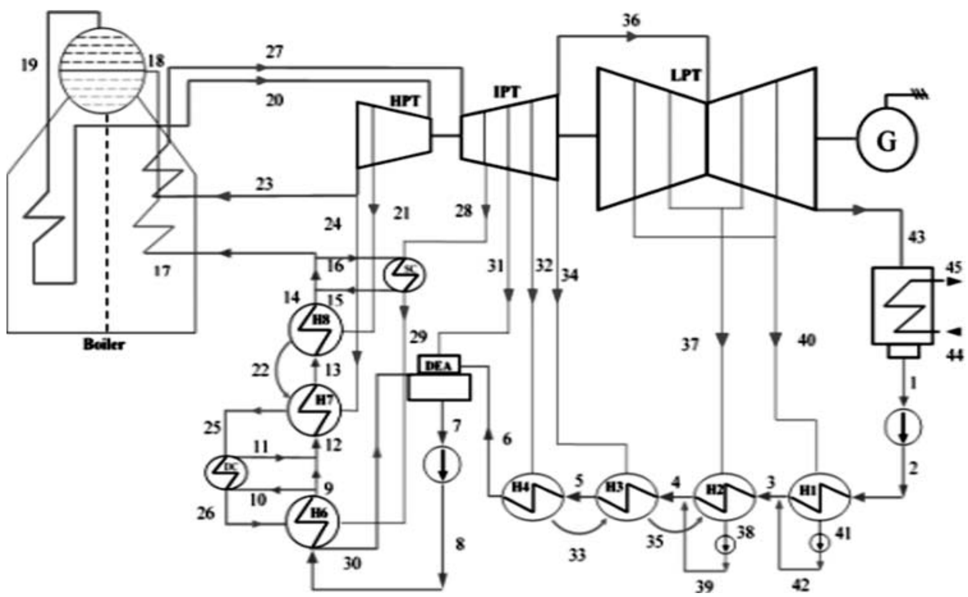

FIG. 1. SCHEMATIC OF POWER PLANT UNIT UNDER STUDY

TABLE 1. ASSUMPTIONS FOR THE THERMODYNAMIC EVALUATION OF STEAM POWER PLANT

1.	Steady-state operation of system components	
2.	Change in kinetic energy (and exergy) and potential energy (and exergy) of fluid streams neglected	
3.	Dead-state condition	101.325 kPa and 298 K
4.	Energy efficiency of the boiler	85%
5.	Combine efficiency of feed water heaters	90%
6.	Isentropic efficiency of steam turbine	90%
7.	Isentropic efficiency of pumps	85%
8.	Lower heating value of furnace oil	40,500 (kJ/kg)

Similarly, power output from IPT and LPT are given respectively as:

$$\dot{W}_{IPT} = \dot{m}_{27}(h_{27} - h_{28}) + (\dot{m}_{27} - \dot{m}_{28} - \dot{m}_{31})(h_{31} - h_{32}) + (\dot{m}_{27} - \dot{m}_{28} - \dot{m}_{31} - \dot{m}_{32})(h_{32} - h_{34}) \quad (3)$$

$$\dot{W}_{LPT} = \dot{m}_{36}(h_{36} - h_{37}) - (\dot{m}_{36} - \dot{m}_{37})(h_{37} - h_{40}) + (\dot{m}_{36} - \dot{m}_{37} - \dot{m}_{40})(h_{40} - h_{43}) \quad (4)$$

The total exergy destruction or irreversibilities occurred in the turbines is determined from the exergy balance as defined below:

$$\dot{I}_T = \dot{X}_{T,in} - \dot{X}_{T,out} - \dot{W}_T \quad (5)$$

where

$$\dot{X}_{T,in} = \dot{X}_{20} + \dot{X}_{27} \quad (6)$$

$$\dot{X}_{T,out} = \dot{X}_{21} + \dot{X}_{23} + \dot{X}_{28} + \dot{X}_{31} + \dot{X}_{32} + \dot{X}_{34} + \dot{X}_{37} + \dot{X}_{40} + \dot{X}_{43} \quad (7)$$

3.2 Boiler

An energy balance of boiler yields the following relation:

$$\dot{Q}_B = \dot{m}_{17}(h_{20} - h_{17}) + \dot{m}_{27}(h_{27} - h_{23}) \quad (8)$$

Also, fuel energy required in producing the steam in boiler is given as:

$$En_{in,F} = \dot{m}_F * LHV \quad (9)$$

Exergy destruction in the boiler is given as:

$$\dot{I}_b = \dot{X}_F - \left[(\dot{X}_{20} - \dot{X}_{17}) + (\dot{X}_{27} - \dot{X}_{23})\right] \quad (10)$$

The exergy inflow associated with the fuel flow is given by:

$$\dot{X}_F = \dot{m}_F x_F \quad (11)$$

In Equation (11), the specific exergy of fuel (methane) is approximated from following expression [15]:

$$X_F = \left(1.003 + 0.0169\frac{k}{j} - \frac{0.0069}{j} * LHV_F\right) \quad (12)$$

3.3 Pumps

The power required and exergy destruction associated to boiler feed water and condensate pumps are determined as follows:

$$\dot{W}_{cons,p} = \dot{W}_{cons,cp} + \dot{W}_{cons,bfp} \quad (13)$$

$$\dot{I}_p = \dot{I}_{cp} + \dot{I}_{bfp} \quad (14)$$

3.3.1 Condensate Pump

Energy and exergy balances of the condensate pump gives the power required and exergy destruction respectively as:

$$\dot{W}_{cp} = \dot{m}_1(h_2 - h_1) \quad (15)$$

$$\dot{I}_{cp} = \dot{X}_2 - \dot{X}_1 - \dot{W}_{cp} \quad (16)$$

3.3.2 Boiler Feedwater pump

Similarly, for the boiler feedwater pump we have:

$$\dot{W}_{bfp} = \dot{m}_6(h_8 - h_7) \quad (17)$$

$$\dot{I}_{bfp} = \dot{X}_8 - \dot{X}_7 - \dot{W}_{bfp} \quad (18)$$

3.4 Feed Water Heaters

The energy and exergy balance as applied to feed water heaters as a combined system gives the following:

$$\eta_{HPH} = \frac{\dot{m}_{17}h_{17} - \dot{m}_8 h_8}{\dot{m}_{21}h_{21} - \dot{m}_{24}h_{24} + \dot{m}_{37}h_{37} + \dot{m}_{40}h_{40}} \quad (19)$$

$$\eta_{LPH} = \frac{\dot{m}_6 h_6 - \dot{m}_2 h_2}{\dot{m}_{32}h_{32} - \dot{m}_{34}h_{34} + \dot{m}_{37}h_{37} + \dot{m}_{40}h_{40}} \quad (20)$$

Similarly for the deaerator, energy balance yields:

$$\eta_{Deaerator} = \frac{\dot{m}_7 h_7}{\dot{m}_{31} h_{31} + \dot{m}_{30} h_{30} + \dot{m}_6 h_6} \quad (21)$$

For obtaining the irreversibilities in these components, exergy balances lead to:

$$I_{HPHs} = \dot{X}_{21} + \dot{X}_{24} + \dot{X}_{28} + \dot{X}_8 + \dot{X}_{17} - \dot{X}_{30} \quad (22)$$

$$\dot{I}_{LPHs} = \dot{X}_2 + \dot{X}_{32} + \dot{X}_{34} + \dot{X}_{32} + \dot{X}_{40} - \dot{X}_6 \quad (23)$$

and

$$\dot{I}_{Deaerator} = \dot{X}_6 - \dot{X}_{31} + \dot{X}_{33} - \dot{X}_7 \quad (24)$$

3.5 Condenser

Energy and exergy balance of condenser are given as:

$$\dot{m}_{43}\left(h_{43} - h_1\right).\eta_c = \dot{m}_{44}\left(h_{45} - h_{44}\right) \quad (25)$$

$$\dot{I}_C = \left(\dot{X}_1 - \dot{X}_{43}\right) - \left(\dot{X}_{45} - \dot{X}_{44}\right) \quad (26)$$

3.6 Overall Plant

The net power output of the plant is given as:

$$\dot{W}_{T,net} = \dot{W}_T - \dot{W}_{cons,p} \quad (27)$$

The energy efficiency and exergy efficiency of the plant are given respectively as:

$$\eta_{thermal} = \frac{\dot{W}_T}{E_{nin,F}} \quad (28)$$

Exergy efficiency

$$\varepsilon = \frac{\dot{W}_T}{\dot{W}_F} \quad (29)$$

4. RESULTS AND DISCUSSION

In this section, results are presented and discussed relating to the performance of the plant and then a parametric study is presented to discuss the effects of operating parameters on the performance. In the parametric study net power output, energy efficiency and exergy efficiency are taken as performance parameters, while the condenser pressure, main steam pressure and main steam temperature are nominated as operating parameters.

4.1 Energy and Exergy Performance Analysis

The model of the plant is simulated to obtain various thermodynamic quantities at all salient state points in Fig. 1 and is tabulated in Table 2. Additionally; some constant parameters are adopted from the "thermodynamic performance" [20] heat balance sheet at ECR condition provided by the power plant authorities. The document was supplied by the manufacturer at the time of commissioning of the plant in 1989 at 200 MW maximum load.

The simulated results are first validated by comparing the data from the authorities and simulated by the model developed in this study under similar operating conditions, as depicted in Figs. 2-3. An excellent degree of conformity can be observed, which proves the effective working of the model.

The net power output, energy efficiency, and exergy efficiency values of the plant are obtained as 186.5 MW, 31.37% and 30.41% respectively.

Fig. 4 elucidates the magnitude of energy loss and exergy destruction in different plant components. According to the figure, the condenser is liable for 68.7% of the total energy loss followed by boiler with 21.83%, whereas, the latter is a major contributor in exergy destruction, i.e. 82.11%, followed by steam turbine with 10.12%. The exergetic analysis leads to a significant outcome that, high temperature components involved in heat transfer with larger temperature difference lead to a remarkable decrease in the performance. Moreover; the feed water heaters (LP and HP) and pumps contribute a little towards energy loss and exergy destruction.

TABLE 2. STATE POINT VALUES AT DIFFERENT LOCATIONS IN FIG.1

State Point	Dryness Fraction	m (kg/s)	P (kPa)	T (K^0)	h (kj/kg)	h (kj/kg. K)	ψ (kj/kg)
0	Compressed water	-	101.325	298.15	104.84	0.367	0.00
01	Saturated water	121.50	11.23	321.26	201.40	0.679	3.47
02	Compressed water	121.50	1800.00	321.39	203.53	0.680	5.30
03	Compressed water	126.84	1620.00	343.83	297.17	0.962	14.81
04	Compressed water	142.34	1458.00	370.76	410.02	1.279	33.31
05	Compressed water	142.34	1312.20	384.76	469.01	1.435	45.62
06	Compressed water	142.34	1180.98	404.00	550.63	1.643	65.42
07	Compressed water	172.22	600.00	429.54	660.00	1.907	96.08
08	Compressed water	172.22	14493.60	431.75	677.88	1.913	112.10
09	Compressed water	172.22	14421.13	449.31	753.54	2.085	136.50
10	Compressed water	34.44	14421.13	449.31	753.54	2.085	136.50
11	Compressed water	34.44	14349.03	462.19	809.62	2.208	155.84
12	Compressed water	172.22	14421.13	451.89	764.76	2.110	140.29
13	Compressed water	172.22	14349.03	478.47	881.41	2.361	182.11
14	Compressed water	172.22	14277.28	496.56	962.59	2.527	213.60
15	Compressed water	34.44	14277.28	496.56	962.59	2.527	213.60
16	Compressed water	34.44	14205.89	508.48	1017.08	2.636	235.70
17	Compressed water	172.22	14205.89	498.97	973.49	2.549	217.91
18	Saturated water	172.22	14063.84	610.21	1572.94	3.626	496.41
19	Saturated steam	172.22	13923.20	609.42	2639.08	5.376	1040.84
20	Superheated steam	172.22	13200.00	811.10	3435.99	6.558	1485.25
21	Superheated steam	7.92	3828.00	633.59	3121.58	6.647	1144.26
22	Saturated water	7.92	3445.20	514.84	1045.30	2.717	239.84
23	Superheated steam	164.30	2388.67	575.87	3017.84	6.679	1030.98
24	Superheated steam	11.37	2388.67	575.87	3017.84	6.679	1030.98
25	Saturated water	19.29	2269.24	492.04	938.41	2.507	195.42
26	Saturated water	19.29	2155.78	465.98	820.58	2.262	150.85
27	Superheated steam	152.93	2269.24	811.10	3549.07	7.477	1324.31
28	Superheated steam	5.94	1139.16	713.59	3348.31	7.527	1108.57
29	Superheated steam	5.94	1082.20	540.25	2976.70	6.954	907.99
30	Saturated liquid	25.23	1028.09	454.27	768.21	2.151	131.59
31	Superheated steam	4.65	652.74	641.81	3203.43	7.568	951.71
32	Superheated steam	5.17	395.56	582.40	3085.46	7.604	822.98
33	Saturated water	5.17	356.00	412.64	587.05	1.734	74.60
34	Superheated steam	3.79	237.34	526.68	2976.37	7.641	702.90
35	Saturated water	8.96	213.60	395.48	513.71	1.553	55.27
36	Superheated steam	133.38	237.34	526.68	2976.37	7.641	702.90
37	Superheated steam	6.54	142.40	475.63	2877.72	7.677	593.23
38	Saturated water	6.54	128.16	379.87	447.46	1.382	39.90
39	Compressed water	6.54	1000.00	379.87	448.10	1.382	40.76
40	Superheated steam	5.34	39.87	368.61	2674.51	7.777	360.28
41	Saturated water	5.34	35.89	346.44	306.79	0.995	14.72
42	Compressed water	5.34	1000.00	346.44	307.57	0.994	15.68
43	Saturated steam	121.50	11.23	321.26	2510.64	7.867	169.56
44	Compressed water	6702.69	350.00	305.15	134.35	0.464	0.59
45	Compressed water	6702.69	250.00	315.15	176.08	0.599	2.10

4.2 Parametric Analysis

4.2.1 Effect of Condenser Pressure on Performance

Fig. 5 demonstrates the impact of condenser pressure on the performance parameters of the plant for a given main steam pressure and temperature, which shows that the net power output and efficiencies decrease with an increase in the condenser pressure. This diminution is rather significant at lower values of condenser pressure. The reason is that the power output from LPT reduces as condenser pressure increases due to lower expansion of the steam in LPT. Additionally, the dryness ratio of the LPT exhaust steam also influences on the turbine power output due thrust developed by the water droplets, though the improved pressure ratio in turns the rise in power output of LPT.

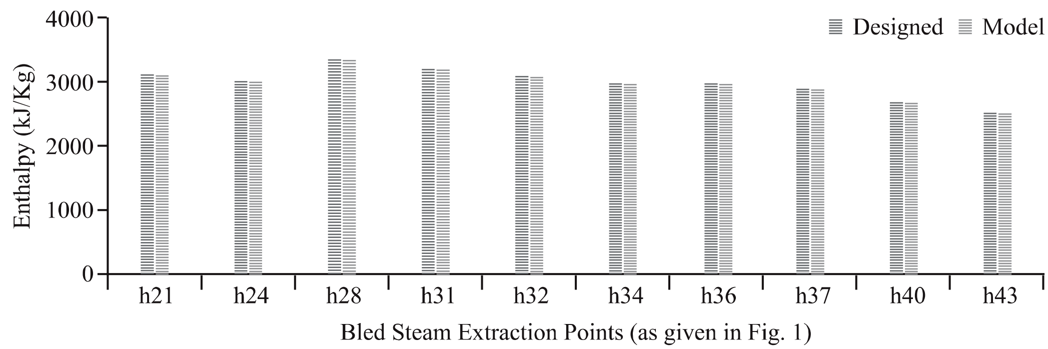

FIG. 2. COMPARISON BETWEEN DESIGNED AND MODELED ENTHALPY VALUES OF BLED STEAM EXTRACTIONS

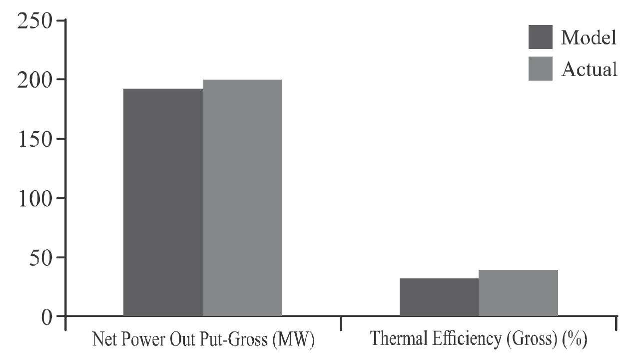

FIG. 3. COMPARISON BETWEEN SIMULATED AND ACTUAL RESULTS OF NET POWER AND EFFICIENCY

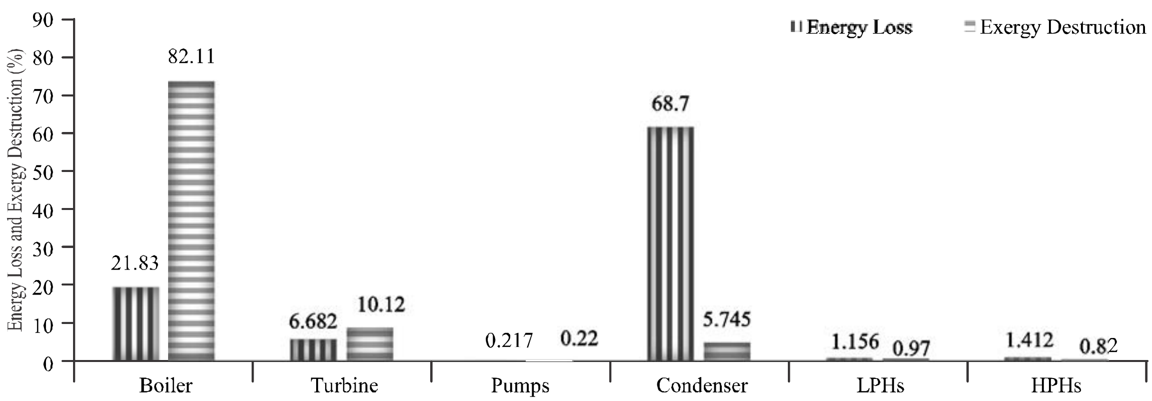

FIG. 4. ENERGY LOSS AND EXERGY DESTRUCTION IN DIFFERENT PLANT COMPONENTS

4.2.2 Effect of Main Steam Pressure on Performance

Fig. 6 illustrates the effect main steam pressure on cycle performance. It is evident that, net power output, energy and exergy efficiencies rise with an increase in main steam pressure for same fuel and steam flow rate. The trend exhibits a slower performance increment with respect to main steam pressure towards the end. Energy and exergy content of the steam increases with rise in main steam pressure, resulting in higher plant performance characters. Feed water regeneration effect (temperature) is varying proportionally with an increase in main steam pressure.

4.2.3 Effect of Main Steam Temperature on Performance

Fig. 7 exhibits the effect of main steam temperature on cycle performance. All the performance indicators like net power output, energy efficiency and exergy efficiencies increase proportionally with an increase in main steam temperature with same fuel and steam flow rate. The variation in all performance parameters with respect to main steam temperature shows nearly a similar trend. With an increase in main steam temperature, the energy and exergy of the main steam increases, this also results as the increase in the plant performance. The feed water regeneration effect improves with an increase in main steam temperature, similar to main steam pressure. However, such enhancement in performance always accompanied with a proportional incrementin the capital cost, which is mainly caused due to improvement in turbine blade and boiler tube design/material. The incremental revenues generated by the improved power output with higher efficiencies may be favorable only if the economic parameters indicate so. Therefore, for opting such improvements, an economic analysis should be considered for more insight of the problem.

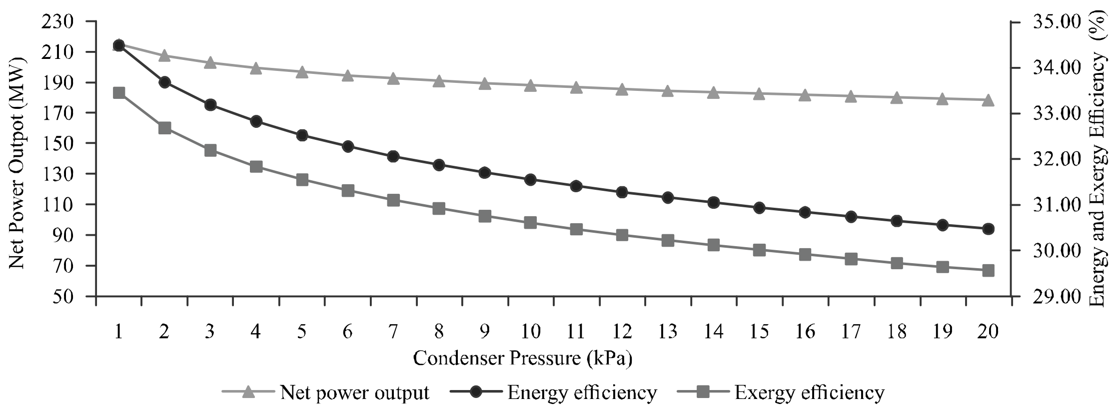

FIG. 5. IMPACT OF CONDENSER PRESSURE ON PERFORMANCE FOR P_{MS}=13200 KPA AND T_{MS}= 811 K

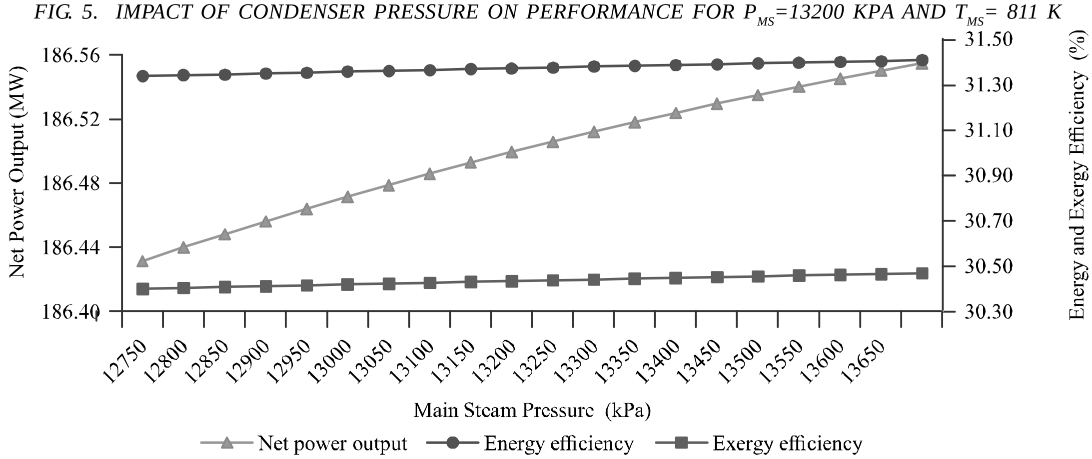

FIG. 6. IMPACT OF STEAM PRESSURE ON PERFORMANCE FOR P_C =11.23 KPA AND T_{MS}= 811 K

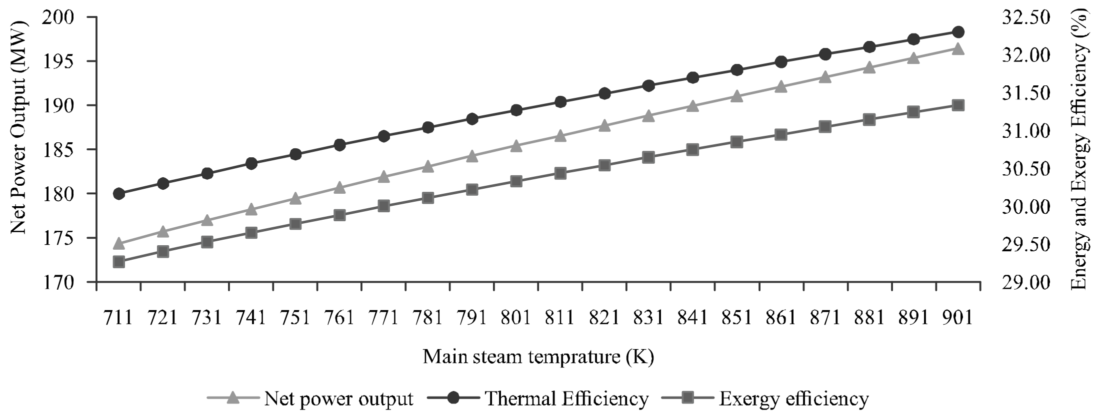

FIG. 7. IMPACT OF STEAM TEMPERATURE ON THE PERFORMANCE FOR P_C=11.23 KPA, P_{MS}=13200 KPA

5. CONCLUSION

This study presents, a thermodynamic analysis of a dual fired, reheat SPP at design conditions by means of energetic and exergetic methods. The power plant is modelled and validated. The comparison shows an admirable agreement among different quantities. The parametric analysis is also performed to analyze the impacts of condenser pressure, main steam pressure and main steam temperature on the performance by varying some important operating parameters as, condenser pressure, main steam pressure and main steam temperature.Net power output, energy and exergy efficiencies of the plant have been determined as, 186.5 MW, 31.37 and 30.41% respectively. The results have also shown that, the condenser contributes a major share in total energy loss, calculated as 280.6 MW (68.7%), followed by boiler with89 MW (21.83%). On the basis of exergetic analysis, it can be concluded that the exergy destruction in boiler is maximum with 350 MW (82.11%), followed by the turbine with 43 MW (10.12%).The parametric study reveals that, the performance improves with an increase in the main steam pressure and temperature as well, whereas, it decreases with an increase in condenser pressure.

6. NOMENCLATURE

En	Energy
h	Specific enthalpy (kJ/kg)
$\dot{I}$	Exergy destruction rate (MW)
$\dot{m}$	Mass flow rate (kg/s)
p	Pressure (kPa)
s	Specific entropy (kJ/kg.K)
t	Temperature (K)
$\dot{Q}$	Heat flow rate (MW)
V	Specific volume (m^3/kg)
$\dot{W}$	power (MW)
$\dot{X}$	Exergy rate (MW)
x	Specific exergy flow (kJ/kg)
Greek Letters	
Ø	Specific exergy rate (MW)
å	Exergy efficiency
ç	Energy efficiency
Abbreviations	
ECR	Economical Continuous Rating
Ext	Extraction
LHV	Lower Heating Value
HPT	High pressure turbine
IPT	Intermediate Pressure Turbine
LPT	Low Pressure Turbine
SPP	Steam Power Plant
VARS	Vapor Absorption Refrigeration System
HPH	High Pressure Heater
LPH	Low Pressure Heater
ECR	*Economical Continuous Rating*
Subscripts	
B	Boiler
bfp	Boiler feed pump
C	Condenser
cp	Condensate pump
cons	Consumption
DC	Drain Cooler
ex_{fg}	Exhaust flue gases
F	Fuel
f	Fan
fw	Feed water
h	hot
H	Heater
isen	Isentropic
i	Inlet
j	Number of carbon
k	Number of hydrogen
ms	Main steam
n	Number
o	Outlet
p	Pump
Q	Heat
rhs	Reheat steam
s	Steam
sh	Super heat
T	Turbine

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