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Thermodynamic Analysis of 77 MW Cogeneration Power Plant

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ABSTRACT:
Cogeneration technology has emerged as a viable and attractive option for process sectors with high heat requirements. This research presents an energy and exergy analysis of a 77 MW steam power plant. An extensive case study is conducted on the Vadinar Power Company Ltd. (VPCL, Nayara Energy) in Jamnagar, India. The plant's performance metrics, including component-wise energy loss, energy destruction, and exergetic efficiency, have been evaluated. The analysis reveals that the condenser accounts for the highest energy loss, with 45.5% being released into the environment. Additionally, the boiler is identified as the primary contributor to the system's largest energy destruction rate. Boilers have an energy efficiency of 42%; however, turbines are more efficient, with an energy efficiency of 72.05%. The primary cause of energy destruction in the boiler system is the significant amount of entropy generated in the combustion chamber during the combustion process.

Keywords: Boiler, Cogeneration, Energy, Exergy, Efficiency

INTRODUCTION

Cogeneration has been used for many years across various industries that require both power and heat simultaneously[1][2]. It is more energy-efficient than traditional power plants for producing thermal and electrical energy. To assess the performance of steam power plants, an international standard for energy quality is essential[3]. Using environmental parameters as a reference state, the most natural and practical standard is the maximum work that a system can achieve in the form of energy. This standard of energy quality is known as "exergy"[4].
Energy analysis is based on the first law of thermodynamics, which is the law of conservation of energy, while exergy analysis is based on the second law of thermodynamics, which describes the degradation of energy[5][6]. To assess the distribution of energy losses and irreversibilities that contribute to a decline in power plant performance efficiency[7][8].

For these reasons, several researchers have proposed using energy analysis alongside or as an alternative to exergy analysis to aid in resource allocation decisions [9] [10]. Recently, exergetic performance has been recognized as a valuable tool for the planning, evaluation, optimization, and improvement of thermal plants. In addition to determining the extent, location, and causes of irreversibilities within the plant, it provides a more comprehensive assessment of the efficiency of each individual plant component [11][12]. Dincer and Kanoglu analyzed and compared the energy and exergy performance of various cogeneration plants [13] .Jiang Feng Wang et al. utilized a genetic algorithm to conduct parametric optimization, using energy efficiency as the objective function[14]. Meksoub identified the boiler as the primary source of energy loss in the plant [15]. Aljundi compared energy losses across subsystems and the overall power plant [16].To examine the impact of ambient temperature on component efficiency deficiencies and the rational efficiency of the power plant, Mehmet Kopac et al. conducted a computational study based on exergy analysis [17].

The primary objective of this study is to evaluate the VPCL plant from both an energy and exergy perspective. To achieve this, calculations have been performed to determine the exergetic efficiency, component-wise energy losses, and the overall percentage of exergy destruction. The concept of exergy provides valuable insights for estimating the minimum required resources, reducing costs, optimizing design, and establishing a stronger foundation for improving power plant performance.

METHODS

1.Experiment set up

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VPCL and a refinery were established in 1998 to meet internal steam and electricity demands. The facility has a total capacity of 120 MW, consisting of three oil-fired boilers with a capacity of 175 TPH each, two steam turbines of 38.5 MW each, and a steam and water supply for the refinery. The company's primary objective is to ensure a continuous supply of steam and power to support the refinery's operations.

Boiler feed pumps enable the refinery's demineralized (DM) water to enter the upper boiler drum. Once the required pressure and temperature are achieved, the DM water passes through the bank tubes, where it is converted into steam before flowing through the turbine. The heat energy from the fuel used in combustion transforms the water into steam. Fluid oil serves as the fuel, and after transferring heat through the water tubes, the combustion gases exit the stack. The process flow diagram, incorporating key components such as the boiler (combustion chamber, economizer, and super heaters), steam turbine, condenser, deaerator, SCAPH, and turbo drives (BFP, CFP, AEP), was developed using data collected from field inspectors and plant management.

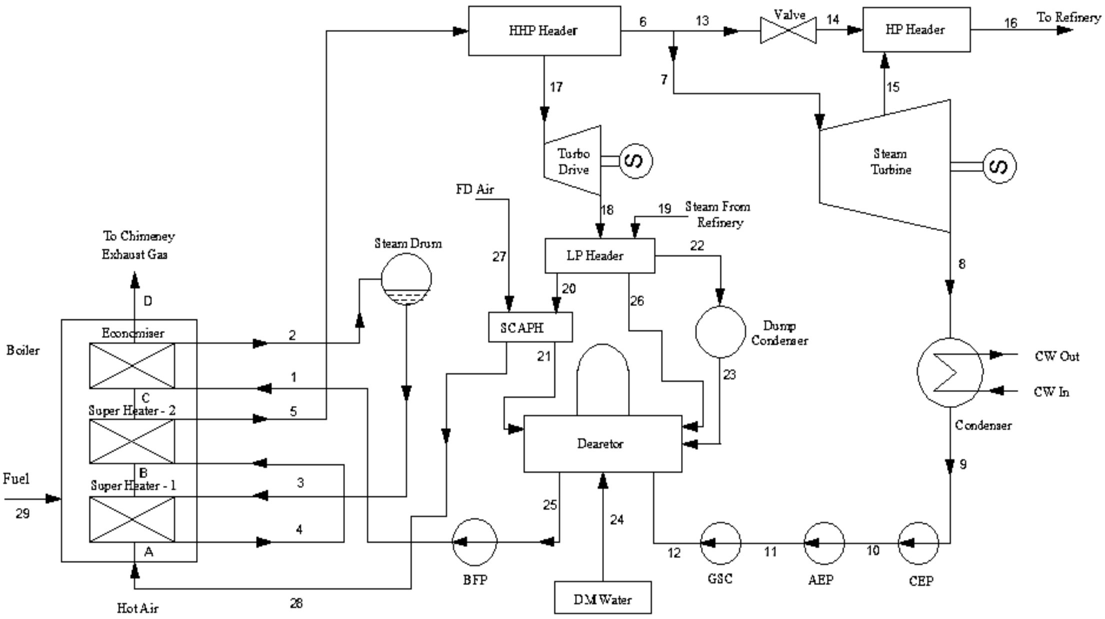

Fig. 1 Schematic Diagram of 77 MW Cogeneration Power Plant
CEP: Condensate Extraction Pump, AEP: Air Extraction Pump, GSC: Gland Steam Condenser, BFP: Boiler Feed Pump

2.Thermodynamic Considerations

For the thermodynamic analysis of the power plant, certain assumptions have been made.

- Potential and kinetic changes in energy and exergy are disregarded.
- The reference environmental conditions are 25 °C and 1.01325 bar of pressure.

Exergy analysis, based on the second law of

$$\Sigma\dot{m}_{in} = \Sigma\dot{m}_{out} \quad (1)$$
$$Q + \dot{W} = \Sigma\dot{m}_{out}h_{out} - \Sigma\dot{m}_{in}h_{in} \quad (2)$$
$$\dot{E}_{x,heat} - \dot{W} = \Sigma\dot{E}_{x,out} + \Sigma\dot{E}_{x,in} + \dot{I}_D \quad (3)$$
$$\dot{E}_{x,heat} = 0 \quad (4)$$

Exergy of the system is

$$\dot{E}_x = \dot{E}_{x,ph} + \dot{E}_{x,ch} + \dot{E}_{x,kn} + \dot{E}_{x,pe} \quad (5)$$

Where $\dot{E}_{xph}$, $\dot{E}_{xch}$, $\dot{E}_{xkn}$, $\dot{E}_{xpe}$ are physical exergy, chemical exergy, kinetic Where subscripts 'in' and 'out' referred to streams entering and leaving the control volume, respectively, the exergy destruction $\dot{I}_D$ and exergy loss thermodynamics, is used to identify the location and extent of maximum energy degradation during the process, aiding in design optimization and further improvements. In contrast, energy analysis, based on the first law of thermodynamics, focuses on minimizing energy loss within the plant. The three fundamental balance equations—mass, energy, and exergy—are applied to determine energy losses, the extent of exergy destruction, and the causes of energetic and exergetic inefficiencies in a thermal system operating under steady-state or steady-flow conditions [4].

$\dot{E}_{xiheat}$ are a measure of the inefficiencies associated with the irreversible process system are considered, the exergy losses are usually taking place in the plant component. When single components of a thermal zero. $\dot{E}_{x,heat} = 0$

exergy& potential exergy. In this study kinetic & potential exergy considered to be negligible. Exergy expressions for different energy stream are as under:

For Stream, $\dot{E}_x = \dot{E}_{x,ph} + \dot{E}_{x,ch} + \dot{E}_{x,kn} + \dot{E}_{x,pe}$ (6)

Where $\dot{E}_{xph}$, $\dot{E}_{xch}$, $\dot{E}_{xkn}$, $\dot{E}_{xpe}$ are physical exergy, chemical exergy, kinetic exergy& potential exergy. In this study

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kinetic & potential exergy considered to be negligible. Exergy expressions for different energy stream are as under:

For Steam, $\dot{E}_x = \dot{m}[(h - h_0) - T_0(S - S_0)]$ (7)

For Liquid fuel, $\dot{E}_x = \Psi . LHV$ (8)

Where Ψ= Exergy factor=0.9 for furnace oil

For a Flue Gas, $\dot{E}_x = \dot{E}_{x,ph} + \dot{E}_{x,ch}$ (9)

$$= \dot{m}\Sigma x_i \left[Cp^h(T - T_0) - T_0 Cp^s ln\left(\frac{T}{T_0}\right)\right] + RT_O \ln\left(\frac{P}{P_0}\right) + \dot{m}\Sigma\left[x_i e_{xi}^{ch} + RT_0 x_i ln x_i\right]$$

Exergy destruction rate ($\dot{I}_D$) &Exergy efficiency (η_{ex}) of each component for the cogeneration plant can be found as follows:

For Boiler exergy destruction rate and exergy efficiency can be expressed as:

$\dot{I}_B = \dot{E}_{x,f} + \Sigma\dot{E}_{x,in,b} - \Sigma\dot{E}_{x,out,b}$ (10)

$\eta_{ex,B} = \frac{\Sigma\dot{E}_{x,in,b} - \Sigma\dot{E}_{x,out,b}}{\dot{E}_{x,f}}$ (11)

For Steam turbine and Turbo drive exergy destruction rate and exergy efficiency can be expressed as:

$\dot{I}_T = \Sigma\dot{E}_{x,in,t} - \Sigma\dot{E}_{x,out,t} - \dot{W}_t$ (12)

$\eta_{ex,T} = \frac{\dot{W}_t}{\Sigma\dot{E}_{x,in,t} - \Sigma\dot{E}_{x,out,t}}$ (13)

For Condenser exergy destruction rate and exergy efficiency can be expressed as:

$\dot{I}_C = \Sigma\dot{E}_{x,in,c} - \Sigma\dot{E}_{x,out,c}$ (14)

$\eta_{ex,C} = \frac{\Sigma\dot{E}_{x,out,c}}{\Sigma\dot{E}_{x,in,c}}$ (15)

For SCAPH exergy destruction rate and exergy efficiency can be expressed as:

$\dot{I}_S = \Sigma\dot{E}_{x,in,s} - \Sigma\dot{E}_{x,out,s}$ (16)

$\eta_{ex,S} = \frac{\Sigma\dot{E}_{x,out,s}}{\Sigma\dot{E}_{x,in,s}}$ (17)

For Dearetor exergy destruction rate and exergy efficiency can be expressed as:

$\dot{I}_{D/A} = \Sigma\dot{E}_{x,in,d} - \Sigma\dot{E}_{x,out,d}$ (18)

$\eta_{ex,D/A} = \frac{\Sigma\dot{E}_{x,out,d}}{\Sigma\dot{E}_{x,in,d}}$ (19)

For Cycle exergy destruction rate and exergy efficiency can be expressed as

$\dot{I}_{Cycle} = \Sigma\dot{I}_{D,allcomponents}$ (20)

$\eta_{ex,Cycle} = \frac{\dot{W}_{net} + \dot{E}_{x,steam\ generated}}{\dot{E}_{x,f}}$ (21)

Table: 1 Value of Thermodynamics Properties at Different State

State	Pressure (bar)	Temp (C^0)	Mass (kg/S)	Specific Enthalpy (kJ/kg)	Specific Entropy (kJ/kg)	Specific Exergy (kJ/kg)	Exergy (MW)	Energy (MW)
1	61.751	152	135	646	1.52	192.936	26.05	87.21
2,3	61.751	237	135	1007.25	1.975	418.596	56.51	135.98
4	61.751	277	135	2783	5.88	1029.166	138.93	375.705
5	61.751	453	135	3380	6.6	1343.096	190.78	456.3
6	61.751	453	135	3380	6.6	1343.096	190.78	456.3
7	61.751	453	95.56	3380	6.6	1343.096	135.03	322.99
8	0.062	39	50.84	2569	8.315	91.026	4.652	131.30
9	0.062	39	51.84	165.75	0.532	7.11	0.36	8.47
10	7.563	40	51.108	170	0.5431	8.0522	0.41	8.69
11	7.563	41	51.108	174.25	0.5549	8.7858	0.45	8.91
12	1.169	42	51.108	178.5	0.57	8.536	0.44	9.12
13	61.751	453	36.67	3380	6.6	1343.096	49.251	121.38
14	40.155	407	36.67	3260	6.8	1233.496	45.23	119.54
15	40.155	407	44.722	3260	6.8	1217.336	55.16	145.79
16	40.155	407	81.39	3260	6.8	1233.496	100.39	265.33
17	61.751	453	2.78	3380	6.6	1343.096	3.9284	9.397
18	4.463	200	2.78	2880	7.12	758.136	2.11	8.00
19	4.463	200	34.73	2880	7.12	758.136	26.33	100.02
20	4.463	200	6.945	2880	7.12	758.136	5.27	20.00
21	1.472	110	6.945	462.8	1.423	38.642	0.27	3.21
22	4.463	200	13.89	2880	7.12	758.136	10.53	40.00
23	4.463	145	13.89	616.25	1.4743	176.8046	2.46	8.565
24	2.098	52	77.5	218.4	0.672	18.04	1.40	16.93
25	1.289	106	144.5	450.4	1.21	89.716	12.96	65.08
26	2.48	110	13.89	2860	7.4	654.696	9.09	39.73
27	1.031	35	202.942	34.84	---	0.84	0.17	7.07
28	1.031	115	202.942	115.01	---	15.82	3.21	23.34
29	Fuel	---	11.67	41488.43	---	37340.19	435.76	484.17
30	2.58	30	1500	130.05	0.428	2.402	3.603	195.075

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31	2.58	34.3	1500	145.78	0.474	4.424	6.636	218.67
A	1.044132	1325	214.622	1313.93	---	922.56	241.71	344.25
B	1.02453	700	214.622	638.931	---	392.56	102.85	167.41
C	1.01874	500	214.622	430.534	---	254.695	66.73	112.8
D	1.0128	200	214.622	155.73	---	101.76	26.66	40.88

RESULT AND DISCUSSION

4.1 Component Wise Energy Loss and Percent of Energy Loss

From an energy analysis perspective, the condenser experiences the highest energy loss, accounting for approximately 45.5% of total losses. This is due to the rejected heat being directly exhausted into the atmosphere, making it unusable. Although the quantity of energy lost is large, it is thermodynamically insignificant due to its low quality.

The condenser has the highest energy loss at 107.77 MW, indicating significant inefficiencies in heat rejection. The boiler follows with 88.95 MW of energy loss, primarily due to irreversibilities in combustion and heat transfer. The stack contributes 37.31 MW, reflecting substantial waste heat emissions. Other components exhibit relatively lower energy losses.

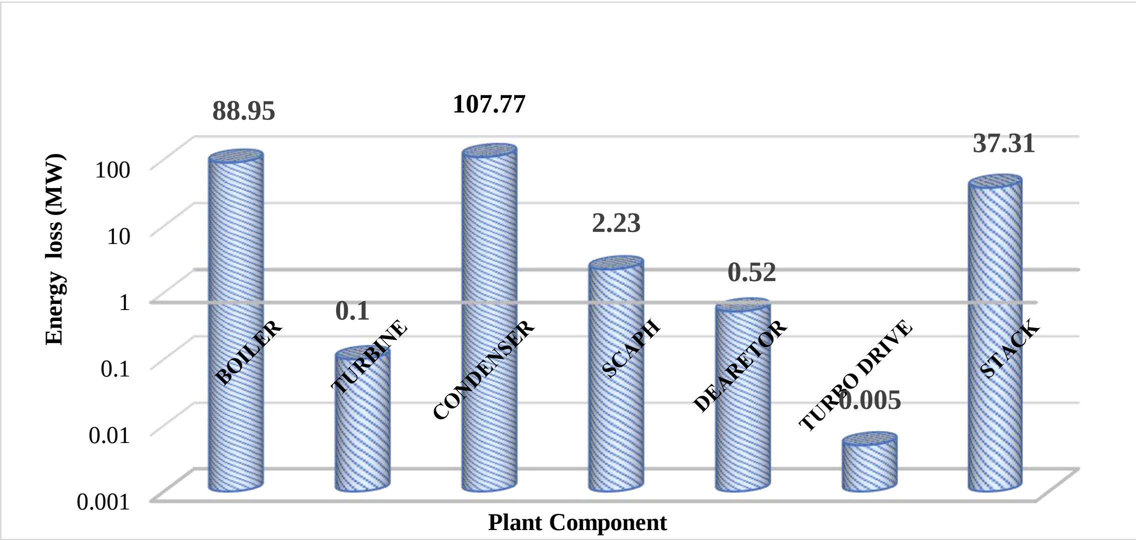

Fig.2 Energy Loss in Plant Components

4.2 Component Wise Exergy Destruction, Percent of Exergy Destruction and Exergetic efficiency

Fig.3 represents exergy destruction across different components of the power plant. Exergy destruction signifies the loss of useful energy due to irreversibilities in the system.

From an exergy analysis perspective, the boiler system accounts for the highest exergy destruction, contributing 81.09% of the total exergy loss in the plant. In contrast, the condenser has a minimal exergy destruction rate of just 0.4%. The boiler is the primary source of inefficiencies due to entropy generation during combustion and heat transfer processes, operating with an exergetic efficiency of only 40.08%.

Modern boilers with advanced technology can utilize only 33% of the fuel input efficiently. Among other components, the turbine and stack also contribute significantly to exergy destruction. Enhancing combustion efficiency, optimizing heat transfer processes, and minimizing irreversibilities in these components can significantly improve the overall performance of the plant.

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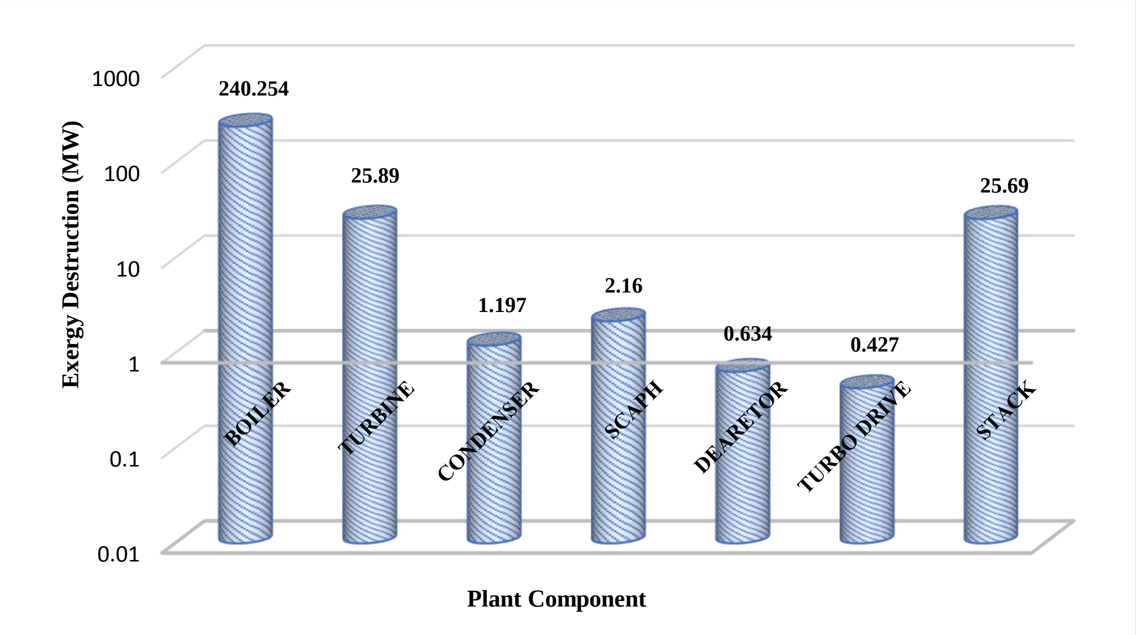

Fig.3 Exergy Destruction in Plant Component

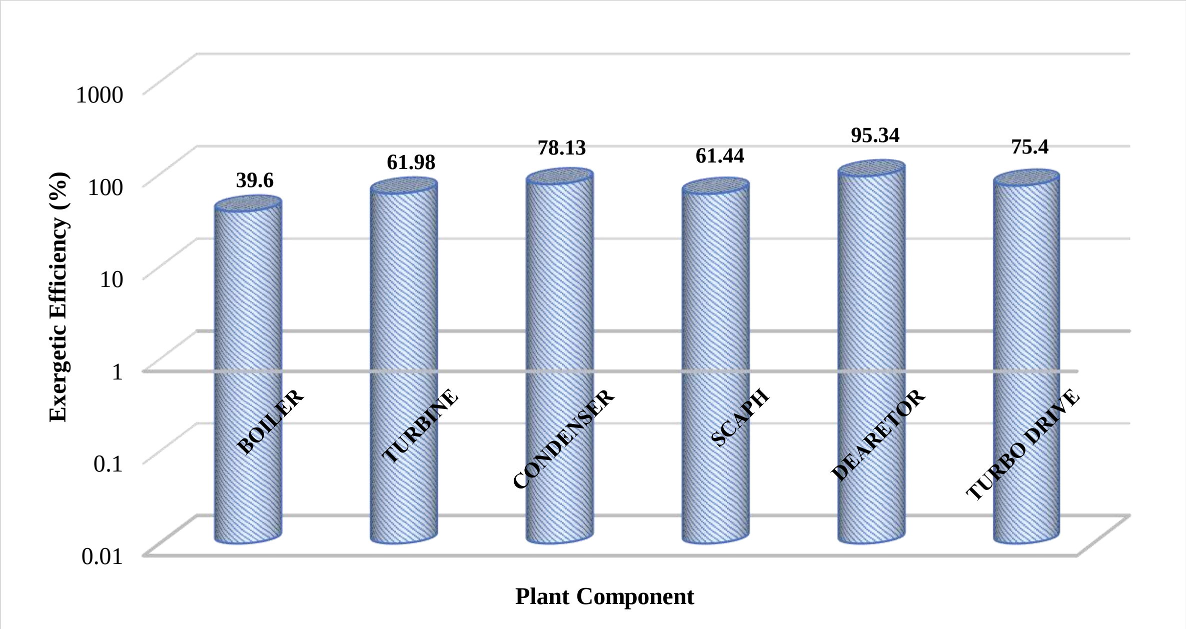

Fig.4 Exergetic Efficiency of Plant Component

4.3 Effect of The Reference Environment Temperature On Exergy Destruction and Exergetic Efficiency of Plant Component

The boiler's exergy efficiency remains low (~40%) and decreases with rising temperature, indicating significant exergy destruction. The turbine maintains stable efficiency (~60%) but slightly declines with temperature. The condenser's efficiency improves from 60% to 80%, suggesting reduced irreversibilities at higher temperatures. SCAPH remains stable (~60%) but slightly declines at elevated temperatures. The deaerator shows a gradual efficiency increase, likely due to better heat exchange. The turbo drive maintains high efficiency (~70-75%) and is least affected by temperature variations.

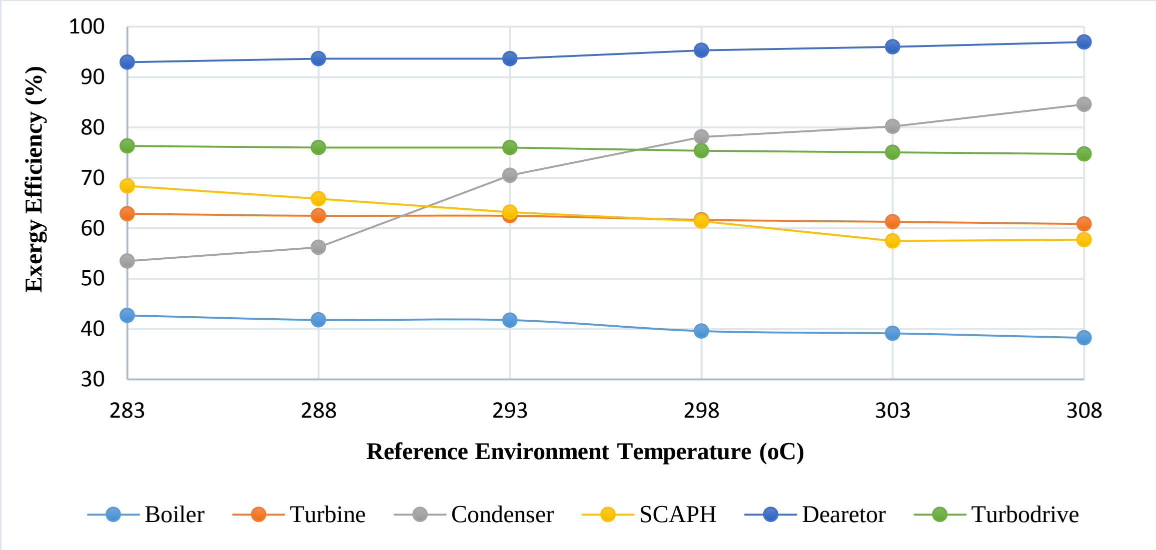

Fig. 5 Exergy Efficiency Versus Reference Environment Temperature (°C)

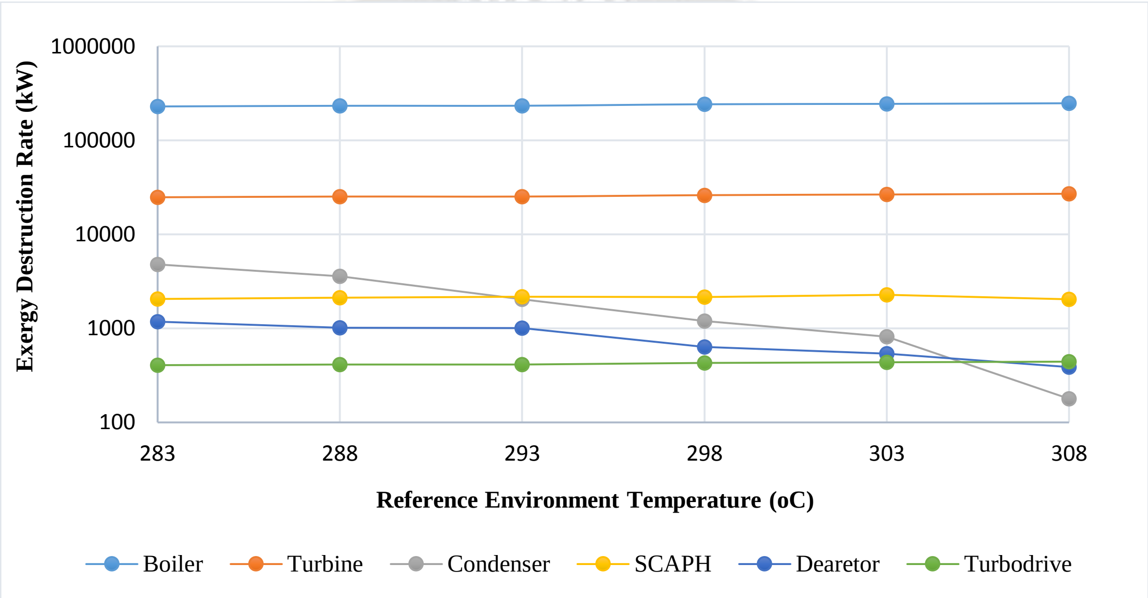

Fig.6 Exergy Destruction Rate Versus Reference Environment Temperature (°C)

CONCLUSION

In this study, an energy and exergy analysis of the cogeneration plant at VPCL in Jamnagar has been conducted. The results indicate that the current power plant generates 43.35 MW of power and produces 315 TPH of steam at a pressure of 40 bar and a temperature of 407°C. The boiler system experiences the highest exergy losses, with an exergetic efficiency of 40.08%. The plant operates with an overall thermal efficiency of 68.90% and an exergetic efficiency of 34.69%. The following conclusions have been drawn from this research.

- The highest losses occur in the condenser, boiler, and stack, suggesting that improving these components could significantly enhance plant efficiency.
- The boiler contributes the most to exergy destruction, with the turbine and stack following as significant sources of inefficiency. Enhancing combustion efficiency, optimizing heat transfer mechanisms, and minimizing irreversibilities in these components can help improve the overall efficiency and performance of the plant.

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