Thermodynamic Evaluation Based Exergy and Energy Analysis of Existing Indramayu Coal-Fired Power Plants

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Abstract. Improvements in industrial processes involve a comprehensive analysis of thermodynamics, specifically the first and second laws, alongside energy and exergy assessments. To address low steam power plant efficiency, each component must undergo a detailed examination to identify and quantify energy and exergy losses. Data from the Indramayu Coal Fired Power Plant informed this evaluation. Results highlight significant exergy destruction in the high-pressure turbine (340 MW) and boiler (320 MW), both operating at less than 20% efficiency. Inefficient heat transfer and insulation contribute to the boiler's exergy destruction. The condenser, responsible for a 50 MW exergy loss, also greatly impacts overall system degradation. Enhancing the steam power plant's thermal efficiency necessitates remedial action, focusing on improving the boiler, high-pressure turbine, and condenser components.

Keywords: Exergy analysis, Energy analysis, Irreversibility, Exergetic efficiency, Exergy destruction, Indramayu power plant

1 Introduction

The development of each country is inseparable from the influence of energy sources [1]. Every activity for the development of a country relies on energy sources since it has a significant role in industrial development and human sustainability. Energy consumption is increasing with population growth and economic expansion [2]. Due to the high efficiency and reliability, as well as the high initial cost of renewable energy, coal remains the dominating energy source till reaching 84% of energy demands [3].

Due to our dependence on fossil fuels, reducing the environmental impact of fossil fuel power plants is very important since it is an unavoidable topic. Environmental analysis should also be conducted to achieve sustainable development, complemented by the economic analysis of the coal-fired power plant system. Carbon capture technology is currently applied to various fossil fuel plants to reduce emissions [4]. However, in industrial observation and economic analysis,

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incorporating CO_2 capture technology in power plants increases electricity purchase prices by up to 29%, so the implementation of this technology cannot be applied massively [5]. Therefore, an effort to reduce the environmental impact of coal power plants is to increase plant efficiency to reduce environmental losses.

The first law of thermodynamics can carry out energy analysis. However, this principle has limitations in terms of not considering the environmental system's properties or the energy quality [6]. The investigation of the first law of thermodynamics also does not consider the concept of irreversibility. In contrast to the second law of thermodynamics, exergy analysis can characterize the irreversibility of processes in the system [7]. The principle of this second law considers the maximum amount of work that can be achieved from the system by examining the distribution of irreversibilities that degrade the system's efficiency.

Many studies have been conducted to analyze the power plant system so that system efficiency can be further increased. Regulagadda et al. conducts a parametric study to review the energy and the exergy of a 32 MW coal-fired power plant to maximize the plant efficiency [8]. From the result of the investigation, It was found that the boiler and turbine had the highest losses, resulting in a significant environmental effect. Aljundi also investigated components contributing to irreversibility at the Jordanian power plant [9]. According to the findings of his investigation, the boiler component had the most exergy destruction reaching 77%, the turbine had 13%, and the fan condenser had 9%. The chemical processes in the combustion system produce the most losses in boilers, which may be addressed by preheating the combustion air and lowering the air-fuel ratio. The exergoeconomic analysis at the power plant was also carried out by Rosen and Dincer, who observed the efficiency of various fuels in the thermal plant system [10]. They reviewed how the relationship between capital costs and thermodynamic losses.

With various advantages obtained through the analysis of the second law of thermodynamics, in this study, the combined analysis of the first law and the second law of thermodynamics was carried out to review which components in the system have the most impact on the efficiency of the coal-fired power plant. This study identifies the components with the highest losses or irreversibility, allowing them to assist in improving the efficiency of power plant performance. Identifying the biggest losses in each component will be expressed in the exergy destruction and the exergetic efficiency. This paper will provide an overview of which components need to be improved to increase system efficiency and reduce environmental impact.

2 Methodology

The efficiency of the power plant system was examined at the actual coal-fired power plant of Indramayu, with a capacity of 3x330 MW. The Indramayu coal-fired power plant is part of a subcritical plant with the phase mixture in the boiler, necessitating the installation of the steam drum component to separate the mixed fluids [11]. The type of boiler used is a type of sub-critical water tube boiler. The fuel utilized is a mixture of medium and low-rank coal from Bukit Asam Company with high heating values (HHV) of 4.884 kcal/kg and 4.312 kcal/kg, respectively, with the 80% and 20% mixture, respectively. State Electricity Company has completed a massive audit that has significantly increased Net Plant Heat Rate (NPHR) from 2,277.95 to 2,612.35 kcal/kWh [12]. It indicates that there would be significant losses in the steam power plant system, demanding in-depth analysis of each component to determine the major contributor to system degradation.

The real data from each condition, such as temperature, pressure, and flow rate, will be processed to provide enthalpy and entropy values derived from REFPROP to describe energy and exergy calculations. The actual data of the Indramayu Coal Fired Power Plant is obtained from the previous study [13]. **Error! Reference source not found.** depicts the schematic diagram of the Indramayu Steam Power Plant facility. The main components of this system consist of a boiler, low pressure (LP) turbine, intermediate pressure (IP) turbine, high pressure (HP) turbine, condenser, heater, boiler feed pump, steam cooler, and other supporting components such as gland steam condenser, and DEA (Diethanolamine) tanks.

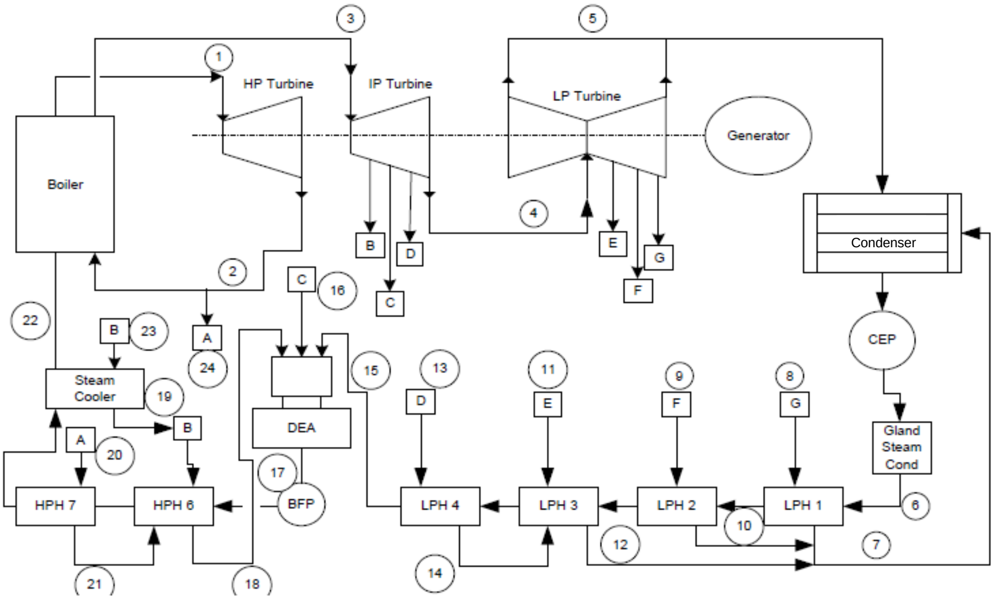

Fig. 1 Schematic diagram of the Unit 3 in Indramayu Coal Fired Power Plant

This study will evaluate each component regarding work generated, heat contributed, exergy destruction, irreversibility, energy, and exergetic efficiency. The mass, energy, and exergy balance for the control volume are as follows:

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{1}$$

$$\sum_i \dot{E}_i + \dot{Q} = \sum_o \dot{E}_o + \dot{W} \tag{2}$$

$$\dot{E}_{in} + \dot{E}_Q = \dot{E}_{out} + \dot{E}_w + \dot{E}_D + \dot{E}_L \tag{3}$$

Where in and out represent the incoming and exiting streams in each condition, and $\dot{m}$, $\dot{Q}$, $\dot{W}$ represent the mass flow rate (kg/s), heat transfer rate to the system (MW) accordingly. While $\dot{E}_D$ represents the exergy of destruction, $\dot{E}_L$ reflects the inefficiency in each component, and $\dot{E}_w$ has the same value as $\dot{W}$. For specific exergy (Ψ), the following equations can be used:

$$\Psi = (h_i - h_0) - T_0(s_i - s_0) \tag{4}$$

Where the exergy rate of the stream is

$$E_i = \dot{m}(\Psi) \quad (5)$$

The exergy flow is separated into numerous components, including physical energy, mixing energy (kinetic and potential), and chemical energy [14]. Since kinetic and potential exergy are ignored in this study, the calculation of exergy flow is impacted by physical exergy, which comprises the total of kinetic, potential, and thermal exergy [15]. Table 1 summarizes the actual data production of the Indramayu Coal Fired Power Plant.

Table 1 Actual Data of Indramayu Coal Fired Power Plant

State	m flow (kg/s)	T [ºC]	P [bar]	h [kJ/kg]	s [kJ/kg.K]	Quality	Exergy [kW]	Energy [kW]
0		25	1	104.92	0.36	Subcooled		
1	241.28	573.1	172.5	3490.5	6.51	Superheated	374790.9	842212.37
2	21.13	329	35.9	3050.8	6.56	Superheated	23231.9	64479.59
3	219.74	534.6	34.2	3530.9	7.27	Superheated	300586.7	775885.45
4	184.65	264	4.4	2992	7.38	Superheated	146532.5	552478.86
5	164.77	38.4	0.067777	160.85	0.55	0	186.69	26504.32
6	196.15	41.2	21.7	174.46	0.583	Subcooled	754.93	34221.62
7	5.99	55.4	0.16067	231.93	0.77	0	35.86	1389.84
8	5.99	57.4	0.2	240.3	0.79	Subcooled	40.65	1439.99
9	7.88	83.5	0.5	2649.6	7.60	Superheated	3046.84	20881.27
10	7.88	71.1	0.32715	297.68	0.96	0	106.15	2345.99
11	6.00	119.3	1	2715.2	7.46	Superheated	2966.83	16296.55
12	20.78	85.1	0.58094	356.43	1.13	0	464.56	7408.11
13	14.78	264	4.4	2992	7.38	Superheated	11730.58	44228.40
14	14.78	113.7	1.6213	477.08	1.45	0	687.23	7052.30
15	196.15	143.1	3.9439	602.47	1.77	0	15486.12	118178.95
16	17.53	345.4	9.2	3150	7.32	Superheated	17002.34	55223.08
17	254.75	175.6	186.4	753.25	2.07	Subcooled	35539.74	191891.96
18	23.91	181.8	10.45	771.01	2.15	0	3169.47	18435.98
19	2.77	208.47	18.5	890.65	2.41	0	490.29	2472.59
20	21.13	329	35.9	3050.8	6.56	Superheated	23231.9	64479.59
21	21.13	212.3	19.969	908.14	2.44	0	3876.76	19193.81
22	249.88	248	183.7	1077.1	2.74	Subcooled	65944.39	269155.32
23	2.77	453.2	18.5	3367.2	7.33	Superheated	328.86	9347.90
24	21.13	334	37.7	3058.8	6.55	Superheated	23449.5	64648.67

We may utilize the second Law Efficiency equation as the main concept to establish the efficiency of each k component to assess the performance of a steam power plant using exergy analysis. The second law efficiency is calculated by dividing the total quantity of exergy produced by the number of input exergy in each component, Where $\sum \dot{E}_{product}$ represents total output exergy, and $\sum \dot{E}_{fuel}$ represents total incoming exergy.

$$\eta II = \frac{\sum \dot{E}_{product}}{\sum \dot{E}_{fuel}} \quad (6)$$

We may undertake the analysis utilizing the idea of exergy destruction to determine how much exergy is wasted or destroyed in a component or system, in addition to the equation of second law efficiency, exergetic efficiency. The exergy destruction is calculated using the following equation:

$$\dot{E}_{D,k} = \sum \dot{E}_{fuel} - \sum \dot{E}_{product} \quad (7)$$

Another key indicator in determining component the quality of its exergy principle is the Exergy Destruction Ratio. We may calculate the ratio of Exergy Destruction to a component by dividing the value of Exergy Destruction (7) by the total amount of exergy that enters each component. In other aspects, the exergy destruction ratio (8) is a criteria for estimating resource degradation.

$$yD,k = \frac{\dot{E}_{D,k}}{\sum \dot{E}_{fuel,total}} \quad (8)$$

For the Boiler component, since the energy and exergy analysis is affected by the type of fuels, the equations will be used as follow:

$$\Psi_{fuel} = \gamma_f \times LHV \quad (9)$$

γf = 1.06 is based on the fuel's Low Heating Value (LHV). The LHV value employed in this investigation was 20,047.43 kJ/kg [9]. Hence, $E_{boiler} = \dot{m}_f \times T_f = \dot{m}_f \times \gamma_f \times LHV$. Next, for the pump component, the energy is analyzed by the isentropic concept process, where the entropy value does not change with the combined pump efficiency is 0.95 based on the previous study [16]. The equation of the pump will be as follow:

$$W_{pump} = \frac{\sum \dot{m}\,(h_{e,i} - h_{in})}{\eta_{combined}} \quad (10)$$

The representative equation of the components in Indramayu Coal Fired Power Plant is described in Table 2. The values of each needed parameter will next be determined using the equations in this table.

Table 2 The Equation of Exergy Destruction and Exergetic Efficiency on each Component

Component	Exergy Destruction	Exergetic Efficiency
High Pressure Heater 6 Heater 6	ED, HPH6 = $(\dot{E}_{x_{17}} + \dot{E}_{19} + \dot{E}_{21})$-$(\dot{E}_{x_{18}})$	ηII,HPH6= $\frac{(\dot{E}_{x_{18}})}{(\dot{E}_{x_{17}}+\dot{E}_{19}+\dot{E}_{21})}$
High Pressure Turbine	E$D,turbine$ = $\dot{E}_{x_1}$- $(\dot{E}_{x_2} + \dot{E}_{x_{wturbine}})$	η$II,turbine$ = $\frac{(\dot{E}_{x_2}+\dot{E}_{x_{wturbine}})}{\dot{E}_{x_1}}$
Low pressure heater	ED,LPH2 = $(\dot{E}_9 + \dot{E}_{10})$- $\dot{E}_{x_{12}}$	ηII,LPH2 = $\frac{\dot{E}_{x_{12}}}{(\dot{E}_9+\dot{E}_{10})}$
Condenser	E$D,condenser$ = $(\dot{E}_{x_5} + \dot{E}_{x_7}) - (\dot{E}_{x_6})$	η$II,condenser$ = $\frac{\dot{E}_{x_6}}{(\dot{E}_{x_5}+\dot{E}_{x_7})}$
DEA Tank	ED,DEA =$(\dot{E}_{x_{15}} + \dot{E}_{x_{16}} + \dot{E}_{x_{18}})$-$(\dot{E}_{x_{17}})$	ηII,DEA = $\frac{(\dot{E}_{x_{15}}+\dot{E}_{x_{16}}+\dot{E}_{x_{18}})}{(\dot{E}_{x_{17}})}$
Boiler	E$D,boiler$ = $(\dot{E}_{boiler} + \dot{E}_{x_2} + \dot{E}_{x_{22}})$-$(\dot{E}_{x_1}+\dot{E}_{x_3})$	η$II,boiler$ = $\frac{(\dot{E}_{x_1}+\dot{E}_{x_3})}{(\dot{E}_{boiler}+\dot{E}_{x_2}+\dot{E}_{x_{22}})}$

3. Result and Discussion

The energy and exergy analysis in Indramayu Steam Power Plant was carried out using the operational data at the power plant. The ambient temperature and pressure used in this study were 101.3 kPa and a temperature of 298.15 K. Energy and exergy calculations may be performed using operational data and ambient condition data, and the results are reported in Table 1, where the enthalpy and entropy parameters were determined using REFPROP 8 software. The second law of thermodynamics is used to evaluate the efficiency of each component because the analysis based on the principle of the first energy law cannot see the irreversibility concept. From the equations that have been described, energy efficiency is summarized in **Figure 2**. From the results of the calculations through the exergetic efficiency, it is found that the DEA tank has the highest efficiency of more than 95%, followed by the low-pressure heater heat exchanger group having the efficiency of 85%. Meanwhile, the condenser, boiler, and high-pressure turbine components have low exergetic efficiency of 2.7%, 5.5%, and 8.7%, respectively. **Figure 2** depicts the amount of efficiency of a component in the thermal plant system in order to produce the most work. The greater the value of exergetic efficiency will represent the greater the amount of work converted into useful energy.

Furthermore, the calculation results of the exergy destruction of each component are presented in **Figure 3**, where the exergy destruction reflects the proportion of irreversibility or losses in a component. **Figure 2** and **Figure 3** illustrate the same finding, that the high pressure turbine and boiler components have the greatest exergy destruction up to 340 MW and 320 MW, respectively. On the other hand, the low pressure heater and DEA Tank have low exergy destruction of 1.760 MW and 0.118 MW respectively. The quantity of exergy destroyed basically tells how much exergy cannot be utilized. It does not always imply a component with a high irreversibility or the best at processing the entire incoming exergy with the total exergy product or destroyed in a component. According to the findings of this research, the components with the highest reversibility are located in the high pressure turbine, boiler, condenser, and low pressure turbine components having an exergetic efficiency of less than 20%. This component greatly affects the total efficiency reduction of the Indramayu Steam Power Plant.

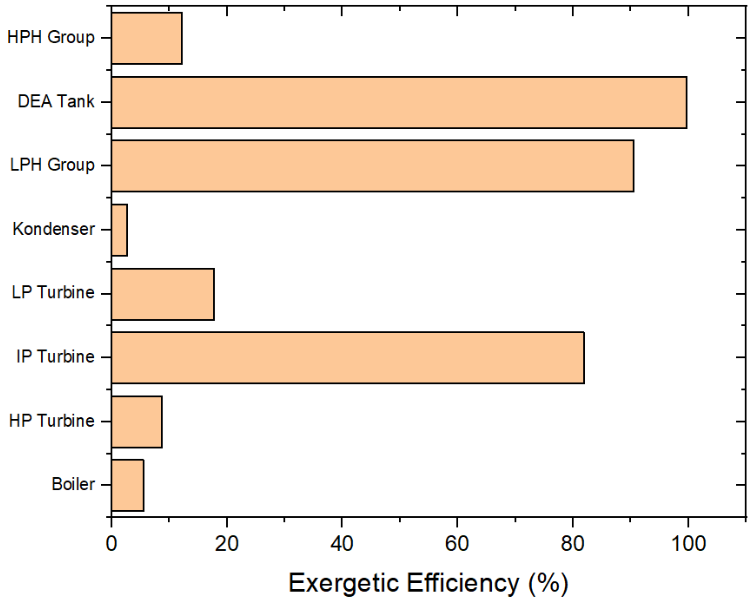

Fig. 2 Exergetic Efficiency of Each Component

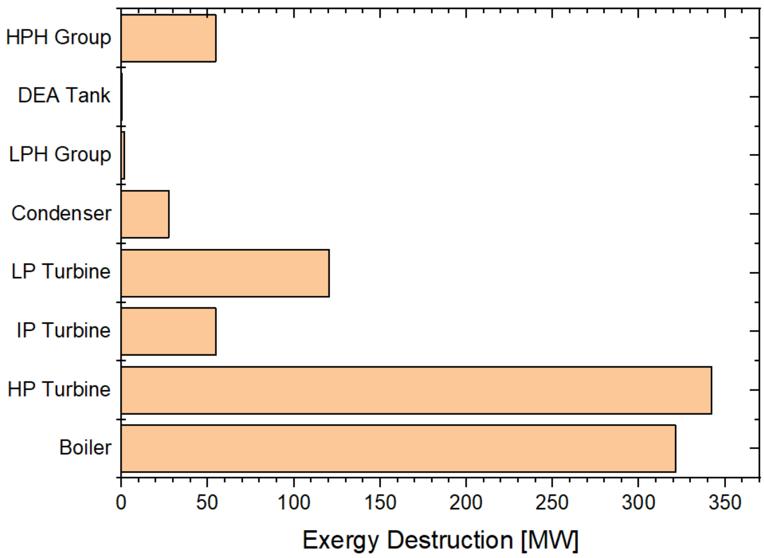

Fig. 3 Exergy Destruction in Each Component

Several possibilities cause the boiler to have the biggest losses. Most steam power plants have minimum boiler efficiency due to non-optimum heat transfer of the fluid in the boiler and the high losses in exhaust gas emission. Selecting the right material for the boiler is one of the keys to preventing large losses and improving the soot-blowing mechanism process. Another aspect that significantly impacts the boiler component is its combustion, which can be improved by enhancing the quality of combustion and the type of fuel used. Burning can be affected by many things. The humidity level of coal affects the combustion rate, so Widhiatmaka, 2017, suggested that there should be a process for drying the coal before it is burned. In addition, excess air also affects the quality of combustion [13]. Arefdehgani, 2015, stated that by reducing excess air in combustion, increasing the temperature of combustion products, and decreasing the value of excess air from 0.4 to 0.15, the energy and exergy efficiencies increase 0.497% and 0.46%, respectively [18]. Rosen & Tang, 2008, reported that Energy and exergy efficiency increases by 3.5% when the stack-gas temperature decreases from 149°C to 87°C [19]. Next, the high level of exergy destruction in the high pressure turbine is caused by the heat loss and the steam leaking in the turbine gland which often occurs in this component. Furthermore, in the condenser component with high exergy destruction due to the large temperature difference in the heat exchange process, increasing the heat transfer coefficient and heat transfer area can assist the condenser perform ideally [17]. A study by Tarla et al. in 2021 revealed that the inefficiency in condenser systems is caused by inadequate steam cooling. This issue can be resolved by avoiding direct cooling between the dumped steam and the cooling water. Instead, the heat from the steam should be transferred to another liquid at a higher temperature than the cooling water. Subsequently, this heat can be transferred from the secondary liquid to the cooling water. This approach could decrease exergy destruction by as much as 30% [20].

4. Conclusion

This study analyzed the Indramayu steam power plant with the first and second laws of thermodynamics. This study estimates the energy and exergy of each component, exergetic efficiency, and exergy destruction, revealing which components have significant irreversibility. This research determined which components contribute the most to the overall system performance degradation. From the calculation results, the components with the greatest irreversibility where the efficiency cannot reach more than 20% are the boiler, the high-pressure turbine, and the condenser. To be able to improve plant performance, the main focus that can be performed is to increase the efficiency of these three components. The combustion quality can be improved in boiler components by lowering the air-fuel ratio and preheating the fluid stream. Lowering excess air could lead to a better exergy efficiency of up to 0.46%, and lowering the gas-stack temperature could lead to a 3.5% better exergy efficiency. The condenser with low exergetic efficiency can be improved by minimizing the temperature difference by maximizing the heat transfer area and coefficient. This could lead to 30% less exergy destruction. Routine cleaning of the condenser also helps maximize the performance of the condenser. The analysis findings may be used to improve the Indramayu Steam Power Plant's total efficiency by improving the boiler's components, high-pressure turbine, and condenser.

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