International Journal of Electrical, Energy and Power System Engineering (IJEEPSE)
e-ISSN: 2654-4644
Vol. 6, No. 3, pp. 200-204, October 2023
Accredited by KEMENDIKBUDRISTEK, No. 230/E/KPT/2022
http://www.ijeepse.ejournal.unri.ac.id

Exergy Analysis of Coal-Based 2 X 7 MW Steam Power Plant

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***Abstract*—In this study, an analysis was conducted on a steam power plant system with a capacity of 2 x 7 MW based on coal. The coal fuel used by the majority of refined sizes is not in accordance with the recommendations of the American Society of Mechanical Engineers (ASME). The main objective of the study was to analyze the system components separately and to measure the exergy value of the components, covering the electrical energy so that it is known which equipment experiences the greatest energy loss as well as knowing the efficiency value of the equipment used. Efficiency and exergy are calculated using plant operation data. The results of the study found that the largest exergy destruction occurred in boilers, meaning that there was the largest energy loss in this section with a value of 37.34 MW (16.71%), while the destruction of the smallest exergy occurred in condensers of 0.58 MW (99.24%).**

Keywords— Efficiency, Exergy, Steam Power Plant

I. INTRODUCTION

Steam power plants are one of the providers of electricity that has great potential for providing energy and is an alternative to meet electricity needs. The utilization of fossil energy (coal) to produce electrical energy must be as efficient as possible. The need for optimization and improvement of power plant performance efficiency is an important factor that needs to be evaluated. Therefore, it is necessary to analyze power plant systems. The exergy of a system is defined as the maximum shaft work that can be performed by the combined system and given reference environment. The reference environment is assumed to be infinite, in equilibrium, and includes all the other systems. Usually, the environment is determined by temperature, pressure, and chemical composition. Exergy is a measure of the departure of a system from its environment. Therefore, it is an attribute of the system and the environment. Once the environment is defined, a value can be assigned to exergy in terms of the property values for the system only, such that exergy can be considered an extensive property of the system [1]–[3]. Exergy analysis is a thermodynamic analysis technique based on the second law of thermodynamics that provides an alternative and enlightening method for rational and meaningful assessment and comparison processes and systems [4], [5]. In particular, exergy analysis yields efficiency, which provides a true measure of how close to ideal performance is, and identifies the causes and locations of thermodynamic losses more clearly than energy analysis [6], [7]. Consequently, exergy analysis can assist in improving and optimizing the design. in their research entitled Exergy analysis of a coal-based 210 MW thermal power plant, found that the main source of irreversibility in the power cycle is the boiler, which contributes to the destruction of exergy by up to 60%. The partial-load operation increased the irreversibility of the cycles, and this effect was more pronounced with load reduction. Increasing the condenser backpressure decreased exergy efficiency [8]–[10]. Successive withdrawals from high-pressure heaters indicate a gradual increase in exergy efficiency for the control volume, excluding boilers, while decreasing exergy efficiency when the entire plant, including boilers, was considered [11]–[13]. Maintaining the main steam pressure before the turbine control valve is in shear mode improves the exergy efficiency in the case of part-load operation [14], [15]. Research by [16] with the title Energy and Exergy Analysis of a Steam Power Plant in Egypt found that energy losses mainly occur in the condenser, with 404,653 MW at maximum load, 306,747 MW at 75% load, and 278,849 MW at 50% load lost to the environment. The percentage ratio of exergy crushing to total exergy destruction was found to be maximum in the turbine system (42% at maximum load, 59% at 75% load, and 46.1% at 50% load), followed by the condenser (28% at maximum load, 20.3 % at

75% load). At 50% load, the feedwater heater showed more exergy damage (27.7%) than the condenser (23.8%) and then the feedwater heater (20.8% at maximum load, 12.1% at 75% load). In addition, the thermal efficiency calculated based on the specific heat input to the steam was 43%, whereas the power cycle exergy efficiency was 44%–48%. The results of the energy analysis show that 69.8% of the total energy lost in the cycle occurs in the condenser as the main energy waste equipment, while the exergy analysis introduces the boiler as the main energy waste equipment where 85.66% of the total energy entering the cycle is lost. Maximum exergy destruction was found to occur in the boiler [17], [18]. Therefore, efforts to improve power plant performance must be directed at improving boiler performance, because this will lead to the greatest increase in plant efficiency[19]–[21]. The purpose of this research is to analyze one unit of steam power plant with coal fuel in terms of exergy which includes destructive exergy so that it is known which equipment experiences the largest energy loss and knows the efficiency value of the equipment used.

II. Methodology

Exergy is energy that can be utilized or a measure of the availability of energy to do work. The exergy of a resource indicates how much work that resource can do in a given environment. The total exergy of a system can be divided into four components, namely physical exergy, potential exergy, kinetic exergy, and chemical exergy, which can be written with the following equation: (Bejan, Tsatsaronis, & Maran, 1996).

$$E^{T} = E^{PH} + E^{KN} + E^{PT} + E^{CH} \quad (1)$$

Exergy is a stationary system relative to the environment such as a steam power plant system has a value of EKN = EPT = 0 so that in calculating the total exergy only physical exergy and chemical exergy are used. Physical exergy is work obtained through a reversible process from the initial temperature and pressure conditions to the conditions determined based on the ambient temperature and pressure.

$$E^{PH} = \dot{m}\,[(hi - ho) - To\,(si - so)] \quad (2)$$

Chemical exergy is exergy associated with changes in chemical compounds. The chemical exergy value can be calculated by:

$$E^{CH} = \dot{m} \times \left(\frac{e^{CH}}{M}\right) \quad (3)$$

For solid fossil fuels containing C, H, O, and N with a mass ratio of oxygen to carbonless than 0.66, the ratio of the specific chemical exergy values can be calculated by the equation:

$$\varphi_{dry} = \left[1{,}0437 + 0{,}1882\left(\frac{H}{C}\right) + 0{,}0610\left(\frac{O}{C}\right) + 0{,}0404\left(\frac{N}{C}\right)\right] \quad (4)$$

Coal chemical exergy value can be calculated by:

$$\varepsilon^{0} = [Ncv + (2442 \times w)] \times \varphi_{dry} + (9{,}417 \times s) \quad (5)$$

so that the chemical exergy value of solid fuel can be calculated by the following equation:

$$E^{CH}{}_{coal} = \dot{m} \times \varepsilon^{0} \quad (6)$$

Destruction exergy is exergy that is destroyed as a result of the inefficiency of a system. The destruction exergy can be found by calculating the difference between the incoming exergy and the outgoing exergy with the following equation:

$$E_{D} = E_{in} - E_{out} \quad (7)$$

Exergy efficiency is the ratio of product exergy to fuel exergy which can be written by:

$$\eta = \left(1 - \frac{E_D}{E_f}\right) \times 100\% \quad (8)$$

Exergetic efficiency indicates the percentage of exergy of the fuel supplied to the system found in the exergy of the product. In addition, the difference between 100% and the actual exergy efficiency value, expressed in percent, is the percentage of fuel exergy that is wasted in this system as exergy annihilation and exergy.

III. Result And Discussion

The coal used for the operation of PLTU 2 x 7 MW has a size of 31.5 – 2.38 mm by 58% and < 2.38 mm by 17%, the majority of which are finely sized not by the recommendations of the American Society of Mechanical Engineers (ASME) which requires a coal size of 32 mm with a maximum mixture of 25% measuring 6 mm for chain grate type boiler stoker operations. The calorific value of coal is 4,021 kcal/kg, with a flow rate of 2,418 kg/s. Data on the value of coal mass fraction according to the ultimate analysis of coal is shown in Table I.

TABLE I. COAL MASS FRACTION

Description	Persentase (%)
Total Moisture	33.89
Ash	5.50
C	42.44
H	3.68
N	0.40
S	0.17
O	13.92

Based on the data in Table I, the chemical exergy values of coal are:

$$\varphi_{dry} = [1.0437 + 0.1882\left(\frac{H}{C}\right) + 0.0610\left(\frac{O}{C}\right) + 0.0404\left(\frac{N}{C}\right)$$

$$\varphi_{dry} = [1.0437 + 0.1882\left(\frac{3.68\%}{42.44\%}\right) + 0.0610\left(\frac{13.92\%}{42.44\%}\right) + 0.0404\left(\frac{0.40\%}{42.44\%}\right)$$

$$\varphi_{dry} = 1.0804$$

$$\varepsilon^{0} = [Ncv + (2442 \text{ x } w)] \text{ x } \varphi_{dry} + (9.417 \text{ x } s)$$

Received: Oct 4, 2023 | Revised: Oct 24, 2023 | Accepted: Oct 30, 2023

ε^0 = [16,823.85 kJ/kg + (2442 x 0.3389)] x 1.0804 + (9.417 x 0.0017)

ε^0 = 19,070.7597 kJ/kg

$E^{CH}_{coal} = \dot{m} \times \varepsilon^0$

E^{CH}_{coal} = 2.418 kg/s x 19,070.7597 kJ/kg = 46,113.0969 kW

The flow chart of the steam power plant is shown in Figure 1. The parameters for the power plant are shown in Table II which shows the enthalpy and entropy values in each state.

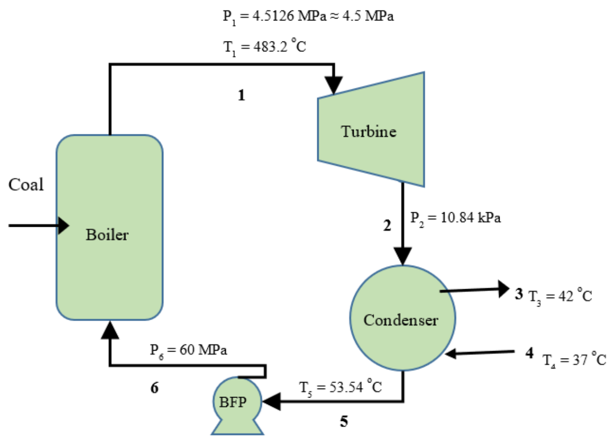

Fig 1. Cycle Diagram of a Steam Power Plant

Figure 1 shows a diagram of a steam power plant that is integrated with a boiler which will later function to heat water with the aim of converting its boiling point into steam. Next, the steam will spin the wheels on the turbine and be passed to the condenser which will eventually enter the BFP until the cycle continues. Then to see the Parameter data of steam power plant in Table II.

TABLE I. PARAMETER DATA OF STEAM POWER PLANT

State	Phase	Temperature, T (ºC)	Pressure, P (MPa)	Entropy, h (kJ/kg)	Entropy, s (kJ/kg K)
1	Steam	483.2	4.5	3,401.3568	6.9801
2	Steam	x=0.8446	0.1084	2,219.6194	6.9801
3	Water	37	-	154.9960	0.5320
4	Water	42	-	175.8940	0.5989
5	Water	53.54	-	224.1514	0.7493
6	Water	-	60	1,213.8000	3.0275
Water at Room Temperature	Water	27	-	113.1940	0.3950

In Table II is the data parameter of the steam power plant where the largest data obtained is the steam data resulting in a temperature of 483.2 ºC, pressure 4.5 MPa, and entropy 3,401.3568 kJ/kg. Then the System Exergy Value data is seen in table 3.

TABLE III. SYSTEM EXERGY VALUE

Stage	Flow rate, $\dot{m}$ (kg/s)	Physical Exergy, E^{PH} (MW)	Chemical Exergy, E^{CH} (MW)	Total Exergy, E (MW)
1	8.84	11.61	0.00	11.61
2	8.84	1.16	0.00	1.16
3	611.11	0.43	1.53	1.96
4	611.11	0.95	1.53	2.47
5	9.06	0.04	0.02	0.07
6	9.06	2.82	0.02	2.84
Coal	2.42	0.00	46.11	46.11

Based on the data in Table II, the Physical Exergy value is calculated by equation (2), then chemical exergy is calculated by equation (3). Furthermore, the total exergy is calculated by equation (1). So that the physical exergy, chemical exergy, and total exergy values obtained from each state, the data are presented in table 3. From the data in table 3, the destruction exergy value is calculated by equation (7), and the exergy efficiency is calculated by equation (8), resulting in the destructive exergy value and exergy efficiency for the turbine, boiler, and condenser equipment as shown in Table IV.

TABLE IV. EXERGY DESTRUCTION VALUE AND EXERGY EFFICIENCY

Equipment	Destructive Exergy, E_D (MW)	Exergy Efficiency, ε (%)
Turbine	10.45	79.10
Boilers	37.34	16.71
Condenser	0.58	99.24

From Table IV it can be seen that the largest destructive exergy value occurs in the boiler of 37.34 MW with an efficiency value of 16.71%, while the smallest destructive exergy value occurs in the condenser of 0.58 MW with an efficiency value of up to 99.24%. The comparison of the destructive value of the exergy is seen more clearly in figure 2 and the efficiency of the exergy in Figure 3.

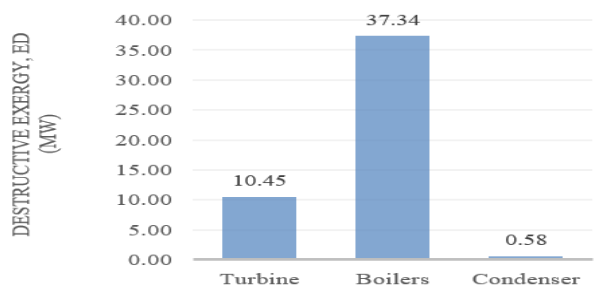

Fig 2. Destructive exergy of steam power plant equipment

Received: Oct 4, 2023 | Revised: Oct 24, 2023 | Accepted: Oct 30, 2023

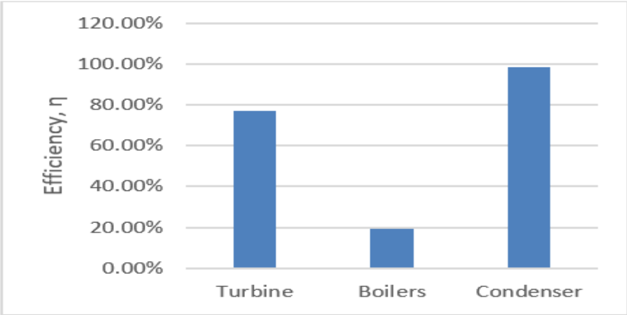

Fig 3. The exergy efficiency of steam power plant equipment

IV. Conclusion

The exergy analysis conducted on a steam power plant with a capacity of 2 X 7 MW that uses coal as fuel where the majority of the coal used is fine in size not by ASME recommendations, that the largest exergy destruction occurs in the boiler, meaning that the largest energy loss occurs in this section with a value of 37.34 MW (16.71%), while the smallest exergy destruction occurs in the condenser of 0.58 MW (99.24%). The results of the exergy efficiency of steam power plant equipment turbine reached 80%, boilers 20% and condenser reached 100%.

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Received: Oct 4, 2023 | Revised: Oct 24, 2023 | Accepted: Oct 30, 2023

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Received: Oct 4, 2023 | Revised: Oct 24, 2023 | Accepted: Oct 30, 2023