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Exergy analysis and Exergetic sustainability index of package boiler

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Abstract
Energy is one of the basic human needs. Economic growth and population growth in a country that continues to increase are directly proportional to society's energy needs. Indonesia is Southeast Asia's largest energy user, with more than 36% of Southeast Asia's primary energy use. Utilization of the energy used will reduce the increase in production costs for an industry. The use of energy is better known as energy conservation. Energy and exergy analysis based on the first and second laws of thermodynamics is used to analyze the thermal system of industrial units. This can be applied to equipment units in the fertilizer industry to identify sources of inefficiency determine their location and the amount of exergy destruction. To reduce exergy destruction, this can be done by modifying the operating conditions of the package boiler. The results show that 94.3% of the total exergy destruction from the boiler package is obtained from the evaporator component with a value of 2.7 x 108 kJ/hr. Modification of the operating conditions of the evaporator is carried out by reducing Boiler Feed Water (BFW) inlet temperature with T 100C (196 – 116℃). The decreased BFW temperature will increase the required latent heat and reduce the convection heat that the flue gas will carry to generate superheated steam. The BFW temperature is optimised by calculating the flue gas temperature and exergoeconomic analysis. Exergoeconomic analysis is performed by calculating the cost rate of exergy destruction (ĊD,k) and exergoeconomic factor (fk). The results obtained were that the temperature optimum of BFW is at 161°C which resulted in the reduction of exergy destruction of 6,2x106 kJ/hr and resulting difference cost losses based on actual data (196℃) of Rp 1,370,354,743/hr. Exergetic Sustainability Index (ESI) is used to demonstrate how reducing a system's environmental impact can be achieved by reducing its exergy consumption (destruction and losses) or increasing its exergetic efficiency. In this research, ESI Value was achieved at 0.918.

Keywords:
Exergy destruction;
Exergoeconomic analysis;
Package boiler;

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INTRODUCTION

According to the National Energy Council's 2019 Indonesian Energy Outlook, Indonesia's energy needs 2025 are predicted to reach 238.8 million tons of barrel oil equivalent (SBM) under the Business as Usual (BaU) scenario. This number will increase to 682.3 million MBS in 2050, assuming an average growth in energy demand during the 2015-2050 period of around 4.9 percent per year [1].

The petrochemical industry is a strategic sector that can stimulate the national economy. This is because the Petrochemical industry plays an important role in encouraging increased production in the agricultural sector, which will support the national food security program in the future. Energy use in the Petrochemical industry is a dominant and vital factor. If energy availability is disrupted, the Petrochemical industry cannot operate normally. Utilization of the energy used will reduce the increase in production costs. One of the units with the highest efficiency reduction in performance is the boiler. The decrease in performance can be measured by how much energy required to run the equipment out is better known as energy conservation [2][3].

Petrochemical plants in Indonesia play a significant role in producing quality fertilizer and boiler equipment as a supporting utility in producing steam. It has two types of boilers as supporting units. One of those two is a package boiler to produce steam, which consists of more than one unit [4]. A thorough review of all the package boiler units will produce accurate energy consumption data.

Energy and exergy analysis based on the first and second laws of thermodynamics is used to analyze the thermal system of industrial units. This can be applied to equipment units in the Petrochemical plant to identify sources of inefficiency and determine their location and the amount of exergy losses. Apart from that, another thing that needs to be considered is determining the most optimal working conditions for the equipment in order to achieve the highest efficiency values.

The study conducted by Costa et al. found that the component that produced the highest exergy destruction value was the combustion chamber, which produced 35.53 MW or 92.2% of the overall exergy destruction [5]. Another research conducted by Ucar et al. shows that the highest exergy destruction occurs in the combustion chamber, with the highest level of exergy destruction at 37.9% of the entire system [6]. Mitrovic et al. found that the component that produced the highest exergy destruction value was the combustion chamber at 288.07 MW or 60.04% of the overall exergy destruction [7]. Oruye et al. also showed that the combustion chamber unit produced the highest destruction value, namely 24.12 MW or 62.18% [8]. This result indicates that energy destruction in the combustion chamber can be reduced by optimizing the combustion process.

Exergy analysis is a medium for identifying the type, location and magnitude of thermal losses. Identifying and qualifying these losses makes it possible to evaluate and improve the thermal system design [9]. The author will research the performance of each unit in the package boiler using an exergy analysis method.

MATERIAL AND METHODS

Exergy Analysis

Exergy is energy that can be utilized (available energy) or a measure of energy availability to do work. Exergy on a resource indicates how much work that resource can do in a particular environment. One of the main functions of the exergy concept is exergy balance in the analysis of thermal systems. Energy balance (exergy analysis) can be viewed as a statement of the energy law of degradation.

The exergy analysis method can show the quality and quantity of heat loss and also the location of energy degradation (measuring and identifying the causes of energy degradation). Most cases of thermodynamic imperfection cannot be detected by energy analysis. Another statement regarding exergy, namely work or the ability to cause work, is always eternal in a reversible process but always reduced in an irreversible process (satisfies the second law of thermodynamics) [10].

The first law of thermodynamics states that energy can neither be created nor destroyed. Energy is available in several different forms and can be converted from one form to another.

The second law of thermodynamics states that energy conversion is only possible as total entropy increases. Based on exergy analysis, energy and entropy can be studied simultaneously. Energy quality is described by the concept of entropy (high entropy means low energy quality). Each different form of energy will produce a different quality of energy and is a theoretical indication of the amount of energy that can be converted into work [11].

Exergoeconomic Analysis

Exergoeconomic analysis combines exergy analysis and economic principles, such as equipment purchase prices, maintenance, operating costs, and other expenses related to thermodynamic inefficiency in total production costs. The results of the exergoeconomic analysis will display cost data from the highest to lowest efficiency levels. So, from these results, the overall design system can be improved.

Exergoeconomic analysis can be done with a calculation of the capital investment rate ($\dot{Z}_k$), followed by a calculation of the Capital Recovery Factor (CRF), cost rate of exergy destruction ($\dot{C}_D$), and the last one calculation of the *exergoeconomic factor* (f_k).

Exergetic Sustainability Index (ESI) Analysis

ESI can be used to measure the quality of a process by considering the principles of conservation of mass and energy. ESI is closely related to sustainable development. A higher ESI value indicates a smaller reduction in resources and environmental impact, or a higher ESI value can indicate a smaller waste ratio and a smaller environmental impact factor. ESI analysis can be done with a calculation of waste exergy ratio (τ) followed by a calculation of Environmental effect factor (γ_{eef}) and the last calculation, the Exergetic Sustainability Index (λ).

Exergy Calculation

Exergy calculation for the Package Boiler can be done with the following steps.

1. The standard value for this calculation

   T_o = 25°C

   $\Delta H_o = C_p$ x T_o

   $\Delta S_o = Q/T_o$

   R = 8,314472 kJ/kmol K

2. The entropy value can be calculated based on the component phase in the stream. The following is a formula for calculating entropy value based on the component phase.

   a. Liquid Entropy

   $$\Delta S = \frac{Q}{T} = \int \frac{Q}{T} = m.C_p\,.\ln\frac{T_2}{T_1}$$

   b. Steam Entropy

   $$\Delta S = \left(\frac{C_p}{R}\ln\frac{T}{T_0} - \ln\frac{P}{P_0}\right) x\ R$$

3. Calculate the value of enthalpy for the stream.

   $$\Delta H = C_p\ \Delta T$$

4. Gibbs energy for stream could be calculated with this following equation.

   $$\Delta G = \Delta H - T_0\,.\Delta S$$

5. The exergy value could be calculated with the following equation.

   $$\varepsilon = (H - H_0) - T_0\,(S - S_0)$$

6. The value of destruction exergy could be calculated with the following equation.

   $$\varepsilon_{dest} = \varepsilon_{in} - \varepsilon_{out}$$

Exergoeconomic Calculation

Exergoeconomic calculation for the Package Boiler can be done with the following steps.

1. Capital investment rate
   $$\dot{Z}_k = \frac{Z_k \,.CRF\,.\,\varphi}{N}$$
2. Capital recovery factor
   $$CRF = \frac{i\,x\,(1+i)^n}{(1+i)^n - 1}$$
3. Cost rate of exergy destruction
   $$\dot{C}_{D,k} = C_{F,k}\,.\,\dot{E}_{D,k}$$
4. E*xergoeconomic factor*
   $$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + \dot{C}_{D,k}}$$

Exergetic Sustainability Index (ESI) Calculation

Exergetic Sustainability Index (ESI) calculation for Package Boiler can be done with the following steps.

1. Waste exergy ratio
   $$\tau = \frac{\dot{E}_{D,k\,(total)}}{\varepsilon_{in\,(total)}}$$
2. Environmental effect factor
   $$\gamma_{eef} = \frac{\tau}{\eta_2}$$
3. Exergetic sustainability index
   $$\lambda = \frac{1}{\gamma_{eef}}$$

Nomenclature:

Q = Heat (Joule)
m = Mass (kg)
ΔH = Enthalpy Change (kJ)
ΔS = Entropy Change (kJ/kmol K)
ΔG = Gibbs Energy Change (kJ/kmol)
Cp = Heat Capacity (kJ/kg ^oC)
ΔT = Temperature Change (^oC)
T = Temperature (K)
To = Initial Temperature (K)
R = Ideal Gas Constant (8,314 J/kmol K)
ε_{dest} = Exergy Destruction (kJ/kmol)
ε_{in} = Exergy Input (kJ/kmol)
ε_{out} = Exergy Output (kJ/kmol)
$\acute{Z}_k$ = Capital Investment Rate, Rp
Z_k = Purchase Equipment Cost, Rp
CRF = Capital Recovery Factor
φ = Maintenance Factor
N = Annual Number of Operation Hours, hrs
i = Interest Rate

n = Equipment Life Time, years
$\dot{C}_{D,k}$ = Cost rate of exergy destruction, Rp
$c_{F,k}$ = Unit exergy cost, (Rp/kJ)
$\dot{E}_{D,k}$ = Exergy Destruction (kJ)
f_k = Exergoeconomic Factor
τ = Waste Exergy Ratio
η_2 = Exergy Efficiency (%)
γ_{eef} = Environmental effect factor
λ = Exergetic Sustainability index (ESI)

RESULTS AND DISCUSSION

Mass Balance and Energy Balance

Exergy analysis can be calculated by first calculating the mass and energy balances. This research used actual data from Boiler Package, which is the average result within one month of operation, namely January 1, 2023 – January 31, 2023. The aim of using actual data is to see the performance of the Package Boiler in accordance with operating conditions in the field so that the analysis results will display data corresponding to the equipment's performance.

The mass balance and energy balance for each Boiler Package component are shown in Table 1, Table 2, Table 3, Table 4, Table 5 and Table 6. The most significant amount of mass and energy for the Boiler Package obtained from the evaporator component was 195,452.837 kg/hour and 291,508,853.752 kJ/hour, respectively.

Table 1. Mass and Energy Balance of Economizer

Compound	Flow rate (kg/hours)		Q (kJ/hours)	
	Input	**Output**	**Input**	**Output**
Boiled Fee Water	92,322.116	92,322.116	40,914,470.164	40,914,470.164
Flue Gas	103,130.721	103,130.721	38,438,073.187	38,438,073.187
Total	**195,542.837**	**195,542.837**	**79,352,543.351**	**79,352,543.351**

Table 2. Mass and Energy Balance of Steam Drum

Compound	Flow rate (kg/hours)		Q (kJ/hours)	
	Input	**Output**	**Input**	**Output**
Saturated Liquid	89,101.484	89,101.484	47,279,674.227	47,279,674.227
Boiled Fee Water	92,322.116	92,322.116	67,390,787.395	67,390,787.395
Total	**181,423.600**	**181,423.600**	**114,670,461.622**	**114,670,461.622**

Table 3. Mass and Energy Balance of Evaporator

Compound	Flow rate (kg/hours)		Q (kJ/hours)	
	Input	**Output**	**Input**	**Output**
Boiled Feed Water	92,322.116	0	67,390,787.395	
Natural Gas	5,997.821	0	224,118,066.357	
Air	97,132.900	0		
Saturated Steam	0	87,706.010	0	47,279,674.277
Blow Down	0	4,616.106	0	3,240,920.941
Flue Gas	0	103,130.721	0	123,400,458.419
Latent	0	0	0	117,587,800.165
Total	**195,452.837**	**195,452.837**	**291,508.853.752**	**291,508.853.752**

Table 4. Mass and Energy Balance of Superheater

Compound	Flow rate (kg/hours)		Q (kJ/hours)	
	Input	**Output**	**Input**	**Output**
Saturated Steam	87,706.010	0	47,290,171.149	0
Superheated Steam	0	87,706.010	0	70,053,473.694
Flue Gas	104,388.137	104,388.137	61,201,375.390	38,438,073.187
Total	**192,089.147**	**192,089.147**	**108,491,546.881**	**108,491,546.881**

Table 5. Mass and Energy Balance of Desuperheater

Compound	Flow rate (kg/hours)		Q (kJ/hours)	
	Input	**Output**	**Input**	**Output**
Saturated Steam	0	9.081.694	0	67,124,138.376
Superheated Steam	87,706.010	87,706.010	70,053,473.694	6,950,502.918
Boiled Feed Water	9,081.694	0	4,021,167.601	0
Total	**96,787.704**	**96,787.704**	**74,074,641.295**	**74,074,641.295**

Table 6. Mass and Energy Balance of Flash Drum

Compound	Flow rate (kg/hours)		Q (kJ/hours)	
	Input	**Output**	**Input**	**Output**
Saturated Liquid	4,616,106	607,551	3,240,201.536	801.974.219
Superheated Steam	0	4,088,555	0	2,438,227.316
Total	**4,616,106**	**4,616,106**	**3,240,201.536**	**3,240,201.536**

Exergy Analysis

Exergy analysis is an initial step in the optimization efforts system. From this analysis, the location of the biggest source of problems can be determined by the system, and then it can be researched further in an effort to optimize the system. Exergy balance calculations aim to determine exergy destruction.

The exergy balance shows the maximum amount of energy that can be utilized by each component in the boiler package to do work in Table 7. The comparison of the input exergy value or energy quality that can be utilized with the output exergy or energy quality that is not utilized will be displayed, and the exergy destruction value for each boiler package component will be compared.

Based on the results of research conducted by Costa et al., it was found that the component that produced the highest exergy destruction value was the combustion chamber of 35.53 MW or 92.2% of the overall exergy destruction [4].

Table 7. Exergy Balance and Exergy Destruction

Component	Exergy (kJ)		Exergy Destruction
	Input	**Output**	
Economizer	24,197,480	17,369,781	6,827,699
Stream Drum	63,632,073	63,632,072	0
Evaporator	385,361,806	118,703,691	266,658,115
Superheater	46,369,882	37,279,352	9,090,530
Desuperheater	21,992,300	21,868,853	123,447
Flash Drum	749,761	683,996	65,765

Other research conducted by Ucar et al. shows that the highest exergy destruction occurs in the combustion chamber, with the highest level of exergy destruction at 37.9% of the entire system [6]. Mitrovic et al. found that the component that produced the highest exergy destruction value was the combustion chamber at 288.07 MW or 60.04% of the overall exergy destruction [7].

Table 7 shows that the evaporator component will obtain the highest exergy destruction value or the highest amount of energy that is not utilized in a system to do work. The results of this research are in accordance with the literature used, where the component that produces the highest exergy destruction value is the evaporator. The highest destruction value resulted from the evaporator component, which amounted to 94.30% of the total exergy destruction of the boiler package. This is because there is chemical exergy in the evaporator, and in other Boiler Package components, there is only physical exergy.

The exergy component in the form of chemical exergy can produce a greater amount of energy than physical exergy. Chemical exergy calculations are carried out when a reaction occurs between fluids in a system, which causes the formation of new compounds or changes in the composition of compounds from the initial state to the final state.

The main causes of high exergy destruction values are combustion reactions, heat transfer, and also friction. These three causes generally occur simultaneously or simultaneously in the combustion chamber in the evaporator component. This causes a significant increase in the exergy destruction value of the evaporator component compared to other components. This results in the highest amount value of exergy destruction in the evaporator compared to other components. Table 7 will be displayed in graphical form in Figure 1. The following is to make it easier to determine the components with the highest exergy destruction in the Boiler Package.

Modification of Boiler Feed Water Temperature

One solution that can be done to reduce the value of exergy destruction in the evaporator component is to reduce the temperature of the boiler feed water. Reducing the BFW temperature will reduce the evaporator input exergy value. This will cause a decrease in the value of exergy destruction. Reducing the BFW temperature also aims to increase the utilization of energy produced from burning natural gas, where the reduction in BFW temperature will be inversely proportional to the latent heat value. Research conducted by Bhaskaran states that reducing the BFW temperature will reduce losses that occur in the system [12].

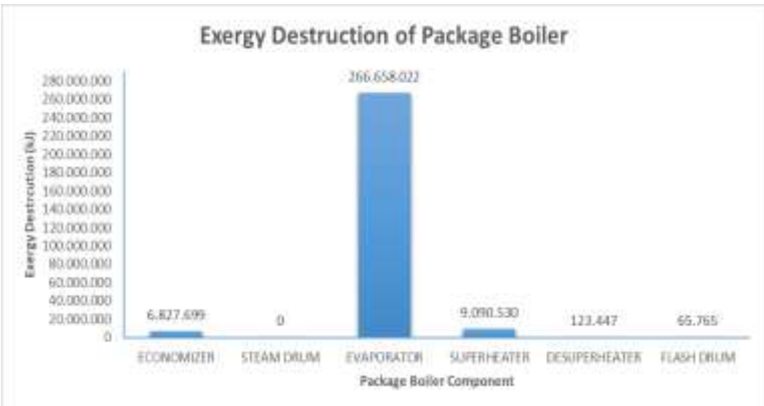

Figure 1. Exergy Destruction Chart of Package Boiler

Latent heat value states the amount of energy needed to generate BFW into saturated steam so that the evaporation process with a low BFW temperature will require greater energy, or in other words, the energy from burning natural gas can be utilized more efficiently.

The BFW input temperature will be reduced in the temperature range of 106-196°C with a ΔT of 10°C. Figure 2 shows that decreasing the BFW input temperature will further reduce exergy destruction. Actual data, at the BFW input temperature of 196 °C, the exergy destruction is 266 x 10^6 kJ and at the lowest BFW input temperature modification is 106 °C, and the exergy destruction is 252 x 10^6 kJ. On these results, it can be stated that there was a decrease in exergy destruction of 14.1x10^6 kJ or 5.3% of the actual data.

These results can be compared with the modification to reduce the amount of excess air carried out by Pattanayak et al. which resulted in a reduction in exergy destruction of 3.9% [13]. Based on the results of this reduction, it can be stated that modification of the BFW input temperature on the evaporator component will have a more significant effect on reducing exergy destruction compared to modification to reduce the amount of excess air.

Exergoeconomic Analysis

Exergy analysis can state exergy damage that causes a loss. The value of these losses will be easier to understand if expressed in economic terms. Table 8 will display the costs wasted due to exergy destruction and the value of exergoeconomic factors.

Based on Table 8, it can be stated that the exergoeconomic factor (f_k) value of the evaporator component is relatively small. It's stated that the cost rate of exergy destruction ($\dot{C}_{D,k}$) will have a significant effect on the economic value produced compared to the value of the capital investment rate ($\acute{Z}_k$)so that the exergoeconomic optimization can be carried out by reducing the value of exergy destruction, namely by reducing the input temperature BFW evaporator components.

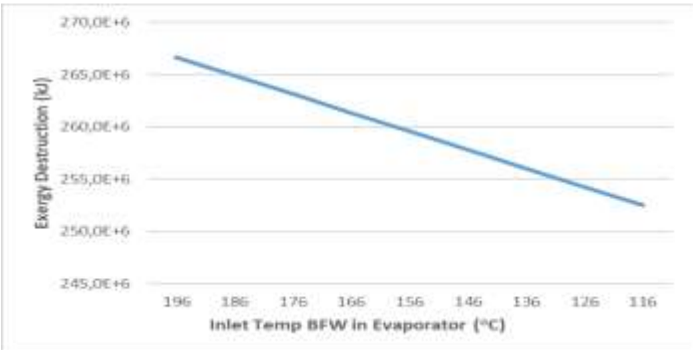

Figure 2. Temperature BFW Reduction versus Exergy Destruction

Table 8. Exergoeconomic Analysis Calculation

T BFW (°C)	Exergy Destruction (kWh)	$C_{D,k}$ (Rp.)	f_k
196	74,071.758	4,444,305.468	0.445
186	73,579.091	4,414,745.442	0.447
176	73,086.449	4,385,186.954	0.448
166	72,593.808	4,355,628.978	0.450
156	72,101.166	4,326,069.978	0.452
146	71,608.525	4,296,511.490	0.453
136	71,115.883	4,266,953.003	0.455
126	70,623.242	4,237,394.515	0.457
116	70,130.600	4,207.836.027	0.459

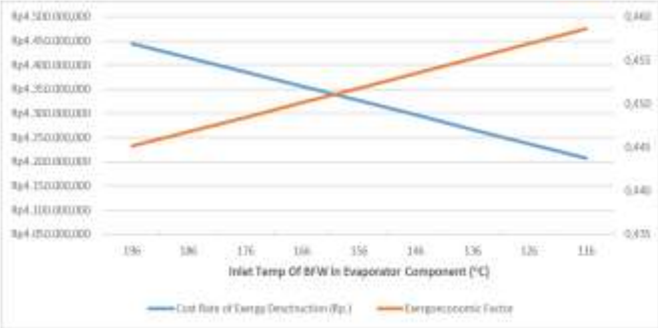

Figure 3. BFW Temp Reduction against Cost rate of Exergy Destruction ($\dot{C}_{D,k}$) and Exergoeconomic Factor (f_k) Chart

Table 9. Waste exergy output and exergy destruction

Waste Exergy Ratio (τ)	Environmental Effect Factor (γ_{eef})	Exergetic Sustainability Index (λ)
0.5214	1.089	0.918

Exergoeconomic optimization is carried out to determine the optimum BFW input temperature of the evaporator component based on exergy and economics. Figure 3 displays the relationship between reducing the BFW input temperature of the evaporator component and exergoeconomic optimization. Based on Figure 3, it can be stated that exergoeconomic optimization is obtained at the BFW input temperature of the evaporator component of 161°C with the resulting loss difference based on actual data (196°C) amounting to IDR 74,488,497.087/month.

Exergetic Sustainability Index (ESI) Analysis

In determining the Exergetic Sustainability Index (ESI) analysis, the waste exergy ratio must first be determined, namely the fraction of total exergy destruction compared to the total exergy entering the system and the environmental effect factor which shows whether waste exergy output and exergy destruction can cause damage to the environment as listed in Table 9.

The greater the efficiency value, the smaller the waste exergy ratio and Environmental Effect factor, and this can result in a greater Exergetic Sustainability Index (ESI), and vice versa. The range of this index is from 0 (zero) to infinity.

By lowering the waste exergy ratio and Environmental Effect factor, the Exergetic Sustainability Index (ESI) will be higher, thereby increasing the efficiency and sustainability of the boiler package. In this case, it can be seen that the efficiency of the package boiler is below 50%, and this is in accordance with the results of exergy destruction, which is quite large [14][15].

CONCLUSION

The results concluded that as much as 94.30% of the exergy destruction to Package Boiler occurred in the evaporator component. This is due to the presence of chemical exergy components which produce high exergy values, so reducing exergy destruction can be achieved by reducing the amount of evaporator input exergy, namely by reducing the Boiler Feed Water (BFW) input temperature. On this research results state that the lower the BFW input temperature on the evaporator component, the lower the resulting exergy destruction.

This causes optimization of the BFW input temperature to be carried out by calculating the temperature of the flue gas output from the evaporator. Based on this, optimum operating conditions are obtained at a BFW temperature of 161°C with a reduction in exergy destruction of 92.11% or 2.19% and a reduction in losses of IDR 35,504,937,278,749/year or 2.33% of the actual data (196°C)

Based on data for the waste exergy ratio with current conditions, the value obtained is 0.5214, and the environmental effect factor is 1.089, resulting in an environmental sustainability index (ESI) value of 0.918. The greater ESI value indicates that the system is more efficient due to the less exergy lost.

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