International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 5, pp 388-393, May-2025

https://doi.org/10.47001/IRJIET/2025.905043

Exergy Analysis of Boiler System Fueled by Palm Shell and Palm Fiber in Medium-Scale Palm Bunch Processing Capacity to Become Crude Palm Oil

[1]Daniel Pasaribu, [2]*Muhammad Nur, [3]Muchammad

[1]Master of Energy, Graduate School, Diponegoro University, Semarang, Indonesia
[2]Professor, Department of Physics, Diponegoro University, Semarang, Indonesia
[3]Professor, Department of Mechanical Engineering, Diponegoro University, Semarang, Indonesia
*Corresponding Author's E-mail: nur.cpr@gmail.com

***Abstract* - Boiler is one of the important components in meeting the steam needs of a production process in industry. Increasing boiler efficiency requires precision of thermodynamic characteristics and performance. This can be reviewed more completely with exergy analysis. Exergy analysis is needed to determine the amount of work loss in a machine or system. In the calculation of exergy, heat capacity data is needed. Therefore, the mass entering the boiler from the fuel is in the form of chemical compounds, so to calculate the heat capacity, calculations need to be made based on the chemical substances contained in the compound. The analysis that will be carried out in this study is to provide resources and energy utilization in the boiler system so that the mass, energy, and exergy balance values can be determined. Based on the calculation results, the boiler efficiency value is 68.71. For the heat efficiency values of 98.59%, 86.97%, and 52.83%. The efficiency of the Second Law of Thermodynamics is 16.81%, 21.21%, with a heat interaction effectiveness value of 0.005% while the exergy efficiency value is 85.51% with an exergetic efficiency value of 97.09% and 17.86%. To optimize the performance of the boiler work system, it can be done by increasing the combustion air temperature which is attempted as high as possible by operating the kiln close to maximum capacity (60% -90%).**

Keywords: Boiler, Thermodynamics, Efficiency, Energy, Exergy.

I. INTRODUCTION

Boilers are one of the important components in meeting the steam needs of a production process in industry. In the palm oil industry, boilers are the systems that consume the most energy so that there will be many factors that can be done to optimize the boiler system. This is because of the many studies that have been done on the function of the boiler. To increase the efficiency of the boiler system, precision is needed in terms of thermodynamic characteristics and performance. This is usually reviewed more completely with exergy analysis.

Exergy is a thermodynamic property that depends on the form of the energy process and the state of its environment. Every system that is not in equilibrium with its environment has an exergy value. If a system is in equilibrium with its environment, then the system has an exergy of zero. Exergy with a value of zero has no ability to do work on its environment.

By using this method, a real picture will be obtained of the magnitude of the loss of a system, what are the causes and where the loss is located in the system, so that improvements can be made to the work system as a whole or to its components only.

Figure 1: Boiler

The analysis that will be conducted in this study is to evaluate the use and utilization of energy in the boiler system

ISSN (online): 2581-3048
Volume 9, Issue 5, pp 388-393, May-2025
https://doi.org/10.47001/IRJIET/2025.905043

so that the mass, energy, and exergy balance values can be determined. In addition, this study also evaluates the exergetic efficiency value in the boiler system so that it can be used as a reference for optimization in the boiler system.

II. METHODOLOGY

Exergy analysis in this study was carried out in several stages, namely entering the required data, including: thermodynamic properties of air, air and steam used for research, temperature, pressure, mass flow rate, O2 and CO2 content, feed water content, boiler water, and fuel.

In this study, the data used to disseminate and analyze are sourced from:

A. Secondary data sources, are supporting analysis data that can provide data, be it historical operational data, references related to the boiler system, or laboratory test data.
B. Primary data sources, namely data obtained from logsheets, observation results, or direct measurements in the field. The primary data include:
    - Fuel consumption data (tons/hour)
    - Discharge data (kg/hour), including: combustion air, feed water, exhaust gas, production steam, and bottom ash
    - Temperature data (oC), including: combustion air, feed water, exhaust gas, production steam, and boiler surface
    - Pressure data (bar), including: combustion air, feed water, exhaust gas, and production steam

In general, this data collection is used to measure or assess the performance of the boiler system, especially regarding the temperature and loading conditions of the boiler. In this study, researchers use data used to measure the extent to which the boiler system performs against actual loading conditions and the variables that influence it.

In addition, this study is also intended to provide the magnitude of the exergy damage value that occurs under operating conditions so that a picture of the parameters that cause exergy damage to the boiler system is obtained.

To complete the energy balance calculation, the step that must be taken is to find the energy equation in a system. This energy equation is used to obtain a strategy in completing the energy balance calculation. The equation that is widely used to complete the energy balance calculation is the equation that is often listed in the First Law of Thermodynamics, namely:

$$\dot{Q} - \dot{W}_X = \frac{dE_{CV}}{dt} + \sum_{inflow} \dot{m}_e \left[h_e + \frac{(V_m)_e^2}{2} + gZ_e \right] - \sum_{outflow} \dot{m}_i \left[h_i + \frac{(V_m)_i^2}{2} + gZ_i \right] \quad (1)$$

The above equation can be simplified to:

$$\dot{Q} - \dot{W}_X = \sum_e \dot{m}_e h_e - \sum_i \dot{m}_i h_i \quad (2)$$

The energy equation for a reaction system is also stated in the First Law of Thermodynamics.

$$\dot{Q} - \dot{W}_X = \sum_p \dot{N}_i \bar{h}_i (T_p, P) - \sum_R \dot{N}_i \bar{h}_i (T_R, P) \quad (3)$$

As long as the flow of mechanical energy (or work) performs rotation whose exergy can be measured, the exergy is automatic work converted into an exergy flow of the same value. Thus, the work flow (W) is proportional to the exergy flow.

$$x_w = W \quad (4)$$

Exergy measurement for heat flow value can be calculated by knowing the previously known heat flow value. The exergy value in heat flow can be determined as follows:

$$x_Q = \left(1 - \frac{T_O}{T_{surface}} \right) Q \quad (5)$$

When the exergy of an ideal gas system is evaluated, a simple approach is to use a formula that describes the change in properties. Thus the exergy value of an ideal gas system is.

$$x_{ideal\ gas} = m c_p T_o \left(\frac{T}{T_o} - 1 - \ln \frac{T}{T_o} \right) + m R T_o \left(\frac{P_o}{P} - 1 - \ln \frac{P}{P} \right) + m R T_o \left(\frac{P_o}{P} - 1 - \ln \frac{P}{P} \right) \quad (6)$$

III. RESULTS AND DISCUSSIONS

Boiler efficiency is a measure of the boiler's ability to meet a given steam demand with a given amount of fuel. To build a boiler with very little or no heat loss is very expensive, therefore boiler efficiency is always less than 100%.Based on these data, the boiler efficiency value based on operating conditions using the direct method.

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 5, pp 388-393, May-2025

https://doi.org/10.47001/IRJIET/2025.905043

Table 1: Boiler Efficiency

Temperature (°C)		Pressure (bar)		Steam	Entalpy (Steam Table)		Output Energy (kJ/jam)
Feedwater T_{in}	Steam T_{out}	Feedwater P_{in} (kg/cm^2)	Steam P_{out} (kg/cm^2)	m (kg/h)	Feed Water h_{in} (kJ/kg)	Steam h_{out} (kJ/kg)	
84	215	1	20.0	3,058	352.80	2,800.50	7,485,067
Input Energy			BOILER EFFICIENCY: DIRECT METOD				
Fuel:			Efficiency =	(Output Energy x 100%)/(Input Energy)			
Consumption (kg/h)	(GCV) (kcal/kg)	Energy (E_{in}) kJ/h		68.71	(%)		
			Excess Air =	3,76 x %O_2 x 100/(100 - %CO_2 -4,76 x %O_2) =			69.86%
743.00	3,491	10,894,015	% O_2 =		8.3	%CO_2 =	15.82

The composition of the fuel also has an effect on the efficiency of the boiler. The difference in combustion in various types of fuel is caused by the different hydrogen content in each fuel, so that the water vapor content in the combustion gas is also different. The greater the ratio between hydrogen atoms and carbon in the fuel, the more air will be produced in the combustion reaction. The more air is produced, the greater the energy needed to evaporate it so that the heat available to generate water vapor is reduced. The following is an illustration of the composition of the fuel consumed by the boiler.

Table 2: Fuel Composition

Component	*M* (kg/kmol)	Mass Flow (kg/h)	Mass Fraction (%)	Molar Flow (kmol/h)	Molar Fraction (%)
C	12	334.57	45.03	0.04	0.00
H_2	2	35.66	4.8	0.06	0.01
O_2	32	152.76	20.56	0.21	0.03
N_2	28	3.86	0.52	7.25	0.98
S	32	44.13	5.94	0.73	0.10
H_2O	18	72.07	9.7	0.25	0.03
Ash	-	99.93	13.45	-	
Total	-	**743**	**100**	**8.52**	**1.15**

Component	*M* (kg/kmol)	Mass Flow (kg/h)	Mass Fraction (%)	Molar Flow (kmol/h)	Molar Fraction (%)
CaO	56	32.74	32.76	0.59	0.59
MgO	40	0.87	0.87	0.02	0.02
SiO_2	60	30.06	30.08	0.50	0.50
Al_2O_3	102	26.64	26.66	0.26	0.26
Fe_2O_3	160	9.62	9.63	0.06	0.06
Total		**99.93**	**100**	**1.43**	**1.43**

The calculation of the mass balance in the boiler is divided into two parts, namely the mass input and mass output. The mass input consists of feed water, fuel and air while the mass output consists of exhaust gas from baking, blow down and steam products. From the results of the calculation of the mass entering and the mass leaving the boiler, the results of the mass balance in the boiler can be known. The results of the mass balance in the boiler are as follows.

Table 3: Mass Balance

Input Mass	**Value**	
1. Feed Water	29,470.00	kg/h
2. Fuel	743.00	kg/h
3. Air Combustion (Primary)	39.35	kg/h
4. Air Combustion (Secondary)	39.35	kg/h
Total	**30,291.70**	**kg/h**
Output Mass	**Value**	
1. Flue Gas	369.80	kg/h
2. Steam	29,350.00	kg/h
3. Blowdown	120	kg/h
4. The Neglected Mass	451.91	kg/h
Total	**30,291.70**	**kg/h**

In the calculation of the energy balance in the boiler, heat capacity data is needed which is adjusted to the phase form of the substance. Heat capacity data can be obtained from several literatures related to heat capacity. Energy calculations in the boiler are in the form of sensible heat, combustion heat, reaction heat, formation heat, convection heat, radiation heat, FD fan motor power and feed water pump power. The energy entering and leaving the boiler is in the form of sensible heat, heat reaction, motor work, heat loss due to convection, and heat loss due to radiation.

From the results of calculating the energy input and output from each component, the energy balance value can be seen in the following table.

Table 4: Energy Balance

INPUT:	**Value**	
1. Feed Water	37,815.61	kW
2. Feed Water Pump	75.00	kW
3. Air Combustion (Primary and Secondary)	0.23	kW
4. FD Fan (Primary and Secondary)	60.00	kW
5. Fuel	2,621.02	kW
6. Heat of Combustion	3,014.59	kW
Total	**43,586.46**	**kW**
OUTPUT:	**Value**	
1. Flue Gas	(219,190.41)	kW
2. Steam	2,977.52	kW
3. Blowdown	722.90	kW
4. Convection and Radiation	11.60	kW
5. Heat of Reaction	(258,941.45)	kW
Total	**43,463.06**	**kW**

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048

Volume 9, Issue 5, pp 388-393, May-2025

https://doi.org/10.47001/IRJIET/2025.905043

Neglected heat = (43,586.46 – 243,463.06) kW
= 123.40 kW
= (1,123.40 /43,586.46) × 100%
= 0.328%

Exergy analysis is needed to determine the amount of work loss in a machine or system. In the calculation of exergy, heat capacity data is needed. Because the mass that enters the boiler is in the form of fuel that has chemical compounds, then to calculate the heat capacity is done based on the chemical name of the compound.

Exergy input can be determined if the work done by the boiler in a process, the amount of net work on the system is equal to the exergy input to the system. Likewise, as long as the calculation of the motor work performed on the system shows the flow of exergy to the system can be considered as exergy entering a process. The exergy leaving the boiler is in the form of boiler exhaust gas exergy, combustion dust exergy, exergy lost due to convection and radiation, steam exergy (product), blowdown exergy, and exergy used for reactions in the boiler.

From the results of the calculation of exergy input and output from each component, the exergy balance value in the boiler is as follows.

Table 5: Exergy Balance

Input:	Value	
Feedwater	622.72	kW
Fuel	2,891.17	kW
Air Combustion	0.0006	kW
Fan Power	135.00	kW
Total	**3,648.89**	kW
Output:	**(kW)**	kW
Flue Gas	(32.84)	kW
Dust	3.84	kW
Steam	613.22	kW
Blowdown	43.29	kW
Convection and radiation	0.57	kW
Reaction	2,920.17	kW
Total	**3,548.25**	kW

Neglected exergy = (3,648.89 – 3,548.25) kW
= 100.64 kW
= (100.64 /3,648.89) × 100%
= 2.76%

The efficiency of fuel use in boilers varies from one to another, depending on the type of boiler and the process used. Boilers are basically a solid gas heat exchanger whose flow is opposite and much of the energy produced is wasted. Basically the problem of heat loss is related to the design of the plant.

Thermal efficiency in boilers:

a. Theoretically (based on energy balance calculations)

$$\eta_1 = \frac{\text{Input Energy} - \text{Lost Energy}}{\text{Output Energy}} \times 100\%$$

$$= \frac{43{,}586.46 - (11.60 + 722.90)}{43{,}463.06} \times 100\%$$

$$= 98.59\%$$

b. Industry (based on fuel consumption)

$$\eta_1 = \frac{\text{Fuel Energy} - \text{Lost Energy}}{\text{Fuel Energy}} \times 100\%$$

$$= \frac{(2.621.02 + 3{,}014.59) - (11.60 + 722.90)}{(2{,}621.02 + 3{,}014.59)} \times 100\%$$

$$= 86.97\%$$

c. Based on products produced

$$\eta_1 = \frac{\text{Steam Energy}}{\text{Fuel Energy}} \times 100\%$$

$$= \frac{2{,}977.52 - (11.60 + 722.90)}{(2{,}621.02 + 3{,}014.59)} \times 100\%$$

$$= 52.83\%$$

The efficiency of the Second Law of Thermodynamics shows the conversion of energy based on whether the input energy is useful or not. The concept of exergy is used to determine the effectiveness of a system in doing work. The effectiveness of a system is the ratio of the actual useful work produced to the reversible or useful work. Effectiveness which is also called the Second Law of Thermodynamics efficiency can be considered as a practical measure of doing work.

The efficiency of the Second Law of Thermodynamics in a boiler can be determined based on several things.

a. In theory (based on exergy calculations)

$$\eta_2 = \frac{\text{Exergy of Steam}}{\text{Input Exergy}} \times 100\%$$

$$= \frac{613.22}{3{,}648.89} \times 100\%$$

$$= 16.81\%$$

ISSN (online): 2581-3048
Volume 9, Issue 5, pp 388-393, May-2025
https://doi.org/10.47001/IRJIET/2025.905043

b. Industry (based on fuel consumption)

$$\eta_2 = \frac{\text{Exergy of Steam}}{\text{Exergy of Fuel}} \times 100\%$$

$$= \frac{613.22}{2{,}891.17} \times 100\%$$

$$= 21.21\%$$

In the case of energy transfer in the form of heat, the efficiency of the Second Law of Thermodynamics is the ratio of the amount of heat used to the heat transferred, so the effectiveness of the heat interaction is:

$$\eta_2 = \frac{\text{Exergy of Convection and Radiation}}{\text{Heat Loss of Convection and Radiation}} \times 100\%$$

$$= \frac{0.00057}{11.60} \times 100\%$$

$$= 0.005\%$$

Three definitions of exergetic efficiency for steady state processes are conventional or simple exergetic efficiency, rational exergetic efficiency, and utilized exergetic efficiency.

Traditional exergetic efficiency is the ratio of the total exergy flow out to the total exergy flow in.

$$\eta_e = \frac{\sum X_{output}}{\sum X_{input}} \times 100\%$$

$$= \frac{3{,}542.59}{3{,}648.89} \times 100\%$$

$$= 97.09\ \%$$

Rational exergetic efficiency is defined by Kotas (1985) as the ratio of the desired output exergy (product exergy) to the exergy used or consumed. Rational exergetic efficiency can be applied to any system, with the expectation that it is naturally lost from the system.

$$\eta_R = \frac{X_{\text{desired output}}}{X_{\text{used}}} \times 100\%$$

$$= \frac{X_{(\text{flue gas+dust+steam+blowdown})}}{X_{(\text{feedwater}+ fuel + air\ combustion)}} \times 100\%$$

$$= \frac{-32.84 + 3.84 + 613.22 + 43.29}{622.72 + 2{,}891.17 + 0.0006} \times 100\%$$

$$= 17.86\%$$

Brodyansky, Sorin relates the useful exergy coefficient. This form of efficiency is an improvement on traditional exergy efficiency, since it reduces the inflow and outflow components that remain unchanged.

$$\eta_u = \frac{X_{\text{output}} - X_{\text{transferred}}}{X_{\text{input}} - X_{\text{transferred}}} \times 100\%$$

$$= \frac{(3{,}542.59 - 2{,}915.08)}{(3{,}648.89 - 2{,}915.08)} \times 100\%$$

$$= 85.51\%$$

IV. CONCLUSION

Based on the results of the calculations and analysis carried out, it can be concluded that the mass balance obtained the value of the feed water to steam ratio. The feed water used was 29,470 kg/hour and the clinker produced was 29,350 kg/hour, so the value of the feed water to steam ratio was 1.004 kg of feed water/kg of steam. This price is still in accordance with the ratio value limit, namely 1.2-1.5 kg of feed water/kg of steam.

The maximum efficiency of a boiler does not occur at full load but at about two-thirds of full load. As the load on the boiler decreases, the efficiency also tends to decrease. At zero output, the boiler efficiency is zero, and any amount of fuel used only adds to the losses.

REFERENCES

[1] Abin Babu, Abuthahir K.A., Rohith P.M., Rahul Unnikrishnan, (2017), *"Exergy Destruction and Optimization of Industrial Boiler at BPCL"*, International Journal of Novel Research in Engineering and Science, Vol. 3, Issue 2, pp: (1-9), ISSN 2394-7349.

[2] Cengel, Yunus A., and Michael, Boles A., (1989), "*Thermodynamics: An Engineering Approach*", International Edition, Mc Graw Hill.

[3] Feriyanto Mandila Pallea, Belyamin, dan Paulus Sukusno, (2019), *"Analisis Eksergi Pada Boiler & Turbin Uap Pembangkit Listrik Tenaga Uap Subcritical 315 MW"*, Prosiding Seminar Nasional Teknik Mesin, Politeknik Negeri Jakarta, 1153-1159, ISSN 2085-2762.

[4] Francis Chinweuba Eboh, Peter Ahlström and Tobias Richards, (2017), *"Exergy Analysis of Solid Fuel-Fired Heat and Power Plants: A Review"*, Energies, 10, 165.

International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048
Volume 9, Issue 5, pp 388-393, May-2025
https://doi.org/10.47001/IRJIET/2025.905043

[5] G. U. Akubue, S. O. Enibe, H. O. Njoku and G. O. Unachukwu, (2014), *"Exergy Analysis of a Steam Boiler Plant in a brewery in Nigeria"*, International Journal of Scientific & Engineering Research, Volume 5, Issue 5, ISSN 2229-5518.

[6] Holman J.P, (1991), "*Perpindahan Panas*", Edisi Keenam, Erlangga.

[7] Jawed Ahmed Jamali et. al., (2017), *"Energy and Exergy Analyses of Boiler and its Parts of Lakhra Coal Power Plant (FBC) Jamshoro"*, Noble International Journal of Scientific Research, ISSN(e): 2521-0246, ISSN(p): 2523-0573, Vol. 01, No. 10, pp: 104-111.

[8] Kameyama H., Yoshida K., Yamauchi S., and Fueki K., (1982), Evaluation of Reference Exergies For The Elemen, "*Applied Energy11*", p. 69-83.

[9] Koestoer Artono Raldi, (2002), "*Perpindahan Kalor*", Edisi Kesatu, Salemba Teknika.

[10] Krishan Kumar et. al., (2015), *"Performance and Exergy Analysis of Boiler"*, International Journal of Science and Research (IJSR), Volume 4 Issue 6, ISSN (Online): 2319-7064.

[11] Muhamad Difa Dharmakusuma, Belyamin, dan Widiyatmoko, (2020), *"Analisis Eksergi Pada Boiler PLTU"*, Jurnal Mekanik Terapan, Vol. 01 No. 01, Hal. 045-053.

[12] Mukesh Gupta, Raj Kumar, (2014), *"Exergoeconomic Analysis of a Boiler for a Coal Fired Thermal Power Plant"*, American Journal of Mechanical Engineering, Vol. 2, No. 5, 143-146.

[13] M. K. Pal, Anil Kumar, and H. Chandra, (2013), *"Energy And Exergy Analysis Of Boiler And Turbine Of Coal Fired Thermal Power Plant"* International Journal of Engineering Research & Technology (IJERT), ISSN: 2278-0181, Vol. 2 Issue 6.

[14] Pherry R. H., (1984), "*Pherry's Chemical Engineer's Handbook*", 6th Edition, McGraw Hill.

[15] Piyush D. Dudharejiya, H. A. Vaidya, (2014), *"Energy And Exergy Analysis Of Boiler In Thermal Power Plant"*, IJSRD-International Journal for Scientific Research & Development, Vol. 2, Issue 03, ISSN (online): 2321-0613

[16] Sajjad Arefdehgani, Omid Karimi Sadaghiyan,(2015), *"Boiler Parametric Study of Thermal Power Plant to Opproach to Low Irreversibility"*, American Journal of Energy Engineering; 3(4): 57-65.

[17] Sarang J. Gulhane, Amit Kumar Thakur, (2013), *"Exergy Analysis of Boiler In cogeneration Thermal Power Plant"*, American Journal of Engineering Research (AJER), Volume-02, Issue-10, pp-385-392, e-ISSN: 2320-0847, p-ISSN: 2320-0936.

[18] William, Reynolds C. and Henry, Perkins C., (1982), "*Engineering Thermodynamics*", Department of Mechanical Engineering, Marquette University, 1515 W. Wisconsin Ave., Milwaukee, WI 53233, 2nd Edition.

[19] Yazici et. al, (2021), *"Identifying The Improvement Possibilities of A Fluidized bed Boiler With Exergy Analysis"*, Journal of Engineering Sciences and Design, 9(3), 911-922, e-ISSN: 1308-6693.

Citation of this Article:

Daniel Pasaribu, Muhammad Nur, & Muchammad. (2025). Exergy Analysis of Boiler System Fueled by Palm Shell and Palm Fiber in Medium-Scale Palm Bunch Processing Capacity to Become Crude Palm Oil. *International Research Journal of Innovations in Engineering and Technology - IRJIET*, 9(5), 388-393. Article DOI https://doi.org/10.47001/IRJIET/2025.905043

****