Journal of Engineering and Applied Technology
Vol. 6, No. 2, August 2025, pp. 62-75

Online ISSN 2716-2265
Printed ISSN 2716-2257

Energy and Exergy Analysis of Coal-Fueled Fire Tube Alstom Boiler Using Direct Method: Case Study at Garment Factory

Septian Trikusuma[1], A.A.P. Susastriawan[2], Toto Rusianto[2]

[1]Postgraduate Student of Mechanical Engineering, AKPRIND University, Indonesia
[2]Postgraduate School of Mechanical Engineering, AKPRIND University, Indonesia
E-mail: Strikusuma@gmail.com *
* Corresponding Author

ABSTRACT

This research analyses the energy and exergy efficiency of a coal-fired fire-tube Alstom boiler operating for five years (2019–2024) in a garment factory using the direct method. Energy efficiency reflects how effectively coal energy is converted into steam, while exergy efficiency assesses the portion of that energy available for useful work. Results indicate a decline in energy efficiency from 75.92% in the first year to 65.47% in the fifth year due to scale buildup, increased heat loss through blowdown and flue gas, and component degradation. Similarly, exergy efficiency dropped from 24.45% to 22.00%, primarily due to heat loss from boiler walls and steam pipes, high-temperature flue gas, and combustion inefficiencies. A temporary efficiency increase in the fourth year resulted from improved maintenance, but the decline continued in the fifth year. These findings emphasise the need for regular maintenance and combustion optimisation. Measures such as routine cleaning, fuel quality monitoring, and thermal insulation improvements can mitigate energy losses and enhance efficiency. Implementing these strategies can sustain or improve energy performance, contributing to industrial sustainability through more efficient energy consumption.

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ARTICLE INFO

Article history
Received:
04 July 2025
Revised:
23 September 2025
Accepted:
02 October 2025

Keywords:
boiler,
energy,
efficiency,
exergy,
direct method

1. Introduction

The garment industry is one of the fastest-growing manufacturing sectors in Indonesia and plays a strategic role in supporting national exports. To support the production process well, this industry is highly dependent on the continuous operation of various support machines, one of which is a steam boiler. Boilers function as a vital component in power generation systems that produce steam as a heating medium, particularly for ironing and drying purposes in the garment manufacturing process [1]. Among the various types of boilers, fire-tube boilers are often chosen by medium-sized industries because of their simple design, relatively low investment costs and ease of operation and maintenance [2], [3]. The garment company that is the object of study in this research has been operating a coal-fired fire-tube steam boiler for more than five years. During that period, the boiler was used intensively for about 330 days per year. This long-term use is very likely to cause a decrease in efficiency due to scale accumulation, fouling, and suboptimal combustion settings [4], [5], [6].

With the increasing industrial need for energy efficiency, several studies have been conducted to analyse boiler efficiency using direct and indirect method approaches [2], [6]-[15]. For example, the study by Wicaksana et al. (2023) [2] at PT Petrocentral Gresik evaluated the efficiency of natural gas-fired fire tube boilers. Other studies by Kharisma and Budiman (2020) [13] at PT Indofood Sukses Makmur Bogasari Flour Mills Division and by Aprilia (2021) [11], Shahab & Amna (2023) [14] and Alifa et al. (2024) [8] on boilers in the oil, gas and manufacturing sectors contributed to the understanding of energy efficiency in different industrial contexts.

However, energy efficiency alone is not sufficient to describe the overall thermodynamic performance of a boiler. Therefore, an exergy analysis approach becomes important to assess the extent to which the available energy is actually being optimally utilised. This analysis provides a more complete picture by considering energy quality as well as losses due to process imperfections based on the second law of thermodynamics. Many studies have applied this approach, such as those conducted by Yohana et al. (2018) [3] on a Wanson I-type fire tube boiler, and Heroza & Pratoto (2022) [16], who studied the utilisation of flue gas heat in the power generation system at PT Semen Padang. In addition, various other studies have also investigated the exergy efficiency of boiler systems in the power generation sector [17] - [26]. These studies have made significant contributions to the understanding of energy efficiency and exergy, but most are sectoral, limited to certain types of industries, and based on short-term operational data.

Although there have been many studies on boiler efficiency, there are limitations to research that combines energy efficiency and exergy analysis simultaneously, especially for firetube boilers in the garment industry. In addition, no study has been found that uses operational data over a long period of time, such as five years, to thoroughly analyse the thermodynamic performance of the boiler. Therefore, this study aims to fill the gap by analysing the energy efficiency and exergy of coal-fired firetube boilers used in the garment industry using a direct method based on operational data for five years (2019-2024). This approach is expected to provide new insights into the long-term performance of boilers in the context of the garment industry, while identifying potential energy and exergy efficiency improvements that can be implemented to improve the sustainability and competitiveness of the industry.

2. Method

2.1. Description of Boiler Machine

The object of this research is a coal-fired fire tube steam boiler, where the coal is burned on a moving chain grate. The boiler used has a capacity of 10 tons per hour. The boiler specifications can be seen in Table 1.

Table 1. Specification of Boiler Machine

Information	Specification
Manufacturing	Velde Boilers and Plants GmbH
Production Year	2018
Made in	Germany
Model	HD6243-10,0
Serial Number	22418
Max. Steam Output	10 t/h
Max. Allowable Pressure	10 bar
Test Pressure	18,5 bar
Volume	34800 liter
Max. Steam Temperature	185 ^{0}C

The working principle of this boiler operates on a 3-pass system, as shown in Fig. 1:

- First pass: The combustion flame and hot gases move toward the rear of the boiler through the furnace tube into the reversal chamber.
- Second pass: The hot gases then travel from the reversal chamber through the fire tubes (smoke tubes) toward the front of the boiler, transferring heat to the surrounding water until they reach the front reversal chamber.

- Third pass: From the front reversal chamber, the hot gases move back toward the rear through the fire tubes, continuing to transfer heat to the water before finally exiting the boiler.

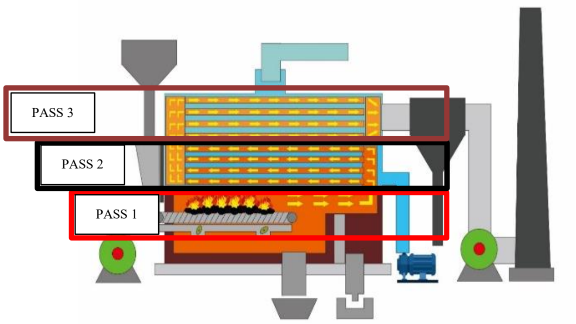

Fig.1 Schematic Flow of 3-Pass Boiler Operation

The 3-pass system ensures optimal heat transfer efficiency from the hot gases to the water inside the boiler. The boiler's heat efficiency highly depends on the condition and cleanliness of the components responsible for heat transfer during steam generation. Therefore, maintaining boiler cleanliness is crucial, both on the water side and the fire side. The condition of the water side is determined by feed water treatment, the frequency of blowdowns, and periodic or annual cleaning of the water chamber. Meanwhile, the fire side can be maintained through the regular use of a soot blower and annual cleaning, which involves brushing the internal surfaces with a wire brush.

Fig. 2 illustrates the overall schematic of the boiler operation. Initially, large coal is crushed into smaller pieces using a crusher machine. The crushed coal is then transported by a conveyor to the coal bucket. Next, the coal bucket moves up to the coal feed hopper, which is approximately 9 meters high, where the coal is poured into the hopper. The guillotine door functions to control the amount of coal entering, allowing the thickness to be adjusted as needed. The coal then enters the combustion chamber, carried by the moving chain grate.

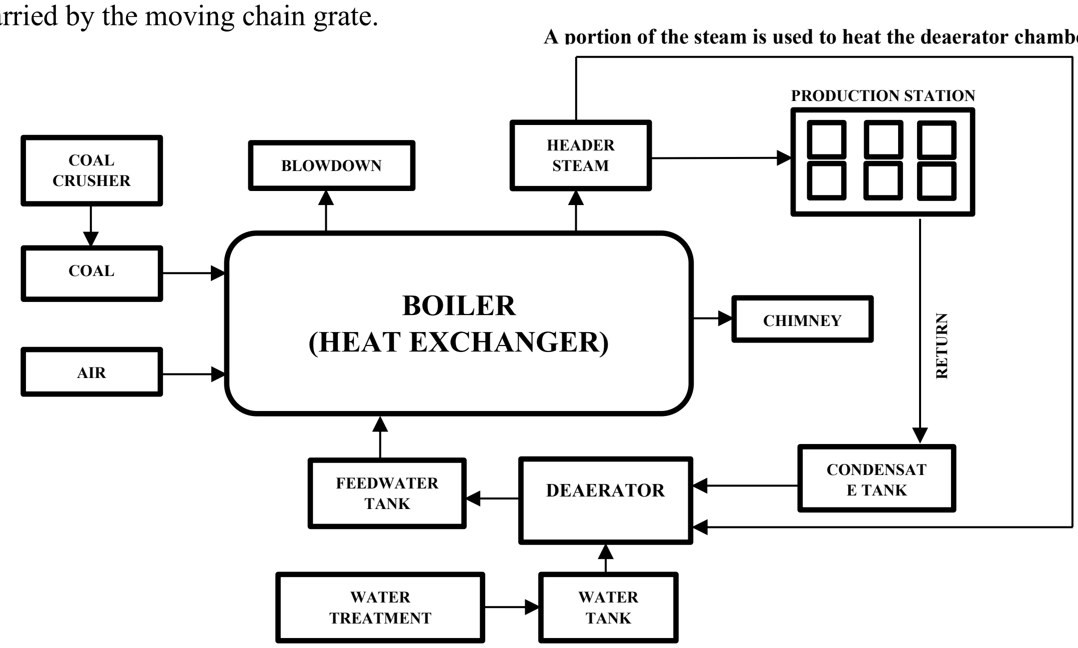

Fig. 2. Overall Schematic of Alstom Fire Tube Boiler Operation

The Forced Draft (FD) Fan blows air into the system to enhance the combustion process, intensifying the fire and transferring heat. Meanwhile, the Induced Draft (ID) Fan acts as an exhaust system, drawing airflow so that the combustion heat can be transferred to the boiler's fire tubes before being released outside. On the other hand, feedwater enters the system after undergoing a softening process in the water treatment softener. After softening, the water is stored in a water tank before being sent to the deaerator. Inside the deaerator tank, the water temperature is increased, making it hot and ready to be transferred to the feedwater tank before finally entering the boiler. This process helps accelerate the evaporation process. The water entering the boiler drum is heated by combustion heat, initiating the heat exchange process. As the water heats up, it transforms into steam, which is then directed to the header and production area. A portion of the steam is also used to heat the deaerator chamber. Additionally, the remaining steam from production is sent to the condensate tank to be reused in the deaerator chamber. To maintain the condition of the components inside the boiler, a blowdown system is implemented. Meanwhile, the flue gases from combustion are expelled through the chimney.

2.2. Data Collection

This research employs a data collection technique that combines qualitative and quantitative methods. The qualitative method is applied through interviews and document analysis, while the quantitative method utilises statistical data. Interviews are conducted by engaging informants who respond to support the research objectives. Document analysis is used to complement the study with written or visual sources, such as images. Meanwhile, the statistical data used generally comes from third parties with authority in data collection and management.

2.3. Coal Fuel

Coal is a fossil fuel derived from plant material and is abundant across various islands in Indonesia. In this country, different types of coal are marketed with varying compositions, depending on their region of origin and the types of plants that once grew in those areas. To achieve the boiler's designed capacity, coal with high calorific value or heat content is required. However, coal with a lower calorific value can also be used as fuel, although it may reduce the boiler's capacity. The specifications of the coal used in the studied boiler can be seen in Table 2.

Table 2. Coal Specification

Specification	**Year**	
	2020	**2021**
Moisture (%)	11.4	5.4
Ash Content (%)	8.0	13.3
Volatile Matter (%)	39.9	40.8
Fixed Carbon (%)	40.7	40.5
Total Sulfur (%)	0.90	1.08
Gross Calorific Value (kCal/kg)	5714	6313
Gross Calorific Value (kJ/kg)	23907	26414

Source: Coal Testing Results by a Third Party at Garment Factory

2.4. Boiler Operational Parameter Over Five Years

Operational parameters serve as a guideline for determining the key aspects to be observed in this study. The operational parameters presented in Table 3 data on flow rate, pressure, and temperature for each of the components listed below. These data are used as the basis for calculating enthalpy and entropy to determine the energy and exergy efficiency of the boiler. The following are the operational parameters used in this research:

Table 3. Boiler Operational Parameters Over Five Years (0ct 2019 – Sept 2024)

Period	Coal Use (kg/h)	FW. Temp. (°C)	Steam Output (kg/h)	Steam Press. (bar)	Steam Temp. (°C)	Flue Gas Temp. (°C)	Enthalpy Feedwater (kCal/kg)	Enthalpy Steam (kCal/kg)	Entropy Steam (kJ/kgK)	Flue Gas Flowrate (kg/h)	Blowdown Flowrate (kg/h)
First Year	560.14	66.64	4081.26	6.59	163.27	197.73	67.02	659.90	6.73	5640.96	508.09
Second Year	568.11	72.55	4172.87	6.77	163.18	198.83	72.03	659.90	6.73	5762.97	521.02
Third Year	608.09	74.09	4263.70	7.11	166	201.55	74.03	660.62	6.70	6134.76	532.59
Fourth Year	620.5	76.45	4498.73	7.5	169.82	201.91	76.03	661.34	6.68	6304.46	559.76
Fifth Year	629.69	75.36	4452.56	7.49	169.82	202.55	75.03	661.34	6.68	6393.47	556.29

2.5. Data Analysis Tool

The software used as an alternative for data processing in the energy and exergy efficiency analysis of the coal-fueled fire tube boiler is Microsoft Excel. Microsoft Excel is a software developed and distributed by Microsoft Corporation. This application is widely used for data processing as it supports the automatic use of functions and formulas. Its simple user interface facilitates the analysis process, making data processing more efficient and user-friendly.

2.6. Formula of Enthalpy and Entropy

The enthalpy and entropy can be obtained using the steam table found in the engineering thermodynamics textbook. The required boiler operation data over five years includes feedwater temperature to determine feedwater enthalpy, Steam temperature to determine steam enthalpy, and Ambient temperature to determine entropy values. However, the steam table has limitations in providing specific data at the actual boiler operating temperatures. Therefore, the author performs interpolation calculations to obtain more accurate values. The interpolation formula used is as follows:

$$Interpolation\ y = y1 + \left(\frac{X - X_1}{X_2 - X_1}\right) . (y2 - y1) \quad (1)$$

where y is the interpolated value (temperature), y_1 is the enthalpy or entropy value at the lowest temperature, y_2 is the enthalpy or entropy value at the highest temperature, X is the desired temperature value, X_1 is the lowest temperature value, and X_2 is the highest temperature value.

2.7. Formula of Energy Efficiency

The direct method calculates boiler efficiency based on the ratio between the energy contained in the steam and the energy supplied through the fuel. The formula is as follows:

$$Energy\ Efficiency = \left(\frac{Q \times (hv - hw)}{q \times GCV}\right) x\ 100\% \quad (2)$$

where Q is the steam flow rate (Kg/h), *hv* is the steam enthalpy (Kcal/Kg), *hw* is the water enthalpy (Kcal/Kg), *q* is the fuel flow rate (Kg/h), and GCV is the gross calorific value of fuel (Kcal/Kg).

2.8. Formula of Exergy

Exergy efficiency measures how effectively a boiler converts energy resources into useful exergy. Boiler exergy efficiency is generally lower than energy efficiency due to irreversibilities such as heat loss, friction, and combustion imperfections. This efficiency is formulated as the ratio of output exergy(E_x^{steam}) to input exergy(E_x^{in}):

$$Exergy\ Efficiency = \left(\frac{E_x^{steam}}{E_x^{in}}\right) x\ 100\% \quad (3)$$

where input exergy $\left(E_x^{in}\right)$ is usually derived from fuel (e.g., coal) and determined by the fuel's calorific value and combustion conditions. Output exergy (E_x^{steam}) primarily related to the thermal energy supplied to the working fluid (water or steam) at a specific pressure and temperature.

Here are some formulas for determining values related to boiler exergy:

- Input Exergy $\left(E_x^{in}\right)$
  The input exergy in a boiler generally comes from the fuel. The formula is:
  $E_x^{in} = q \text{ x } \beta \text{ x } GCV$ ………………………..……………………...……………………...……(4)

  where q is the fuel flow rate (kg/s), GCV is the gross calorific value of fuel (kJ/kg), and β is the chemical exergy factor of coal is given by (0,90 – 1,08)

- Steam Exergy (E_x^{steam})

  The output exergy from the boiler is in the form of the generated steam exergy:

  (E_x^{steam})= Q x $[(h_{steam} - h_0) - T_0 \cdot (S_{steam} - S_0)]$ ……………………………………………....(5)

  where Q is the steam flowrate (kg/s), h_{steam} is the specific enthalpy of steam (kJ/kg), h_0 is the specific enthalpy of water at ambient conditions (kJ/kg), S_{steam} is the specific entropy of steam (kJ/kg°K), S_0 is the specific entropy of water at ambient conditions (kJ/kg°K), and T_0 is the ambient temperature.

- Exergy Losses in the Chimney
  The calculation of exergy losses through the boiler chimney is carried out using equation (6), where, mfg is the flue gas flow rate.
  $E_{x,chimney} = mf_g \text{ x } [(h_g - h_0) - T_0 \text{ x } (S_g - S_0)]$……………………………………………………(6)

- Exergy Loss due to Irreversibility
  The value of exergy loss due to irreversibility ($E_{x,loss}$) can be calculated using equation (7).
  $E_{x,loss} = E_{x,in} - (E_{x,steam} + E_{x,chimney})$………………………………………………………….(7)

- Exergy Loss due to Blowdown
  To calculate the exergy loss caused by blowdown, parameters such as blowdown flow rate, blowdown enthalpy and entropy, and ambient temperature are required. Use equation (8) to calculate the blowdown exergy, where m_{bd} is the blowdown flow rate.
  $E_{x,bd} = m_{bd} \text{ x } [(h_{bd} - h_0) - T_0 (S_{bd} - S_0)]$ ……………………………………………………….(8)

- Exergy Loss Ratio
  The exergy loss ratio is calculated to measure the amount of exergy destroyed within the system using equation (9).
  $Rasio\ Kerugian\ Eksergi = \left(\frac{E_x^{loss}}{E_x^{in}}\right) x\ 100\ \%$...(9)

3. Results and Discussion

3.1. Energy and Exergy Efficiency

Based on the data in Table 4, there is a noticeable trend of declining energy efficiency and exergy efficiency in the boiler system over five years of operation. This decline reflects the degradation of the boiler's thermal performance, which commonly occurs due to fouling, component wear, or irregular maintenance practices.

Table 4. Energy and Exergy Efficiency Boiler Over 5 Years of Operation

Energy and Exergy Efficiency Boiler Over 5 Years of Operation (2019 – 2024)				
Period	**Coal Use (Kg/h)**	**Steam Output (Kg/h)**	**Energy Efficiency (%)**	**Exergy Efficiency (%)**
First Year (2019-2020)	560.14	4081.26	75.87	24.45
Second Year (2020-2021)	568.11	4172.87	70.61	23.00
Third Year (2021-2022)	608.09	4263.70	65.45	21.65
Fourth Year (2022-2023)	620.50	4498.73	66.66	22.42
Fifth Year (2023-2024)	629.69	4452.56	65.47	22.00

Fig. 3 shows a declining trend in the average energy efficiency of the boiler over five years of operation. In the first year (2019–2020), the energy efficiency reached 75.87 %, and the exergy efficiency was 24.45 %. These values reflect optimal operating conditions, as the boiler was still new, free from scale buildup, and combustion performance was relatively stable. This finding is consistent with other studies, which state that initial boiler efficiency is generally high because the system has not yet experienced thermal degradation or deposit accumulation [27], [28], [29], [30].

However, in the second year (2020–2021), the energy efficiency decreased to 70.61% and the exergy efficiency to 23.00 %. This decline can be attributed to the initial formation of fouling layers on the heat transfer surfaces, as well as imperfections in the combustion process. The gradual decrease in boiler efficiency typically begins with minor fouling that is not promptly addressed [31], [32], [33]. The most significant performance decline occurred in the third year (2021–2022), marked by a drop in energy efficiency to 65.45 % and exergy efficiency to its lowest point of 21.65%. This occurred despite the fact that the coal used during this period had a high calorific value of 6,313 kcal/kg, which should have supported optimal heat transfer. The sharp decline indicates the worsening accumulation of fouling over time. Fouling — deposits or contaminants adhering to heat transfer surfaces — severely affects the effectiveness of heat transfer within the boiler. The presence of scale, dirt, or deposits on the pipe surfaces hinders heat transfer from combustion gases to the water inside the boiler. This condition leads to an increase in flue gas temperature, ultimately contributing to greater heat loss from the system [15].

Fouling in boilers can occur in two main areas: first, inside the fire tubes of the boiler due to coal combustion dust adhering to the tube walls; and second, on the outer surface of the fire tubes or parts of the boiler that are in direct contact with water. The second type of fouling generally forms due to poor water quality, which can be indicated by the Total Dissolved Solids (TDS) value. The higher the TDS level, the greater the potential for scale or deposit formation on pipe surfaces. To address this issue, the blowdown process is implemented as a form of preventive maintenance. Blowdown aims to discharge a portion of the water from the system to control TDS concentration, thereby preventing scale formation on pipe walls. However, the blowdown process also results in exergy losses because it discharges part of the energy still contained in the steam water. This loss further contributes to the reduction of both thermal and exergy efficiency of the overall boiler system [34].

In the fourth year (2022–2023), a slight improvement was observed: energy efficiency increased to 66.66 %, and exergy efficiency rose to 22.42 %. This improvement was attributed to maintenance actions or cleaning of the heat exchanger. This aligns with findings from other researchers, who state that a lack of preventive maintenance accelerates scale formation in heat exchanger components and leads to decreased efficiency [3], [6]. However, the improvement did not last long. In the fifth year (2023–2024), energy efficiency declined again to 65.47 %, and exergy efficiency dropped to 22.00 %, indicating that without intensive and continuous maintenance, the effects of previous improvements are only temporary. The lower exergy efficiency compared to energy efficiency suggests significant exergy losses, caused by various factors such as combustion inefficiencies, heat losses through the boiler walls, and steam pipe surfaces [25], as well as exergy losses through the chimney caused by high flue gas temperatures [23], [35], which indicates that there is still exergy potential remaining in the flue gas.

Compared to other research, the boiler efficiency obtained in this research still falls within a reasonably good range. A study conducted by Shahab & Amna (2023) [14] reported a boiler efficiency of 48.15 % using the direct method, which is significantly lower than the results of this study. This indicates that the boiler analysed in the present research demonstrates better performance in effectively generating thermal energy. Meanwhile, the study by Kharisma and A. Budiman (2020) [13] recorded a fire-tube boiler efficiency of 87 %, which is higher than the first-year efficiency in this study, at 75.87 %. Similarly, Aprilia and Hardjono (2021) [11] reported an efficiency of 84.71 %, and Wicaksana et al. (2023) [2] reported 86 %, both showing higher efficiency figures compared to the present study. These differences are most likely due to factors such as operational conditions, maintenance practices, and the age of the boilers used in each study. The decline in energy efficiency observed in this study may also be associated with the aging of the boiler, as well as potential scale accumulation, decreased combustion performance, or other factors affecting heat transfer in the system. Compared to the study by Aprilia and Hardjono (2021) [11], which demonstrated that regular maintenance can maintain high boiler efficiency, the findings of this study highlight the need to evaluate maintenance strategies to improve long-term energy efficiency.

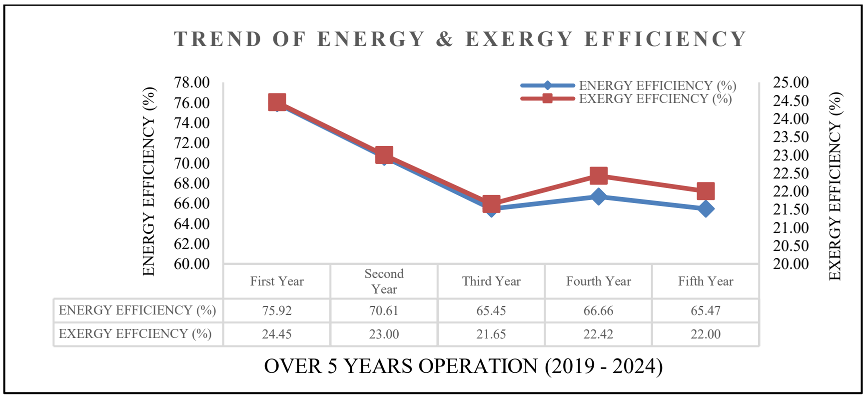

Fig. 3. The Trend of Energy and Exergy Efficiency Boiler Over Five Years of Operation

In addition, in terms of exergy efficiency, the results of this study show higher values compared to the findings reported by Yohana et al. (2018) [3], who recorded a boiler exergy efficiency of 13.29 % at PPSDM Migas Cepu. However, the exergy efficiency values in this study remain lower than those

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reported by Dharmakusuma et al. (2020) [36], who achieved an exergy efficiency of 34.62 %, and by Omara et al. (2024) [23], who reported an overall power plant system exergy efficiency of 34.1 %. Furthermore, Wulandari & Basri (2022) [37] reported a significantly higher exergy efficiency of 53.94 %, indicating that their system performance was still in optimal condition. These variations in results may be attributed to several factors, such as the type of boiler used, operational conditions, maintenance practices, and the quality of the fuel.

3.2. Fuel Consumption and Steam Output

Fig. 4 presents two types of charts: a bar chart showing the average coal consumption over five years of operation, and a line chart illustrating steam production by the boiler during the same period. Based on calculations using the direct method, boiler performance data from 2019 to 2024 was obtained. There is a clear upward trend in average coal consumption, increasing from 560.14 kg/hour in the first year to 629.69 kg/hour in the fifth year. However, this increase in fuel consumption was not accompanied by a significant rise in steam output. Steam production showed only minor fluctuations, with the highest output of 4,498.73 kg/hour recorded in the fourth year, which then declined to 4,452.56 kg/hour in the fifth year. Notably, in the third year, there was an indication of reduced energy conversion performance in the boiler, marked by high coal consumption without a corresponding increase in steam production.

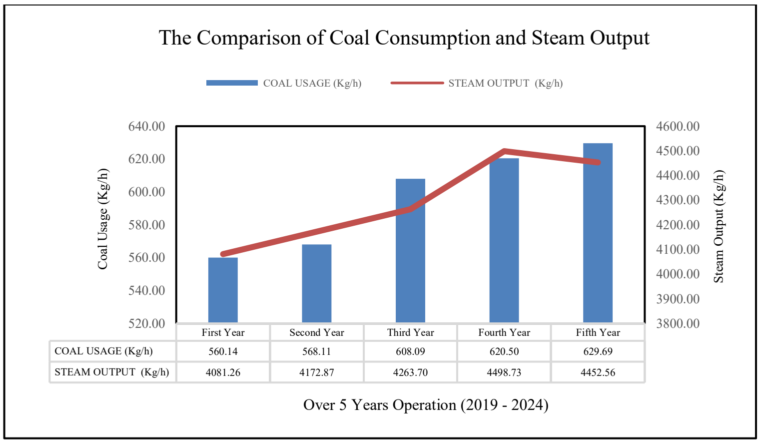

Fig. 4. The Comparison of Coal Consumption and Steam Output Boiler Over Five Years of Operation

The chart in **Fig. 4** reinforces earlier findings from the analysis regarding the decline in energy and exergy efficiency over the five-year operating period. This indicates that accumulated performance degradation due to fouling, reduced combustion quality, and heat losses has directly affected the boiler's ability to convert the chemical energy of coal into thermal energy in the form of steam. These findings are important as a basis for evaluating system maintenance and improvement, as well as for supporting decision-making in future operational optimisation.

3.3. Exergy Boiler

Table 5 presents the average exergy values of the boiler over five years of operation. Exergy loss data indicate that irreversibility (exergy destruction) is the main contributor to the low efficiency of the system. Exergy loss due to irreversibility increased from 2,481.41 kW in the first year to 3,215.92 kW in the fifth year, reflecting a rise in entropy caused by imperfect combustion and increasingly inefficient heat transfer. Exergy loss through the chimney also rose, from 62.42 kW to 74.31 kW, indicating higher flue gas temperatures due to suboptimal heat transfer—likely caused by fouling on the heat exchanger surfaces. This aligns with the findings of Aghapour Sabagh et al. (2023), who stated that an increase in flue gas temperature is a direct indicator of fouling that impedes heat conduction.

Table 5. The Average Exergy Values of The Boiler Over Five Years of Operation

Period	Exergy Flue Gas (Chimney) (kW)	Exergy Irreversibility (Ex loss) (kW)	Exergy Blowdown (kW)	Exergy Output (kW)	Exergy Input (kW)	Exergy Ratio (%)
First Year	62.42	2481.41	8.11	823.06	3366.89	73.70
Second Year	64.37	2767.28	8.32	844.93	3676.58	75.25
Third Year	71.09	3099.55	8.51	874.82	4045.47	76.59
Fourth Year	73.84	3152.05	8.94	931.48	4157.38	75.80
Fifth Year	74.31	3215.92	8.88	925.84	4216.07	76.23

Meanwhile, exergy loss through blowdown remained relatively stable, increasing slightly from 8.11 kW to 8.88 kW, which is consistent with the nature of blowdown as a process that removes saturated water and dissolved solids. The exergy loss ratio also showed an increase, from 73.70 % to 76.23 %, indicating that a large portion of the input energy could not be effectively converted into steam.

The data findings from the boiler over five years of operation highlight the importance of enhancing the monitoring of operational parameters, particularly in efforts to improve exergy efficiency. One strategic step that can be taken is the optimisation of the combustion process through the implementation of real-time monitoring systems for combustion chamber temperature, airflow, and flue gas flow. In addition, other necessary measures include routine boiler cleaning to reduce fouling formation, optimisation of the combustion system to minimise irreversibility, monitoring of fuel and feedwater quality, and the implementation of regular preventive maintenance. All of these actions should be integrated into a sustainable energy management system to maintain optimal boiler performance over the long term. One of the main limitations of this study is the unavailability of data related to airflow rate, flue gas flow, and combustion chamber temperature, due to the absence of measuring instruments on the corresponding components in the boiler system. Therefore, the author estimated these parameters manually using available secondary data and then calculated them using relevant equations. This approach may reduce the precision of the exergy efficiency analysis, as heat losses cannot be monitored comprehensively and accurately. Hence, future studies are recommended to incorporate a more comprehensive and well-instrumented measurement system in order to obtain more accurate and representative results of the actual operating conditions.

4. Conclusion

The energy and exergy efficiency analysis of the coal-fueled fire tube Alstom boiler at the garment factory has been performed using the direct method. It can be concluded that:

The boiler's energy efficiency exhibited a declining trend from the first to the fifth year of operation. In the first year, the average energy efficiency reached 75.92 %, but it gradually decreased to 65.47 %

in the fifth year. The main factors contributing to this decline include: Accumulation of scale on heat transfer surfaces, increasing thermal resistance and Increased heat loss through radiation and flue gases. The highest energy efficiency over the five-year period occurred in the first year, peaking at 78.13 % in October 2019. However, as the boiler aged, energy efficiency continued to decline, reaching its lowest point in the fifth year at 61.66 % in November 2023. The boiler's exergy efficiency was consistently much lower than its energy efficiency. The average exergy efficiency over five years ranged from 24.45 % (first year) to 22.00 % (fifth year). The low exergy efficiency indicates that a significant portion of the energy entering the boiler degraded into unusable energy due to: Heat loss through the boiler walls and piping system, Exergy loss through flue gases that still contain potential energy, and Imperfect combustion processes leading to energy wastage.

Although coal consumption increased annually (from 560.14 kg/h in the first year to 629.69 kg/h in the fifth year), this increase did not always correspond directly to a proportional rise in steam output. This indicates that as more energy was consumed, energy losses within the system also grew due to factors such as scale buildup and declining equipment performance.

In the fourth year, energy efficiency experienced a slight improvement compared to the third year, rising from 65.45 % to 66.66 %. This increase was likely due to better maintenance or more stable operational conditions, such as improvements in combustion processes and reduced scale accumulation. In the fifth year, energy efficiency declined again to 65.47 %, while exergy efficiency also dropped to 22.00 %. This suggests that the boiler's performance continued to deteriorate due to increasing irreversibilities within the system, which were also associated with the aging of the boiler unit.

Acknowledgment

The authors would like to express their sincere gratitude to Universitas AKPRIND Indonesia for their support throughout this research. Special thanks are also extended to the Garment Factory for their valuable guidance and assistance during the course of this study. Lastly, we express our appreciation to the reviewers for their constructive feedback, which has helped improve the quality of this manuscript.

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