

Energy, Exergy and Cost of Exergy Destruction for Coal-Fired Boiler in the Beverage Industry

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ABSTRACT

This paper performs an energy and exergy analysis based on data obtained from selected boilers in the beverage industry. The boiler output is 16 tons/h with a pressure of 8 bar, and the steam output is saturated vapor. A boiler is designed for coal - fired fuel (sub-bituminous coal) with an economizer (heat exchanger) for recovered waste heat. This study aims to illustrate the energy, exergy, energy efficiency and exergy efficiency of the boiler, to identify the energy and exergy effect, including the exergy destruction costs of various loads. The data observation and recording have been made under the Thailand climatic conditions during the year 2023. The results indicated that the maximum energy and exergy efficiencies were approximately 87.98% and 27.45%, respectively, at 100% boiler load, while the minimum energy and exergy efficiencies were approximately 58.82% and 18.16%, respectively, at 25% boiler load. The highest exergy destruction, about 24,447,952 kJ/h, was also observed at 100% boiler load. The results demonstrated that as the boiler load increased, both energy and exergy efficiencies increased accordingly. The cost analysis revealed that the maximum cost of per hour was estimated at 4,323 ฿ for 100% boiler load. The analysis results confirmed that the boiler load is a major parameter influencing the overall performance of the boiler.

1. Introduction

Energy is a fundamental driver of economic development and social well-being, supporting industrial activity, technological progress, and essential services in modern societies. However, the energy sector also represents the largest source of global greenhouse gas emissions. Rapid population growth, urbanization, and technological advancement continue to drive a steady increase in global energy demand, while fossil fuels remain the dominant source of primary energy despite the accelerating deployment of renewable technologies such as solar and wind power [1–6]. This continued reliance on fossil fuels creates persistent challenges in balancing energy security, economic growth, and environmental sustainability. Recognizing these challenges, the United Nations introduced the Sustainable Development Goals (SDGs), which emphasize improved energy efficiency, reduced dependence on fossil fuels, and the transition toward cleaner and more sustainable energy systems [7, 8]. Nevertheless, thermal processes in industry and power generation remain heavily dependent on conventional fuels, particularly coal and natural gas. These processes consume large amounts of energy and are responsible for significant environmental impacts, including greenhouse gas emissions and air pollution. As a result, improving the efficiency of thermal systems remains a critical priority in efforts to reduce environmental burdens while ensuring reliable energy supply. To achieve this objective, exergy analysis has emerged as an essential complement to conventional energy analysis. While energy analysis based on the first law of thermodynamics focuses on the conservation of energy,

it does not account for energy quality or the ability of energy to perform useful work. Exergy analysis, grounded in the second law of thermodynamics, addresses this limitation by quantifying irreversibility and identifying where and how useful energy potential is destroyed within a system [9–15]. This approach enables a more comprehensive evaluation of system performance and provides valuable insights into the sources of inefficiency. Numerous studies have applied energy and exergy analyses to fossil fuel-based thermal systems and have consistently identified boilers, turbines, and combustion chambers as the primary contributors to exergy destruction. These studies also indicate that both energy and exergy efficiencies generally decline at lower operating loads [16–23]. Consequently, energy and exergy analyses have been widely used to assess performance, guide system optimization, and identify improvement opportunities across thermal power plants in various countries [24–28]. These findings underscore the importance of optimizing fossil fuel-based thermal systems to reduce exergy losses and environmental impacts while maintaining operational reliability.

This study examines the energy and exergy performance of coal-fired boilers used in the beverage industry, where thermal energy demand in Thailand's food sector accounts for approximately 60–80% of total industrial energy consumption. Boilers operating within the food and beverage sector represent 39.79% of all industrial boilers and contribute nearly 71% of the national steam production capacity (78,432 tons/h). Previous studies consistently indicate that both energy and exergy efficiencies increase with

higher boiler loads, and the findings of the present study confirm a similar trend. A review of the Thai literature reveals that no prior research has comprehensively evaluated energy efficiency, exergy efficiency, and the economic cost of exergy destruction for coal-fired boilers specifically in the beverage industry. This study was therefore conducted to address this research gap. The analysis was performed using the Direct Method, which enables accurate determination of overall energy efficiency, exergy efficiency, and total exergy destruction with relatively low uncertainty. However, due to data limitations, this approach does not permit detailed assessment of component-level losses. This limitation is acknowledged, and the results are intended to provide a foundation for future investigations focusing on detailed loss distribution and performance improvement strategies. A comprehensive breakdown of individual subsystem losses would require application of the Indirect Method, involving additional measurements, data collection, and instrumentation to evaluate specific operating parameters. This presents a valuable opportunity for further research.

2. System description, analysis and methodology

The food industry requires fuel in its production processes. One common form of energy used for heating the production process is steam, which is produced from the boiler. Currently, coal is the primary fuel used in boilers within the food industry. This is because coal is a fuel with a low price per unit of heat (Cost per MJ). This affordability is the motivation for entrepreneurs to invest in changing the type of fuel used in the steam production system from liquid fuels such as heavy oil or diesel oil to solid fuels such as coal in large quantities [29]. However, when considering the energy efficiency and exergy efficiency, the value will be lower than steam production from boilers using gas and liquid fuels. This is due to the lower combustion efficiency of solid fuels, this means that the amount of heat energy that must be feed into the steam production system will be higher. Additionally, the use of coal contributes to environmental pollution and carbon dioxide (CO₂) emissions, which are major contributors to global warming. Due to the high energy consumption of the food and beverages industry in Thailand, according to the Thailand Energy Efficiency Situation 2023 [30] is conducted by the Department of Alternative Energy Development and Efficiency (DEDE), is an organization under the Ministry of Energy of Thailand, the heat energy used in the food industry is as high as 60-80% of the total energy used in the factory (in MJ).

Currently, the price of the above fuels has increased, affecting production costs. Therefore, some entrepreneurs have switched to using solid fuels, such as coal or biomass, which will significantly reduce the cost of heat energy. However, solid fuels have a greater impact on the environment due to their low combustion efficiency, which requires more fuel. Therefore, the importance of the steam production system has been recognized by conducting a study to find the energy efficiency and exergy efficiency of coal - fired boiler systems in Thailand's food industry.

In the food and beverage industry, thermal energy is primarily utilized during cooking and sterilization processes. The sterilization temperature varies depending on the product type and the sterilization technique employed, typically ranging from 72°C to 150°C. This thermal energy demand is met using saturated steam generated by industrial boilers. In this study, the boiler is designed for coal - fired fuel (sub-bituminous coal) with an economizer (heat recovery equipment) to recover waste heat from flue gases and preheat the boiler feedwater. It produces saturated steam at a pressure of 8 bar, corresponding to a temperature of approximately 175°C, as determined from steam tables. The generated steam is distributed through thermally insulated pipelines to various processing points. At the point of utilization, the steam pressure is regulated via a pressure-reducing valve to match the specific operational requirements of each production stage.

The system schematic diagram of the scope of consideration is shown in Fig.1. The system consists of a Coal - fired boiler (CFB) integrated with an economizer, steam header, deaerator, feed water pump, coal screw transmission and process production. The figure shows the schematic of a steam boiler system, which generates and distributes steam for industrial processes. Fuel is supplied to the boiler, where combustion occurs, producing heat energy. This heat is transferred to water inside the boiler, converting it into steam. The generated steam flows to a steam header, which serves as a distribution point for delivering steam to different processes or equipment within the plant. A deaerator is also included in the system. The function is to remove dissolved gases (such as oxygen and carbon dioxide) from the feedwater before it enters the boiler. This step is crucial for preventing corrosion in the boiler and steam distribution system. The feedwater, after being treated in the deaerator, is pumped into the boiler to sustain continuous steam production.

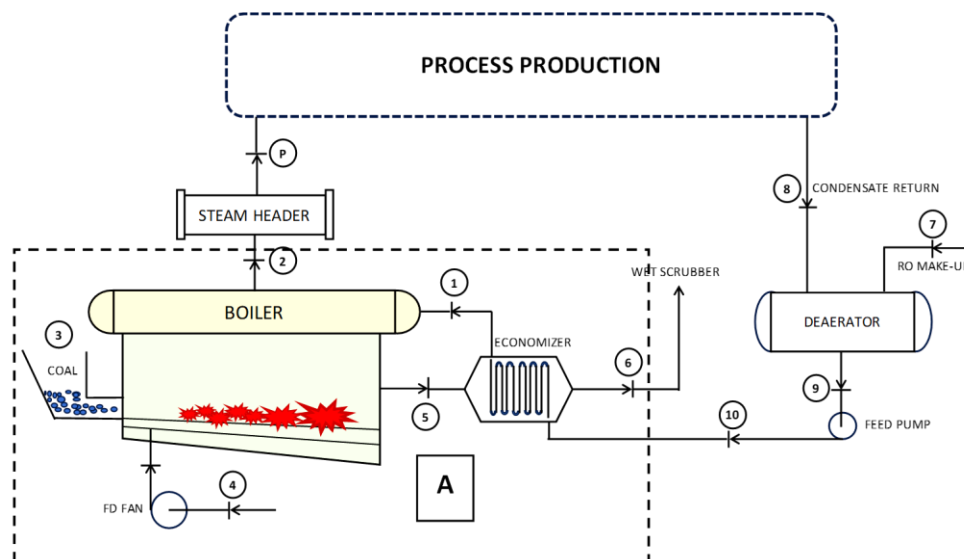


Fig. 1 Schematic diagram of beverage process production.

2.1 Performance analysis

In this section, to evaluate the performance of a CFB, thermodynamic variables related to energy and exergy were analyzed. The energy and exergy performance of the boiler was evaluated under various load conditions, using thermodynamic parameters obtained through measurement and calculation, such as mass flow rate, pressure, temperature, enthalpy, and entropy. The analysis was conducted to determine the energy efficiency and exergy efficiency of the system by three basic equations i.e., mass balance, energy balance and exergy balance rates were evaluated with the assumption by the following [31]:

- 1) The processes were considered under steady state condition.
- 2) The kinetic, potential and chemical interactions energy effects were not considered.
- 3) Dead state condition (Temperature and pressure) was assumed to be is 30°C and 1 atm.
- 4) Exergy losses associated with the flue gas were excluded from the scope of the present study.

The mass balance for the control volume system can be analyzed using the following equation [28]:

$$\sum \dot{m}_i = \sum \dot{m}_e \quad (1)$$

Where the $\dot{m}_i$ is the mass flow rate brought into the system and $\dot{m}_e$ is the mass flow rate leaving the system.

$$\sum_i \dot{E}_i + \dot{Q}_{cv} = \sum_e \dot{E}_e + \dot{W}_{cv} \quad (2)$$

Where the $\dot{E}_i$ and $\dot{E}_e$ are the energy flow rate brought into the system and leaving the system, respectively. $\dot{Q}_{cv}$ is the rate of the energy transfer to system as heat. $\dot{W}_{cv}$ is the rate of work done by the control volume. The entropy balance is [16]:

$$\dot{S}_{gen} = \sum \dot{S}_e - \sum \dot{S}_i \quad (3)$$

Where the $\dot{S}_i$ is the entropy flow rate brought into the system and $\dot{S}_e$ is the entropy flow rate leaving the system and $\dot{S}_{gen}$ is the entropy generation. The exergy balance equation for a control volume system can be expressed as follows [24]:

$$\dot{E}x_{dest} = \sum \left(1 - \frac{T_o}{T_k}\right) \dot{Q}_k - \dot{W}_{cv} + \sum_i \dot{m}_i ex_{f,i} - \sum_e \dot{m}_e ex_{f,e} \quad (4)$$

Where $\sum \left(1 - \frac{T_o}{T_k}\right) \dot{Q}_k$ is the exergy transfer at temperature T_k , and the subscripts i and e denote inlets and outlets, respectively. $\sum_i \dot{m}_i ex_{f,i}$ is the exergy transfer rate at inlets and $\sum_e \dot{m}_e ex_{f,e}$ is the exergy transfer rates at outlets. Where the $\dot{E}x_{dest}$ is the time rate of exergy destruction of irreversibility within the system [13].

$$ex_{f,i} - ex_{f,e} = (h_i - h_e) - T_o(s_i - s_e) + \frac{(V_i^2 - V_e^2)}{2} + g(z_i - z_e) \quad (5)$$

Where the h is the specific enthalpy, s is the specific entropy, V is the velocity of the fluid, z is the height or elevation of the fluid, g is the acceleration due to gravity and the subscripts i and e denote inlets and outlets, respectively. T_o is the environment temperature in Kelvin (K),

Generally, the boiler efficiency (η) is analyzed using the direct method that provided the overall efficiency is determined by the amount of input and output energy. In this boiler is used the coal - fired fuel; the input energy is heat released by the combustion of coal - fired, while the useful energy is the heat in steam output. This efficiency can be evaluated using the formula (6), according to the 1st Law of thermodynamics [16]:

$$\eta = \frac{\dot{m}_w(h_{w,o} - h_{w,i})}{\dot{m}_{CF}(CHV_{CF})} \quad (6)$$

The measurement of input energy requires knowledge of the calorific heat value of the coal - fired CHV_{CF} and its mass flow rate ($\dot{m}_{CF}$). The useful energy is determined by measuring the water mass flow rate ($\dot{m}_w$), temperature and pressure before heat exchanger (economizer) and after the boiler corresponding to the specific enthalpy of water ($h_{w,i}$ and $h_{w,o}$).

Illustrating the performance of the boiler; the exergy efficiency (ε) is significant determined, which is combined by the energy conservation law and entropy generation. The ε can be determined from the formula (7), according to the 2nd Law of thermodynamics [16]:

$$\varepsilon = \frac{\dot{m}_w[(h_{w,o} - h_{w,i}) - T_o(s_{w,o} - s_{w,i})]}{\dot{m}_{CF}(Ex_{ch,CF})} \quad (7)$$

Where: the $s_{w,i}$ and $s_{w,o}$ are the specific entropy before heat exchanger and after the boiler, respectively. T_o is the environment temperature (Kelvin). The chemical exergy of coal - fired ($Ex_{ch,CF}$) is assumed equal as the calorific heat value of the coal - fired (CHV_{CF}).

2.2 Cost of exergy destruction

The $\dot{E}x_{dest}$ in the boiler is important to determine the cost of input exergy ($C_{Ex_{CF}}$), there are two parts of exergy destruction: 1) the exergy destruction due to energy transfer from the hot gas to the water flowing in the tube, and 2) the destruction of exergy is caused by the combustion process. The cost of coal-fired fuel (C_{CF}) is 1.768×10^{-4} \$/kJ (a sub-bituminous coal price of 3.30 \$/kg corresponds to the purchase price paid by the factory to the supplier during August 2023 – July 2024) based on input exergy ($\dot{E}x_{CF}$), which is assumed to be equal CHV_{CF} ; it can be determined as follow [32]:

$$\dot{C}_{\dot{E}x_{dest}} = C_{CF} \dot{E}x_{dest} \quad (8)$$

Based on a schematic diagram in Fig. 1 to analyze each system component, the mass, energy and exergy balances were constructed and represented in Table 1. and Table 2.

Table 1 Energy balance equations [24].

Components	Energy Balance
Boiler	$\dot{Q}_B = \dot{m}_w(h_2 - h_1) + \dot{m}_p h_5 - \dot{m}_a h_4 - \dot{m}_{CF} h_3$
Economizer	$\dot{m}_5 h_5 + \dot{m}_{10} h_{10} = \dot{m}_1 h_1 + \dot{m}_6 h_6$

Table 2 Exergy balance equations [24].

Components	Exergy Balance
Boiler	$\dot{E}x_{dest} = \dot{E}x_1 - \dot{E}x_2 + \dot{E}x_3 + \dot{E}x_4 - \dot{E}x_5$
Economizer	$\dot{E}x_{dest} = \dot{E}x_5 - \dot{E}x_6 + \dot{E}x_{10} - \dot{E}x_1$

2.3 Methodology

This paper examines a fire tube steam boiler unit in the beverage industry as a case study to evaluate its energy efficiency (η), exergy efficiency (ε), quantify the exergy destruction ($\dot{E}x_{dest}$) and also cost of exergy destruction ($\dot{C}_{\dot{E}x_{dest}}$) in the boiler and the Coal-Steam Ratio (CSR) is defined as the mass of coal consumed per the steam produced by the boiler (t_{Coal}/t_{Steam}). The steam boiler output is 16 tons/h operate at a steam pressure of 8 bar, and the steam output is saturated vapor.

Table 3 Collection data.

Basic information	Boiler Load (%)			
	25	50	75	100
Combustion chamber temperature, T_{cc} (°C)	579.9	631.4	673.2	731.0
Flue gas temperature T_{fg} (°C)	256.7	280	298.6	324.2
Inlet water temperature of economizer, $T_{eco,in}$ (°C)	50	50	50	50
Outlet water temperature of economizer, $T_{eco,out}$ (°C)	80	84	91	94.5
Steam temperature at outlet of boiler, $T_{boil,out}$ (°C)	175	175	175	175
Steam pressure at outlet boiler, $P_{boil,out}$ (bar)	8	8	8	8
Coal consumption rate, $\dot{m}_{CF}$ (kg/h)	1,161.17	1,473.99	1,835.35	2,164.35
Feed water flowrate, $\dot{m}_w$ (kg/h)	5,268.26	8,564.10	11,548.40	15,000.00
Air flowrate, $\dot{m}_a$ (kg/h)	8,805	11,394	13,922	16,541
Condensate water flowrate, $\dot{m}_{cd}$ (kg/h)	1,053.65	1,712.12	2,309.68	3,000
Make-up water flowrate, $\dot{m}_{mw}$ (kg/h)	4,214.61	6,851.12	9,238.71	12,000
Calorific heat value (kJ/kg _{CF})	18,661	18,661	18,661	18,661

A boiler is designed for coal - fired fuel (sub-bituminous coal) with an economizer (heat exchanger) for recovered waste heat. A deaerator is used to gather the condensate water return from the process production together mixed with the water resource from the reverse osmosis (RO) plant, and removed the dissolved gasses in the deaerator before sending feed water (FW) to the economizer. Feed water in the deaerator is supplied by feed water pump to an economizer to gradually raise feed water temperature, and benefit from the combustion flue gas (preheating process). After preheating, the feed water is sent to the boiler and received heat from the combustion of coal - fired to generate saturated steam, and send it to the steam header (SHD). Steam header will act separately steam from the boiler to the manufacturing processes. In this study, steam boiler operation at 25%, 50%, 75%, and 100% loads were considered. Boiler operation at increased load, the steam pressure at steam header is maintained as about 8 bar. Data collection and recording were systematically carried out over the course of one year to ensure representative and comprehensive operational performance analysis. From the boiler operation log sheet of factory for the year, the operating hours at 25%, 50%, 75%, and 100% were 1,314 h, 4,380 h, 2,628 h, and 438 h, respectively. The thermodynamics properties of operating conditions are listed in Table 3.

Table 3. lists the average collected data in operating conditions at various loads i.e., combustion chamber temperature, flue gas temperature, inlet and outlet water temperatures of economizer, steam temperature, steam pressure, amount of air, feed water, coal - fired consumption, condensate water and make up water, calorific heating value. The calorific heat value of coal - fired (sub - bituminous coal), CHV_{CF} is 18,661 kJ/kg (average value).

Detailed parameters of the CFB have been measured and recorded by proper instruments with its accuracy. The temperature of various positions was measured by thermometer data logger with type K thermocouple (range: 0 to 1,250°C with accuracy $\pm 0.5\%$) connected to a data logger (Hioki: Model-LR 8400 - 20). An ultrasonic flow meter (Micronics portaflo: MF220B, accuracy: $\pm 0.5\%$ to $\pm 2\%$) was used to measure feed water. The coal - fired consumption was feed by screw transmission and measured by a large mechanical scale. The steam pressure gauge (WEKSLER: Model-EA14, range: 0 to 200 psi) was measured the boiler's steam pressure. Hot wire anemometer (KIMO: Model VT 100, range: velocity 0.15 to 30 m/s and temperature -20 to 80°C) was used to measure air velocity at the force draft fan is inlet of boiler. Thermo-hygrometer (UNI-T: UT330C, accuracy: $\pm 0.5\%$ to $\pm 3\%$) was used to record the ambient condition. Electrical power analyzer (KYORITSU KEW 6305: Model-8125 (500A), range 0.1 to 3000 A., accuracy: $\pm 0.3\%$ rdg $\pm 0.2\%$ f.s. The data interval was recorded every 15 minutes.

2.4 Uncertainty analysis

Exergetic efficiency is approximated using some measurements. The approximated efficiency may have uncertainties due to errors in the measured parameters. The approximated efficiency can be written as a function as follows

$$\psi = \psi(x_1, x_2, x_3, \dots, x_n) \quad (9)$$

The uncertainty in the approximated exergetic efficiency (w_ψ) can be approximated as follows [41]

$$w_\psi = \left[\left(\frac{\partial \psi}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial \psi}{\partial x_2} w_2 \right)^2 + \dots + \left(\frac{\partial \psi}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (10)$$

In which $w_1, w_2, \dots, w_n$ is error in the i th estimated parameters.

In this study the temperature and water flowrate were measured with appropriate instrumentation. The uncertainty associated with each measured and calculated parameter was determined using Eq. (10). The overall measurement uncertainty was estimated at $\pm 2.1\%$ for temperature and $\pm 2.5\%$ for water flow rate, and the average uncertainty of the exergy efficiency was found to be $\pm 0.91\%$ at boiler loads of 50–75%.

3. Result and discussion

Exergy destruction ($\dot{E}x_{dest}$) and its associated cost ($\dot{C}_{\dot{E}x_{dest}}$) are critical for evaluating the thermodynamic performance of steam boilers and identifying opportunities for efficiency improvement in the beverage industry. In this study, energy and exergy data were collected over one year from a CFB operating at four load levels: 25%, 50%, 75%, and 100%. The boiler's energy and exergy performance increase with load. Input energy, representing the total thermal energy supplied through fuel combustion, rises from 21.67×10^6 kJ/h at 25% load to 40.39×10^6 kJ/h at full load. Similarly, output energy, delivered as steam or hot water, increases from 12.75×10^6 to 35.53×10^6 kJ/h. Input exergy, reflecting the high-quality portion of energy capable of performing useful work, coincides with input energy in this study, indicating that fuel exergy was approximated by its total energy content. Output exergy also increases with load but remains consistently lower than input exergy due to unavoidable losses arising from system irreversibility. Efficiency metrics further highlight the influence of load on boiler performance. Energetic efficiency, which measures the conversion of energy into useful heat, increases from 58.82% to 87.98%, while exergetic efficiency, accounting for irreversibility under the second law of thermodynamics, rises from 18.16% to 27.45%. Both trends indicate enhanced thermodynamic performance at higher loads. System irreversibility are also evident in entropy generation and exergy destruction. Entropy generation, quantifying energy degradation, increases from 28,968 to 80,381 kJ/h.K, while exergy destruction, representing the corresponding loss of energy

Table 4 Energy and exergy analysis of coal - fired boiler.

Components	Boiler Load (%)			
	25	50	75	100
Boiler with Economizer				
Input energy, (kJ/h)	21,668,110	27,505,597	34,248,806	40,388,194
Output energy, (kJ/h)	12,746,225	20,693,568	27,531,797	35,533,142
Input exergy, (kJ/h)	21,668,110	27,505,597	34,248,806	40,388,194
Output exergy, (kJ/h)	3,935,519	6,393,710	8,563,868	11,085,190
Energetic efficiency, η (%)	58.82	75.23	80.39	87.98
Exergetic efficiency, ε (%)	18.16	23.25	25.00	27.45
Entropy generation, $\dot{S}_{gen}$ (kJ/h.K)	28,968.30	47,015.81	62,363.73	80,381.23
Exergy destruction, $\dot{E}x_{dest}$ (kJ/h)	8,810,706	14,299,858	18,967,928	24,447,952

quality, rises from 8.81×10^6 to 24.45×10^6 kJ/h. These patterns consistently illustrate the impact of higher loads on energy utilization and unavoidable losses. The boiler and economizer were identified as key components for analysis, as significant thermal energy is lost through flue gas. Incorporating an economizer allows partial recovery of this waste heat to preheat feedwater, reducing overall fuel demand [33]. As shown in Table 1, the economizer outlet water temperature increases proportionally with boiler load, reflecting improved heat recovery. For exergy evaluation, the chemical exergy of the coal-fired fuel ($Ex_{ch,CF}$) was assumed equal to its calorific heat value (CHV_{CF}) in accordance with established conventions [8]. Results summarized in Table 4 reveal variations in both energy efficiency and exergy destruction across operational loads. These findings underscore the importance of exergy analysis for identifying system irreversibility, quantifying avoidable losses, and guiding cost-effective optimization strategies, while supporting environmental and sustainability objectives [11, 12].

3.1 Temperature in the boiler

Figure 2 illustrates the variation of combustion chamber temperature (T_{ch}) and flue gas temperature (T_{fg}) as functions of boiler load. Both parameters exhibit a positive correlation with increasing load, indicating that higher load conditions intensify the combustion process and associated heat transfer phenomena. The combustion chamber temperature (T_{ch}) increases markedly from approximately 580 °C at 25% load to around 740 °C at full load, reflecting enhanced combustion rates and greater thermal energy generation within the furnace. Conversely, the flue gas temperature (T_{fg}) demonstrates a more gradual increase, rising from about 250 °C to 320 °C over the same load range. This moderate trend suggests efficient heat recovery through the convective heat exchange surfaces, effectively balancing combustion efficiency and heat loss. Fig. 3 presents a comparison between the flue gas temperature (T_{fg}) and the economizer inlet temperature ($T_{eco,in}$) at various boiler loads. Similar to the trend observed in Fig. 2, the flue gas temperature increases progressively with load, ranging from approximately 250 °C at 25% load to about 330 °C at full load, consistent with the intensified combustion dynamics. In contrast, the economizer inlet temperature ($T_{eco,in}$) remains relatively stable, fluctuating slightly around 50 °C, irrespective of load variation. This stability indicates that the feedwater preheating system effectively maintains constant inlet conditions, ensuring steady economizer performance and mitigating potential thermal stress. Comparative analysis of the two figures reveals that the combustion chamber temperature (T_{ch}) exhibits the steepest gradient with increasing boiler load, underscoring its direct dependence on combustion intensity. The flue gas temperature (T_{fg}), although also influenced by combustion rate, increases more moderately due to progressive heat extraction within the boiler's convective zones. Meanwhile, the nearly constant economizer inlet temperature ($T_{eco,in}$)

reflects effective thermal management and insulation within the feedwater circuit. Overall, the results demonstrate that increasing boiler load enhances both combustion efficiency and heat transfer effectiveness, while the downstream thermal regulation mechanisms maintain operational stability and minimize energy losses. This behavior can be attributed to the proportional increase in coal feed rate and combustion air supply at higher loads, which elevates the flame temperature and the mass flow rate of the resulting hot gases [34]. Given that the boiler's heat transfer surface area remains constant, the increased thermal energy and gas flow lead to higher flue gas exit temperatures. These elevated flue gases subsequently transfer additional heat to the feedwater within the economizer, thereby raising its temperature prior to re-entry into the boiler. This process improves the overall thermal efficiency of the system while simultaneously reducing the temperature of the discharged flue gases, contributing to lower heat losses to the environment [10, 35]. Collectively, these findings highlight the intricate interrelationship among combustion intensity, heat transfer limitations, and waste heat recovery in coal-fired boiler systems. Such interactions play a decisive role in determining both the energy and exergy efficiencies of boiler operation.

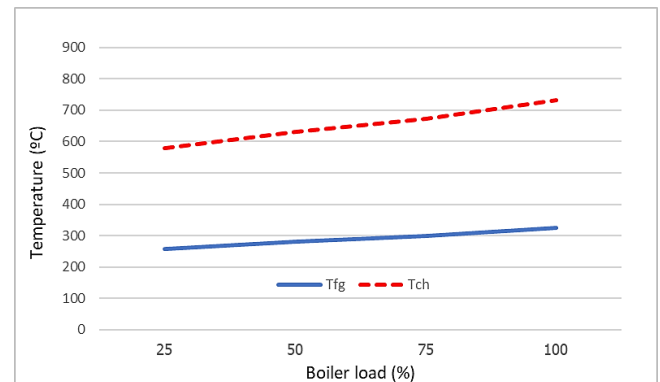


Fig. 2 Combustion chamber and flue gas temperatures.

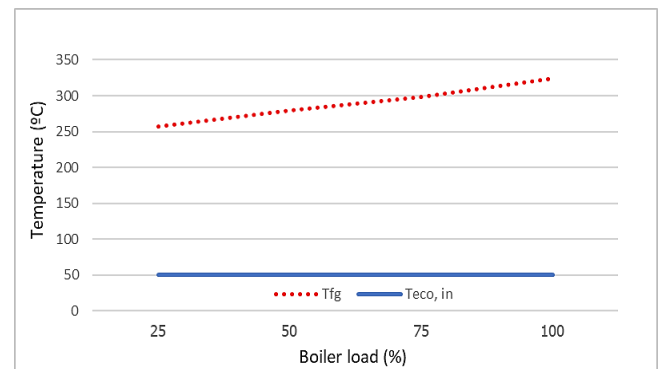


Fig. 3 Flue gas and inlet water temperatures of economizer.

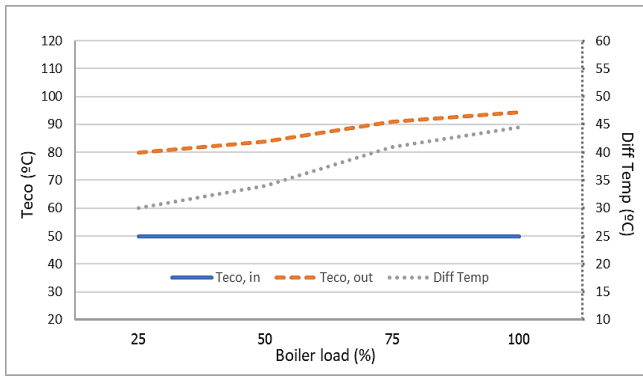


Fig. 4 Inlet and outlet water temperatures of an economizer.

Figure 4 illustrates the relationship between boiler load and the economizer water temperature at both the inlet ($T_{eco,in}$) and outlet ($T_{eco,out}$), along with the corresponding temperature difference (ΔT_{eco}). The results indicate that the inlet temperature remains nearly constant at approximately 50 °C under all load conditions, reflecting the stability of the feedwater supply. In contrast, the outlet temperature exhibits a gradual increase from approximately 80 °C at 25% load to about 95 °C at full load, signifying enhanced heat transfer performance within the economizer as the boiler load increases. This behavior can be attributed to the elevated flue gas temperature and mass flow rate at higher loads, which intensify the heat exchange process. The temperature difference (ΔT_{eco}), represented by the dotted line, also demonstrates a positive correlation with boiler load, increasing from around 30 °C to 45 °C. This trend indicates improved economizer effectiveness at higher operating loads due to the greater thermal potential between the flue gas and feedwater streams. The widening temperature gap between $T_{eco,out}$ and $T_{eco,in}$ confirms that energy recovery within the economizer is more efficient under full-load conditions. Nevertheless, a portion of the available thermal energy is inevitably lost through mechanisms such as heat dissipation to the boiler walls, incomplete combustion, and heat retention within the boiler structure, all of which contribute to a reduction in overall system efficiency [33, 34]. The flue gas flows through the economizer while the feedwater passes counter, allowing efficient thermal exchange. The economizer functions as a heat recovery unit, capturing residual heat from the flue gas—otherwise lost to the environment—and transferring it to preheat the boiler feedwater. The measured temperature differentials between the flue gas and inlet water at 25%, 50%, 75%, and 100% boiler loads were 206.7 °C, 230.0 °C, 248.6 °C, and 274.2 °C, respectively. The observed increase corresponds to the higher flue gas temperatures at elevated loads, which enhance the driving force for convective heat transfer and consequently improve the overall thermal efficiency of the system [10, 36].

3.2 Energy, exergy and exergy destruction

The energy and exergy analysis of the CFB equipped with an economizer was conducted, and the results are summarized in Table 4. It is evident that a reduction in boiler load led to a decrease in both energy and exergy efficiencies, which is consistent with previous studies on load-dependent thermodynamic performance of industrial boilers [10, 33]. Fig. 5 illustrates the relationship between boiler load and the rate of energy flow (kJ/h) for both the input energy from coal and the output energy in steam. Both parameters exhibit an approximately linear increase with increasing boiler load, indicating a direct proportionality between the boiler's operating capacity and its overall energy conversion performance. Throughout all load conditions, the energy input from

coal consistently exceeds the energy output in steam, reflecting the inherent thermal losses associated with combustion and heat transfer processes. At 25% load, the energy supplied by coal and the corresponding energy in steam are approximately 21.67×10^6 kJ/h and 12.75×10^6 kJ/h, respectively. As the load increases to 100%, these values rise to about 40.39×10^6 kJ/h and 35.53×10^6 kJ/h. The difference between the energy input and output represents system losses, which decrease progressively with higher load levels. Specifically, the losses were 8.92×10^6 , 6.82×10^6 , 6.70×10^6 , and 4.90×10^6 kJ/h at 25%, 50%, 75%, and 100% loads, respectively. This trend indicates an improvement in energy conversion efficiency at higher loads, primarily due to intensified combustion and enhanced heat transfer effectiveness. These factors contribute to a reduction in relative losses through flue gas discharge, radiation, and incomplete combustion. Overall, the results indicate that an increase in boiler load leads to higher energy input from fuel and greater useful energy output in the form of steam, accompanied by an improvement in thermal efficiency. Although the total conversion efficiency remains below 100% due to inherent energy losses, operation near full load provides notably better performance. These observations align well with previous studies [10, 36], underscoring the importance of maintaining optimal load conditions to achieve maximum energy and exergy efficiency in industrial coal-fired boiler systems.

The input and output exergy of the CFB were analyzed, with the input exergy assumed to be equivalent to the input energy. This assumption follows the standard approach for fossil fuel-fired systems, in which the chemical exergy of the fuel is considered approximately equal to its calorific value. [36-38]. Fig. 6 illustrates the variation of exergy input and output as a function of boiler load. The chemical exergy of coal and the exergy of steam are plotted against boiler loads ranging from 25% to 100%. The exergy in coal represents the fuel's available work potential supplied to the system, whereas the exergy in steam denotes the useful exergy output associated with steam generation.

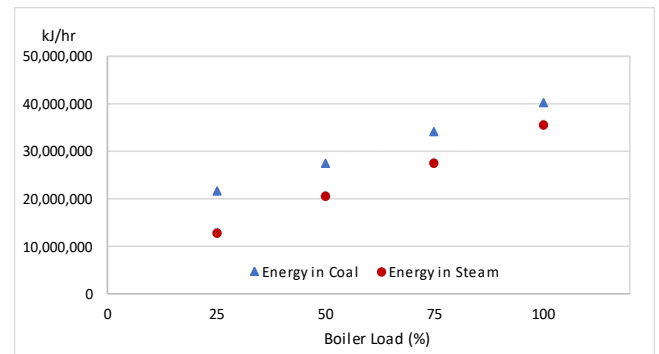


Fig. 5 Input and output energy of coal - fired boiler.

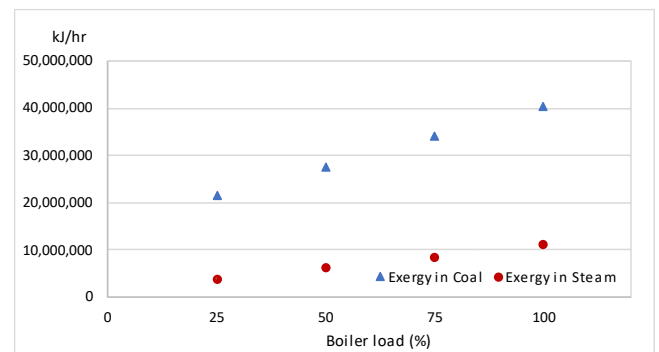


Figure 6 Input and output exergy of coal - fired boiler.

As shown, both the input and output exergies increase nearly linearly with the rise in boiler load. At 25% load, the coal exergy is approximately 21.67×10^6 kJ/h, while the steam exergy is about 3.94×10^6 kJ/h. Under full-load operation (100%), these values increase to approximately 40.39×10^6 kJ/h and 10.09×10^6 kJ/h, respectively, indicating that higher fuel input at elevated loads results in greater energy conversion and steam production. Despite this proportional increase, the exergy in steam remains substantially lower than the exergy in coal throughout the operating range, reflecting significant irreversibility and exergy destruction within the combustion and heat transfer processes. The gentler slope of the steam exergy curve compared to that of coal suggests a marginal decline in exergy conversion efficiency at higher loads, likely due to intensified entropy generation and non-ideal heat transfer effects. Overall, the results indicate that although boiler output improves with increasing load, the system continues to experience considerable exergy losses. Enhancing combustion efficiency and optimizing heat recovery could mitigate these losses and improve overall exergy performance. The maximum output exergy occurs at full-load operation, demonstrating enhanced utilization of the fuel's available work potential at higher loads [10]. Conversely, reducing the boiler load proportionally decreases the output exergy due to intensified relative irreversibility such as incomplete combustion, flue gas heat loss, and thermal gradients within the boiler structure [32]. This trend underscores the importance of operating coal-fired boilers near their design capacity to maximize thermodynamic efficiency and minimize exergy destruction.

Figure 7 depicts the variation of exergy destruction with boiler load ranging from 25% to 100%. The results reveal that exergy destruction increases almost linearly with load. At lower loads, the exergy destruction remains minimal owing to the reduced fuel input and smaller temperature gradients within the system. As the load increases, intensified combustion and heat transfer irreversibility, together with higher fuel consumption, result in greater exergy destruction. The maximum exergy destruction, approximately 25×10^6 kJ/h, is observed at full-load operation (100%). This trend is characteristic of boiler systems, where elevated thermal stresses and non-ideal combustion at higher loads promote increased entropy generation and, consequently, higher exergy destruction [33, 36]. Furthermore, the rise in exergy destruction at full load can be attributed to larger thermal gradients, greater heat losses to the surroundings, and enhanced frictional and combustion irreversibility [10, 38]. Overall, these findings emphasize the importance of exergy analysis in identifying inefficiency sources and optimizing boiler operation to achieve a balance between energy production and exergy loss.

As illustrated in Fig. 8, the entropy generation of the boiler at 25%, 50%, 75%, and 100% loads was 28,968 kJ/h.K, 47,016 kJ/h.K, 62,364 kJ/h.K, and 80,381 kJ/h.K, respectively. It is apparent that entropy generation decreases with a reduction in boiler load, indicating lower thermodynamic irreversibility under part-load conditions [10, 33]. This trend is consistent with the observed decrease in exergy destruction at lower loads, as entropy generation is inherently linked to the degree of process irreversibility [36]. Furthermore, the minimum exergy destruction in the output steam is achieved when the temperature difference between the economizer outlet water and the feedwater is relatively high, signifying enhanced heat recovery efficiency and improved utilization of the available energy in the flue gas. These results underscore the significant contribution of heat recovery components in minimizing exergy destruction and entropy generation, thereby enhancing the overall thermodynamic efficiency and sustainability of coal-fired boiler operations [37].

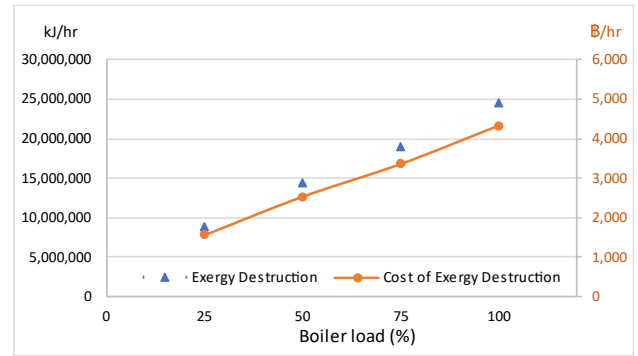


Fig. 7 Exergy destruction and Cost of exergy destruction.

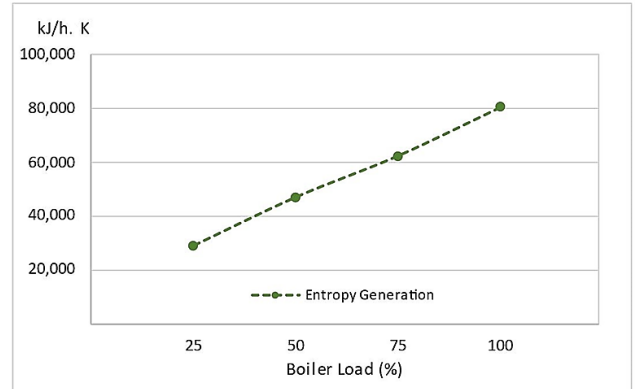


Fig. 8 Entropy generation of coal - fired boiler.

3.3 Energy and exergy efficiency

As illustrated in Figure 9, the energy and exergy efficiencies of the CFB exhibit a distinct dependence on the boiler load, with values ranging from 58.82% to 87.98% for energy efficiency and from 18.16% to 27.45% for exergy efficiency. The maximum efficiencies were attained at full load (100%), whereas the minimum values occurred at 25% load. This variation reflects the typical operational characteristics of thermal systems, in which increased load enhances heat transfer effectiveness, minimizes relative heat and radiation losses, and promotes better utilization of the chemical energy available in the fuel [10, 33]. As the load increases, improved combustion stability and reduced excess air further contribute to the rise in both energy and exergy efficiencies. It is also evident that the energy efficiency consistently exceeds the exergy efficiency under all load conditions. This difference arises from their fundamental definitions: energy efficiency, governed by the first law of thermodynamics, considers only the quantity of energy conserved, whereas exergy efficiency accounts for the quality and usability of energy by incorporating the effects of irreversibility, entropy generation, and thermodynamic degradation [36, 38, 39].

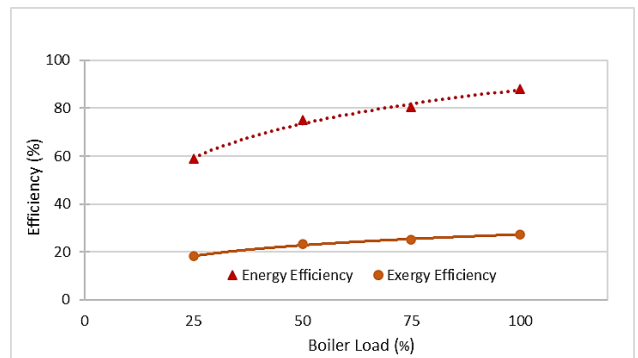


Fig. 9 Energy and exergy efficiencies.

Consequently, exergy efficiency provides a more realistic assessment of the system's true performance. These findings emphasize the significance of integrating exergy analysis alongside conventional energy evaluation. While energy analysis identifies general performance trends, exergy analysis reveals the specific sources and magnitudes of inefficiencies within the system, thereby offering valuable guidance for improving combustion efficiency, optimizing heat recovery, and enhancing the overall sustainability of industrial coal-fired boiler operations [40].

3.4 Cost of exergy destruction

The cost of energy generation in a CFB exhibits a pronounced dependence on boiler load and the corresponding useful energy output, with coal consumption constituting the principal operational expense. As presented in Fig. 7, both exergy destruction and its associated cost demonstrate a progressive increase with rising boiler load. The maximum values of exergy destruction and cost, approximately 24.45×10^6 kJ/h and 4,323 \$/h, respectively, were observed under full-load operation (100%), whereas the minimum values of 8.81×10^6 kJ/h and 1,558 \$/h occurred at 25% load. Considering the exergy destruction (cost of exergy destruction) over a one-year operating period at boiler load conditions of 25%, 50%, 75%, and 100%, the corresponding values were $11,577 \times 10^6$ kJ/y (2,046,861 \$/y), $62,633 \times 10^6$ kJ/y (11,073,581 \$/y), $49,848 \times 10^6$ kJ/y (8,813,076 \$/y), and $10,708 \times 10^6$ kJ/y (1,893,210 \$/y), respectively. The total exergy destruction amounted to $134,766 \times 10^6$ kJ/y, representing approximately 52.5% of the input exergy, with a total cost of exergy destruction of 23,826,728 \$/y. Given a total annual production of 25,468,775 boxes, the cost of exergy destruction per unit of product was therefore calculated to be 0.9355 \$/box. This nearly linear trend reflects the direct influence of higher fuel consumption and intensified combustion processes at elevated loads, which in turn amplify thermodynamic irreversibility within the system. This irreversibility arises from increased heat losses, frictional effects, and deviations from ideal combustion, all of which contribute to reduced exergy efficiency and elevated operational costs. The observed relationship underscores the strong coupling between the thermodynamic and economic performance of the system. As boiler load increases, the growing extent of exergy destruction results in a proportional rise in the cost of inefficiencies, signifying that higher output levels, while improving energy throughput, may also impose greater economic penalties if not properly optimized. Therefore, a comprehensive understanding of this relationship is essential for improving the cost-effectiveness and sustainability of CFB operations. By correlating exergy-based performance indicators with financial metrics, plant operators can identify optimal load conditions, minimize fuel wastage, and enhance overall system efficiency, thereby supporting more sustainable and economically viable energy management strategies.

3.5 The Coal-Steam Ratio (CSR)

The monitored data on coal consumption and steam production, as summarized in Table 3, were utilized to calculate the Coal-Steam Ratio (CSR), as illustrated in Fig. 10. The CSR values corresponding to boiler loads of 25%, 50%, 75%, and 100% were determined to be $0.22 \text{ t}_{\text{Coal}}/\text{t}_{\text{Steam}}$, $0.172 \text{ t}_{\text{Coal}}/\text{t}_{\text{Steam}}$, $0.159 \text{ t}_{\text{Coal}}/\text{t}_{\text{Steam}}$, and $0.144 \text{ t}_{\text{Coal}}/\text{t}_{\text{Steam}}$, respectively. The results reveal a distinct non-linear decreasing trend in CSR with increasing boiler load, indicating that the quantity of coal required to generate one ton of steam progressively diminishes as the boiler approaches its design capacity. This improvement can be attributed to enhanced combustion efficiency, more effective heat transfer within the boiler tubes, and improved performance of the economizer and air preheater at higher operational loads.

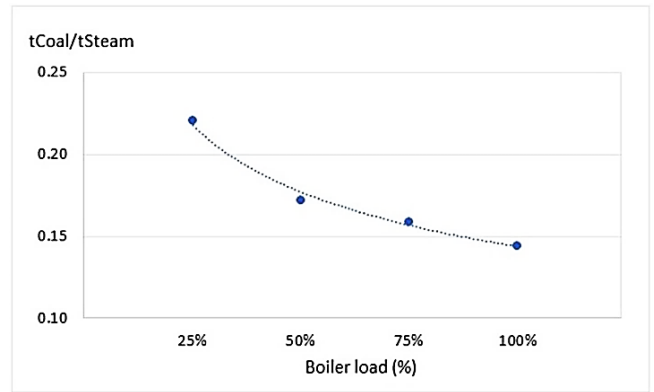


Fig. 10 Coal-Steam Ratio (CSR).

At lower boiler loads, incomplete combustion and higher relative heat losses occur due to reduced furnace temperatures and inefficient heat recovery, resulting in elevated CSR values. Conversely, at higher loads, the system operates under more favorable thermal conditions, leading to more complete combustion and better utilization of the supplied heat energy. This relationship underscores the critical role of maintaining an optimal load range to ensure efficient fuel use and cost-effective operation. Furthermore, minimizing CSR not only reduces operational costs but also contributes to lower greenhouse gas emissions and decreased particulate matter release, thereby supporting sustainable energy production. Overall, these findings emphasize the necessity of load optimization as a key strategy for improving the thermodynamic and economic performance of coal-fired boilers. The results of this analysis are discussed in detail as follows.

- 1) As the boiler load increases, both the coal and air supply to the combustion chamber are elevated to meet the higher energy demand. Enhanced mixing of fuel and air promotes more complete combustion, thereby improving the combustion efficiency (η_{CB}) and maximizing the conversion of the coal's chemical energy into thermal energy. Consequently, the temperature of the hot gases in the combustion chamber (T_{CC}), rises with increasing load, which enlarges the temperature difference between the hot gases and the saturated water at 8 bar. According to the principles of convective heat transfer, a larger temperature gradient drives a higher rate of heat transfer, thereby increasing the heat exchange efficiency of the boiler. This behavior not only enhances the thermal performance of the boiler but also reduces fuel consumption per unit of steam generated, emphasizing the importance of maintaining optimal combustion conditions and proper air-fuel mixing to achieve both energy efficiency and operational sustainability.
- 2) As noted previously, the exhaust gas temperature exiting the combustion chamber increases with higher boiler loads. The elevated combustion chamber temperature (T_{fg}) enhances the driving force for heat transfer between the flue gases and the boiler feedwater within the economizer, thereby improving the heat exchanger's effectiveness. Consequently, the outlet water temperature from the economizer ($T_{eco,out}$) rises from 80 °C at 25 % load to 94.5 °C at 100 % load, reflecting more efficient utilization of the available thermal energy in the flue gas. Preheating the feedwater to a higher temperature reduces the enthalpy difference required for phase change in

the boiler, which in turn decreases the coal consumption per ton of steam generated. This demonstrates the critical role of the economizer in both energy conservation and the enhancement of overall boiler efficiency, highlighting its importance in optimizing fuel usage and reducing operational costs in coal-fired boiler systems.

- 3) Insulation plays a critical role in minimizing heat loss from the boiler to the surrounding environment. High-quality insulation with appropriate thickness helps maintain a nearly constant boiler surface temperature across different load conditions, thereby reducing thermal energy losses. From the collected data, the average boiler surface temperature was observed to be approximately 50–55 °C, while the ambient temperature ranged from 33–35 °C. This relatively small temperature difference ensures that heat losses through the boiler surface remain nearly constant, irrespective of the boiler load, which contributes to maintaining higher boiler efficiency at elevated loads. Proper insulation not only enhances energy conservation but also reduces unnecessary fuel consumption and operational costs, while minimizing environmental impacts associated with wasted energy. The effectiveness of insulation is therefore a key factor in optimizing the thermal and exergy performance of coal-fired boiler systems.

Boiler efficiency generally increases with higher boiler loads due to improved combustion performance, enhanced heat transfer rates, and more effective utilization of auxiliary systems such as economizers and other heat recovery devices. Nevertheless, in industrial practice, boilers rarely operate at steady full-load conditions, as operational demands fluctuate continuously throughout the year. These fluctuations are influenced by production schedules, variable product demand, planned maintenance, and unexpected equipment downtime. Analysis of the operational data indicates that approximately 80% of the boiler's annual operating hours occur at 50% and 75% of its nominal load, highlighting that full-load operation is infrequent and transient. This operational reality renders the consistent achievement of peak efficiency impractical, emphasizing the need for strategies that optimize performance across a spectrum of partial loads. Effective management of boiler performance under variable load conditions necessitates careful consideration of both thermal and exergy losses, particularly during extended periods of low-load operation. Implementing comprehensive energy and exergy management practices is therefore critical for maximizing the useful energy output while minimizing fuel consumption and associated emissions. Such measures include adaptive load control, optimization of combustion parameters, and systematic monitoring of heat recovery systems, all of which contribute to maintaining operational efficiency and sustainability. By integrating these approaches, industrial CFB can achieve a balance between energy efficiency, reliability, and operational flexibility, despite inherent load variability. Overall, the findings underscore the importance of adopting a holistic, data-driven approach to boiler operation. Ensuring that boilers are operated and maintained with an awareness of load-dependent efficiency patterns enables industrial facilities to minimize energy losses, enhance sustainability, and achieve more predictable performance outcomes. The strategic focus on partial-load optimization and exergy-informed operation represents a key pathway toward improved energy management in modern industrial settings.

4. Conclusion

The present study integrates the energy and exergy concepts to evaluate the energy, exergy, and exergy destruction to evaluate the efficiency and exergy destruction cost of the boiler. The examination of energy and exergy analysis based on data obtained from selected boilers in the beverage industry. The results show that the operation and boiler load have a significant effect on the performance of the boiler. The following results are obtained in the present study:

- Temperature difference between output and input of boiler has affected to the exergy destruction.
- The maximum output energy and output exergy of about 35,533,142 kJ/h and 11,085,190 kJ/h were observed for 100% of the boiler load.
- At 100% of boiler load, the maximum energy and exergy efficiencies are about 87.98% and 27.45%, respectively.
- Energy and exergy efficiencies will decrease as the boiler load decreases.
- Exergy destruction has a significant relationship with the output exergy of the boiler.
- The exergy destruction has affected the exergy efficiency and cost of exergy destruction.
- Total exergy destruction reached $134,766 \times 10^6$ kJ/y, equivalent to 52.5% of the input exergy.
- The resulting exergy destruction cost per product unit is identified as 0.9355 \$/box.

By considering all the results mentioned, it can be observed that the variation load of boiler has impacted on the overall performance of boiler i.e. efficiency and cost of coal. The results confirmed that the boiler load is a major parameter influencing the overall performance of the boiler. The evaluation of energy and exergy efficiencies of boilers used in the beverage industry in Thailand using the indirect method would allow a more detailed assessment of losses in key components, such as flue gas losses and combustion efficiency. This approach would provide deeper insights into major sources of inefficiency and offer greater opportunities for improving overall boiler performance.

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