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Calculation of boiler efficiency with mixed methane gas fuel using indirect method

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Abstract

A boiler is a pressurized vessel utilized for the production of high-temperature steam, efficiency common issue with boiler systems, particularly fire-tube boilers, is inefficiency due to heat losses in both the steam and fuel systems, which reduces overall operational efficiency. Hence, it is imperative to compute the efficiency of fire tube boilers to comply with efficiency regulations in operational procedures in the field. This study employs theindirect method to calculate efficiency. The results show an efficiency of 80.436%, meeting the minimum efficiency standard range of 7%—90%.

Keywords:
Fire-tube boiler, efficiency, methane gas, indirect method.

1 Introduction

A boiler is an enclosed container designed to transfer the heat produced by combustion into water until it transforms into either heated water or steam [1]. Boilers function as shell-and-tube heat exchangers, heating water to generate steam or high-pressure hot water. Typically, heat is produced by burning fuels like coal, oil, or gas [2]. Boilers are essential components in a wide range of industrial operations and electricity production [3]. Furthermore, the majority of industrial heating systems rely on boilers for producing hot water or steam. Consequently, an effective boiler also plays a substantial role in conserving energy associated with heating processes [4]. Water is an efficient and economical medium for transferring heat to other processes. Steam, at a certain pressure and temperature, has energy that can be used to transfer heat as calorific energy to other processes [5].

The performance and emission characteristics of boilers fueled by mixed methane and other gases have been the subject of numerous studies. Blending methane with hydrogen can significantly alter combustion dynamics, leading to changes in flame temperature, NOx emissions, and overall efficiency [6].

Numerous prior studies have been undertaken to evaluate the efficiency of boiler machines, specifically through the utilization of direct and indirect methods for calculating the performance of fire-tube boilers used for pellet grain products [7]. The objective of this study is to assess and calculate the effectiveness of a boiler whose 39.48 kg/cm^2 of High-Pressure Steam (HP Steam), and 48.46 T/hour of capacity HP Steam.

The attempt to improve boiler efficiency aims to avoid wasting fuel and reduce operational costs [8]. Energy loss is an important factor that needs to be identified in determining boiler efficiency, by calculating efficiency using indirect methods. It is intended that the hot steam produced can be used efficiently in the plant. The advantage of this method is that it provides a more accurate representation of the boiler's efficiency, as it takes into account the energy losses that occur during the combustion process [9].

2 Materials and Methods

The method used in this research is an analysis using the indirect method which includes several stages of calculations that will be carried out in Microsoft Excel software.

This study aims to identify heat loss in fire tube boilers to determine their efficiency according to operational standards. It employs indirect methods for calculations, incorporating equations from various literature sources, direct observation, and literature review. Then, the field data is processed and analyzed using indirect method calculations. The indirect method of calculating boiler efficiency entails measuring all losses that transpire within the boiler system, encompassing losses resulting from fuel quality, flue gas, and radiation [9].

To assess a boiler's performance, evaluating the boiler's efficiency is crucial. The testing of boiler efficiency aims to determine the optimal efficiency, which might differ from the tested results. Consequently, necessary measures can be implemented to enhance the identified issues and attain peak efficiency. The equations used forassessing fire tube boiler efficiency using the indirect method are formulated from the Bureau of Energy Efficiency's standard calculations for boiler efficiency [10]. The specifications of the fire tube boiler used are:

1. Fuel : Mixed methane fuel
2. Capacity : 55 TPH
3. Pressure : 45 kg/cm^2
4. Temperature : 500˚C

2.1 Calculation Procedure and Measuring Instruments

To calculate heat loss in dry flue gas (L_1) is defined as Eq. 1.

$$L_1 = \frac{m \times C_p \times (T_f - T_a)}{\text{GCV of fuel}} \times 100 \tag{1}$$

m = Mass of dry flue gas (kg/kg of fuel)
C_p = Flue gas specific heat (kcal/kg)
T_f = Temperature of flue gas (˚C)
T_a = Ambient temperature (˚C)

Heat loss due to the formation of water from hydrogen in fuel (L_2) is defined as Eq. 2.

$$L_2 = \frac{9 \times H_2 \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100 \tag{2}$$

H_2 = hydrogen percentage in fuel
C_p = Specific heat of superheated steam (kcal/kg˚C)
T_f = Temperature of flue gas (˚C)
T_a = Ambient temperature (˚C)
584 = The latent heat associated with the partial pressure of water vapor

Heat loss due to moisture in fuel (L_3) is defined as Eq. 3.

$$L_3 = \frac{M \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100 \tag{3}$$

M = moisture in fuel
C_p = Specific heat of superheated steam (kcal/kg˚C)
T_f = Temperature of flue gas (˚C)
T_a = Ambient temperature (˚C)
584 = The latent heat associated with the partial pressure of water vapor

Heat loss due to moisture in air (L_4) is defined as Eq. 4.

$$L_4 = \frac{\mathrm{AAS} \times \mathrm{humidity\ factor} \times \mathrm{C_p} \times (\mathrm{T_f} - \mathrm{T_a}) \times 100}{\mathrm{GCV\ of\ fuel}} \tag{4}$$

AAS = Actual mass of air supplied
C_p = Specific heat of superheated steam (kcal/kg˚C)
T_f = Temperature of flue gas (˚C)
T_a = Ambient temperature (˚C)

Heat loss due to partial conversion of C to CO (L_5) is defined as Eq. 5.

$$L_5 = \frac{\%CO \times C}{\%CO + CO_2} \times \frac{5744}{\mathrm{GCV\ of\ fuel}} \times 100 \tag{5}$$

CO = Volume of CO in flue gas
CO_2 =Volume of CO_2 in flue gas
C = Carbon content in kg/kg fuel

Surface heat loss (L_6) is defined as Eq. 6.

$$L_6 = 0.548 \times \left[\left(\frac{T_s}{55.55}\right)^4 - \left(\frac{T_a}{55.55}\right)^4\right] + 1.957 \times (T_s - T_a)^{1.25} \times \sqrt{\left[\frac{(196.85V_m + 68.9)}{68.9}\right]} \tag{6}$$

V_m = Wind velocity
T_s = Temperature of surface (K)
T_a = Ambient temperature (K)

Heat loss due to unburnt in fly ash (L_7) is defined as Eq. 7.

$$L_7 = \frac{\left(\frac{\mathrm{total\ ash\ collected}}{\mathrm{kg\ of\ burnt}}\right) \times \mathrm{fly\ ash\ GCV} \times 100}{\mathrm{GCV\ of\ fuel}} \tag{7}$$

Heat loss due to unburnt in bottom ash (L_8) is defined as Eq. 8.

$$L_8 = \frac{\left(\frac{\mathrm{Total\ ash\ collected}}{\mathrm{kg\ of\ fuel\ burnt}}\right) \times \mathrm{bottom\ ash\ GCV} \times 100}{\mathrm{GCV\ of\ fuel}} \tag{8}$$

The power plant performance evaluation was carried out based on the data collected from the Production Activity Control and Monitoring Centre (refer to Fig. 1). Fig. 1 describes the work process of the boiler, while the gas fuel (methane) is supplied in the combustion chamber. The water is treated in a Boiler Water Feed (BFW) and heated by an economizer before entering to wall water tube. The water then evaporated until it became superheated steam.

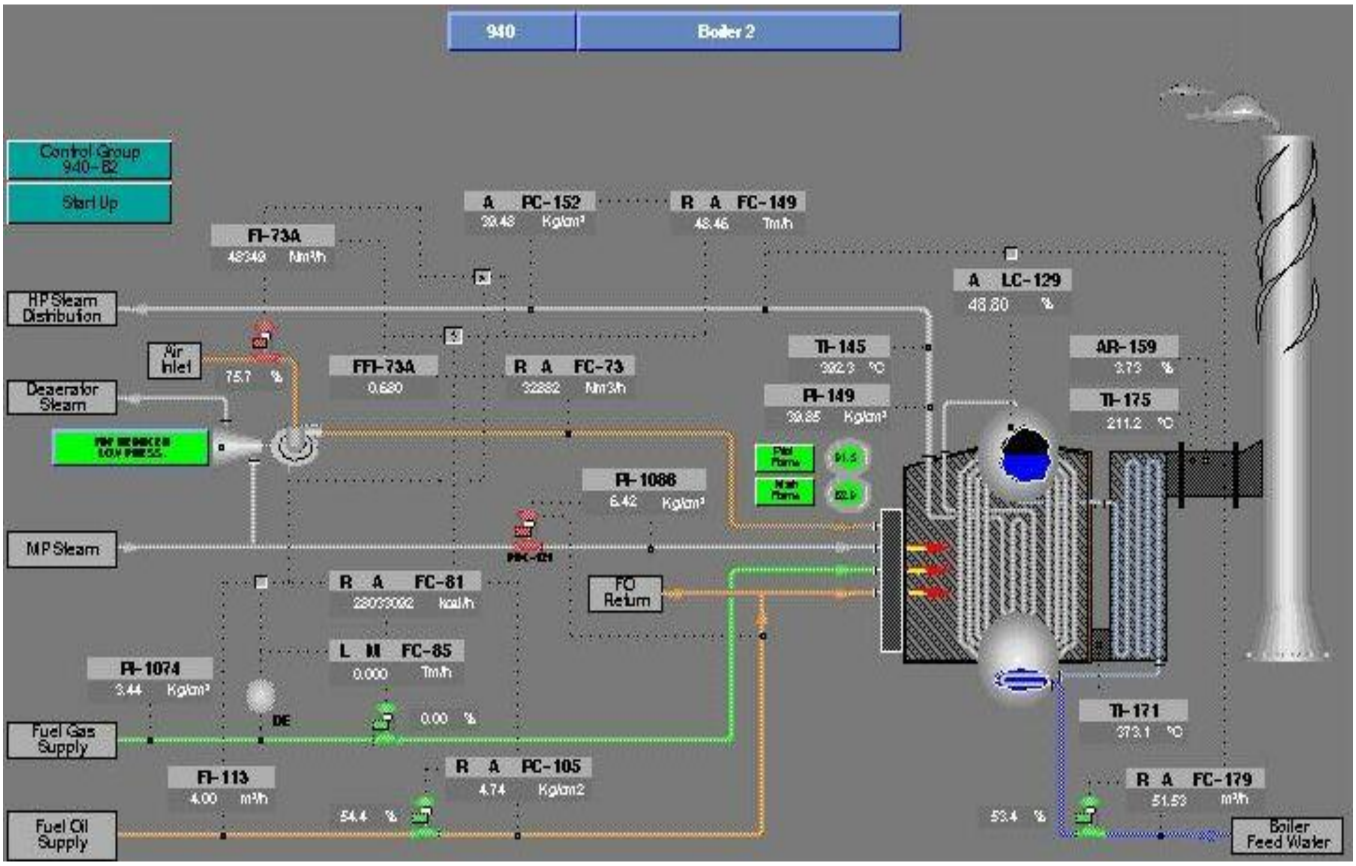

Fig. 1. Process control of boiler.

The data collection method for monitoring boiler performance is comprehensive, starting with a request for detailed information on the fuel composition, which is essential for assessing efficiency and emissions. This understanding enables more accurate performance evaluations and optimization efforts. Additionally, operational data is gathered through the Plant Information Management System (PIMS) that is attached to equipments such as flow meters, temperature sensors, pressure sensors, and gas analyzer, which continuously tracks real-time parameters during operation. Combining static fuel composition data with dynamic operational data allows for a robust analysis of boiler efficiency. By utilizing real-time monitoring, deviations or inefficiencies can be quickly identified and addressed, helping maintain optimal performance, extend lifespan and reduce operational costs.

2.2 Analysis method

The analysis method employed for evaluating the efficiency of a fire-tube boiler fueled by mixed methane gas is the indirect method, commonly referred to as the heat loss method. This approach calculates the boiler's efficiency by determining all potential heat losses within the system rather than measuring the output directly, providing a comprehensive evaluation of the boiler's performance and highlighting areas for potential efficiency improvements. The method involves assessing various operational data, including fuel composition, flue gas temperatures, ambient temperatures, and moisture content in both the fuel and air. Several types of heat losses are quantified, such as those from dry flue gas, moisture in the fuel, moisture in the air, and losses associated with the combustion of hydrogen in the fuel. Each loss type is calculated using specific formulas that incorporate relevant operational parameters, with the heat loss due to dry flue gas determined by the mass of the gas, its specific heat, and the temperature difference between the flue gas and the surrounding air. After computing all losses, the total heat loss is subtracted from 100% to yield the boiler efficiency. This method clarifies the boiler's efficiency while aiding in pinpointing specific inefficiencies in the system, allowing operators to implement targeted improvements, optimize combustion processes, and enhance heat recovery systems for better energy efficiency and reduced operational costs.

3 Results and Discussion

When calculating boiler efficiency using the indirect method, different fuel types influence the types of losses that need to be considered. For gaseous fuels, only 6 types of losses are typically calculated because certain losses associated with solid and liquid fuels are not relevant [10].

1. Heat losses from dry flue gas (L_1).
2. Heat losses from hydrogen in fuel (L_2).
3. Heat losses from moisture in fuel (L_3).
4. Heat losses from moisture in the air (L_4).
5. Heat losses from carbon monoxide (L_5)
6. Heat losses from surface radiation, convection and others (L_6).

3.1 Boiler Efficiency Calculations

The average Relative Humidity (RH) in Riau is approximately 90%, with an average ambient temperature of 25°C. Air humidity can be measured utilizing psychrometric charts, as outlined in [11]. The RH data was obtained from the Meteorological, Climatological, and Geophysical Agency (BMKG) at the Sultan Syarif Kasim II Meteorological Station. This humidity parameter is essential for calculating boiler efficiency via the indirect method, particularly for determining the heat loss percentage attributable to moisture in the air (L_4), which incorporates the humidity factor.

Based on the psychometric charts in Fig. 2, we can determine the value of air humidity, it is 0.018.

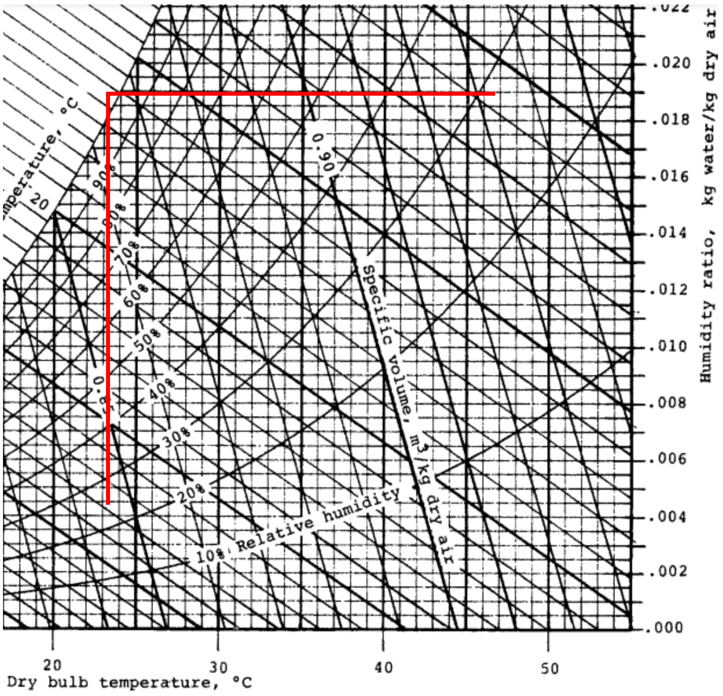

Fig. 2. Psychometric charts.

Using the data from Table 1, the values of elements content in the fuel composition can be calculated. The molar mass of carbon (C) is 12.011 g/mol. The molar mass of methane (CH_4) is 16.043 g/mol, which is derived from the molar mass of carbon (12.011 g/mol) and hydrogen (4×1.008 g/mol).

Table 1. Gas component data

Gas Component	Mole (%)
C_1 (CH_4)	87.942
C_2 (C_2H_6)	4.1549
C_3 (C_3H_8)	2.0225
iC_4 (C_4h_{10})	0.3714
nC_4 (C_4H_{10})	0.4731
iC_5 (C_5H_{12})	0.1434
nC_5 (C_5H_{12})	0.0952
C_6+ (C_6H_{14})	0.2024
N_2	0.2851
CO_2	4.3021
H_2S	0.0001

The carbon content is:

$$\frac{12.011\text{g/mol(C)}}{16.043\text{g/mol(CH}_4\text{)}} \times 100(\%) = 74.87\%$$

The carbon content of CH_4 in fuel is:

$$74.87\% \times 87.942 = 65.842\%$$

The carbon content in fuel is:

$$\begin{aligned}\text{Carbon} &= \text{Carbon content}(c1 + c2 + c3 + iC4 + nC4 + iC5 \\ &\quad + nC5 + (c6 +) + N_2 + CO_2 + H_2S + H_2O)\% \\ &= 65.842 + 3.323 + 1.651 + 0.306 + 0.391 + 0.119 \\ &\quad + 0.079 + 0.169 + 0 + 1.173 + 0 + 0)\% \\ &= 73.0571534\%\end{aligned}$$

The equation is applied to the remaining elements and gas components from Table. 1, with the results presented in Table 2.

Table 2. Ultimate and proximate analysis data of fuel for the indirect method

Descriptions	Values
Carbon	73.0571534%
Hydrogen	23.5218017%
Nitrogen	0.2851%
Oxygen	3.13585075%
Sulfur	0.00009412%
Moisture	0.0078
GCV of fuel	12575.45 cal/g
Air humidity	0.018
Flue gas analysis	
Flue gas temperature	211.2°C
Ambient temperature	25°C
CO_2 % in flue gas by volume	10
O_2% in flue gas by volume	3

The Gross Calorific Value (GCV) or HHV of fuel was obtained by using the data from Table A-25 from Thermodynamics: An Engineering Approach book.

HHV of methane (CH_4) in fuel:

$$\begin{aligned}HHV_{fuel}(CH_4) &= HHV(CH_4) \times \text{mole\%} \\ &= 55510 \times 87.942\% \\ &= 48816.6kJ/kg\end{aligned}$$

GCV of fuel:

$$\begin{aligned}GCV &= \text{HHVfuel } (c1 + c2 + c3 + iC4 + nC4 + iC5 + nC5 \\ &\quad + (c6 +) + N_2 + CO_2 + H_2S + H_2O) \\ &= 52615.622 \frac{kJ}{kg} \times 0.239 \\ &= 12575.45\ cal/kg\end{aligned}$$

The flue gas temperature was taken from the exhaust temperature in Fig. 1. The ambient temperature is 25°C based on data by BMKG. And the CO_2 and O_2 percentage are 10% and 3% [12]. These are the data required for indirect method calculations.

3.2 Operational Data

1. Theoretical air required for combustion

$$= \frac{\left[(11.6 \times C) + \left\{34.8 \times \left(H_2 - \left(\frac{O_2}{8}\right)\right) + (4.35 \times S)\right\}\right]}{100}$$

$$= \frac{\left[(11.6 \times 3{,}136) + \left\{34.8 \times \left(23.522 - \left(\frac{3{,}136}{8}\right)\right) + (4.35 \times 0)\right\}\right]}{100}$$

$$= 16.523 \text{ kg/kg of fuel}$$

2. Excess Air supplied (EA)

$$= \frac{(O_2 \times 100)}{(21 - O_2)}$$

$$= \frac{(3 \times 100)}{(21 - 3)}$$

$$= 16.666\ \%$$

3. Actual mass of Air Supplied/kg of fuel (AAS)

$$= \left[\frac{1 + EA}{100}\right] \times \text{Theoritical air}$$

$$= \left[\frac{1 + 16.666}{100}\right] \times 16.523$$

$$= 19{,}277 \text{ kg/kg of fuel}$$

4. Mass of dry fuel gas (m)

$$= \text{Mass of} (CO2\ +\ SO2\ +\ N2\ +\ O2) \text{ in flue gas} \\ +\ N2 \text{ in air weare supplying}$$

$$= \left(\frac{0.73057 \times 44}{12} + 0.043 \times 44\right) + \frac{0.00 \times 64}{32} + 0.0028 \\ + \frac{3 \times 23}{100} + \frac{19.277 \times 77}{100}$$

$$= 20.108 \text{ kg/kg of fuel}$$

3.3 Boiler Efficiency Calculation

3.3.1 Heat Loss Percentage in Dry Flue Gas

$$L_1 = \frac{m \times C_{p\,\text{flue gas}} \times (T_f - T_a)}{\text{GCV of fuel}} \times 100$$

$$L_1 = \frac{20.108 \times 0.238 \times (211.2 - 25)}{12575} \times 100$$

$$= 7.109\ \%$$

Typically, the heat loss due to dry flue gas is the greatest in a boiler [12]. This type of loss occurs when hot combustion gases exit the boiler through the flue without transferring their heat effectively to the water or steam being generated. This loss can be significant because it involves the largest amount of heat escaping, and therefore represents the greatest opportunity for improving boiler efficiency through heat recovery systems or better combustion control.

Heat loss due to dry flue gas is considered the biggest loss because it involves both the sensible heat of the flue gas and the latent heat of water vapor contained in the flue gas, which can be substantial depending on the fuel type and combustion conditions.

3.3.2 Heat Loss Percentage due to Evaporation of Water due to Hydrogen in Fuel

$$L_2 = \frac{9 \times H_2 \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

$$L_2 = \frac{9 \times 0.23 \times \{584 + 0.57(211.2 - 25)\}}{12575} \times 100$$

$$= 11.617\ \%$$

Heat is lost during the combustion of hydrogen because the byproduct is water, which is then transformed into steam, releasing latent heat. When hydrogen combusts, it reacts with oxygen to form water vapor (H_2O) [13]. This reaction is exothermic, releasing energy. However, the water produced is initially in liquid form and to become steam, it must absorb a significant amount of energy known as the latent heat of vaporization. This energy absorption happens at a constant temperature, typically 100 degrees Celsius at standard atmospheric pressure, and represents the energy required to change the state from liquid to gas without changing temperature. The data of specific heat of superheated steam was obtained from interpolation of Table A-4 from Thermodynamics: An Engineering Approach book by using the pressure and temperature data from Fig. 1

The latent heat absorbed by the water to become steam is not available for useful work and is thus considered a loss in the energy conversion process. In practical applications like fuel cells or internal combustion engines, this latent heat loss reduces the overall efficiency of the system, as some of the energy from hydrogen combustion is diverted to converting water into steam instead of being harnessed directly for mechanical or electrical work [13].

3.3.3 Heat Loss Percentage due to Moisture in Fuel

$$L_3 = \frac{M \times \{584 + C_p(T_f - T_a)\}}{\text{GCV of fuel}} \times 100$$

$$L_3 = \frac{0.0078\ \times \{584 + 0.57(211.2 - 25)\}}{12575} \times 100$$

$$= 0.042\ \%$$

The superheated vapor of moisture entersthe boiler with the fuel leaves. The heat required to raise the moisture to its boiling point, the heat released during the process of evaporation, and the additional heat It was necessary to increase the boiling point of the evaporated moisture (steam) to equal that of the exhaust gas.

3.3.4 Heat Loss Percentage due to Moisture in the Air

$$L_4 = \frac{AAS \times \text{humidity factor} \times C_p \times (T_f - T_a) \times 100}{\text{GCV of fuel}}$$

$$L_4 = \frac{19.277 \times 0.018 \times 0.57 \times (211.2 - 25) \times 100}{12575}$$

$$= 0.292\%$$

As the incoming air flows through the boiler, it becomes extremely hot, causing the release of water vapor in the form of humidity. This heat should be considered as a boiler loss since it is expelled through the stack. The losses are determined by utilizing the air humidity measurements obtained from the psychometric charts.

3.3.5 Heat Losses from Partial Conversion of Carbon (C) to Carbon Monoxide (CO)

$$L_5 = 0$$

Since there is no Carbon Monoxide (CO) contained in the fuel, the losses due to partial combustion are considered to be zero. This is because CO is a primary indicator of incomplete combustion. Incomplete combustion occurs when there is not enough oxygen to allow the fuel to react completely to produce Carbon Dioxide (CO_2) and water (H_2O). Instead, it produces Carbon Monoxide (CO) and other hydrocarbons as by-products.

When combustion is complete, all the carbon in the fuel converts to CO_2. However, in partial or incomplete combustion, some of the carbon is released as CO, which signifies inefficiencies and losses in the combustion process [14]. If the fuel does not produce any CO, it implies that the combustion is complete and efficient, with no significant losses due to incomplete combustion.

3.3.6 Heat Loss Percentage from Radiation and Convection Loss

$$L_6 = 0,5\%$$

Typically, the estimation of surface loss and other unaccounted losses is based on the characteristics and dimensions of the boiler, as indicated in reference [9]. Losses in industrial fire tube/packaged boiler are 1.5% to 2.5%, losses in industrial water tube boilers are 2% to 3%, and losses in power station boilers are 0.4% to 1%.

After calculating using the indirect method, the results from each loss are shown in Table 3.

Table 3. Boiler losses and efficiency

Losses	Percentage (%)
Heat losses in dry flue gas (L_1)	7.109
Heat loss due to the formation of water from h2 in fuel (L_2).	11.617
Heat losses due to moisture in fuel (L_3)	0.042
Heat loss due to moisture in the air (L_4)	0.292
Heat loss due to partial conversion of C to CO	0
Radiation and convection loss	0.5
Boiler efficiency (indirect method)	80.436

3.4 Discussion

Based on calculation results, the boiler efficiency by indirect method is 80.436%. This outcome satisfies the boiler's standard efficiency value since an efficient boiler is defined as having an efficiency value between 70% and 90% [15].

Refers to Fig. 3 the boiler's greatest losses came from heat loss percentage due to the evaporation of water due to hydrogen in fuel (L_4).

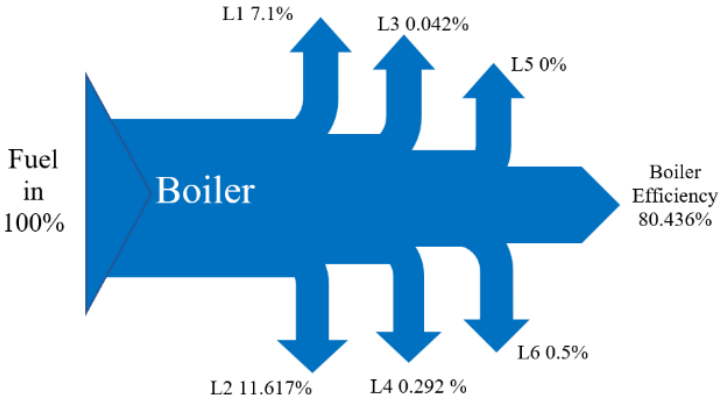

Fig. 3. Sankey charts of the boiler efficiency

Thermal losses originating from dry flue gas, hydrogen in the fuel, fuel moisture, air, surface radiation, and surface convection substantially affect boiler efficiency. Loss due to dry flue gas transpires when the flue gas is not fully harnessed to transfer heat prior to expulsion, thereby diminishing efficiency. To mitigate this loss, improving insulation and adopting heat recovery systems such as economizers or condensing heat exchangers is recommended.

Hydrogen-related heat loss arises when hydrogen in the fuel reacts with oxygen from the combustion air to produce water vapor, resulting in a loss of usable heat. The result shows that this loss is the biggest loss because the content of hydrogen in fuel is high. Maintaining an optimal fuel-to-air ratio and utilizing combustion control systems can ensure complete combustion and reduce excess water vapor production. Moisture-related loss in the fuel occurs when the moisture content absorbs heat during combustion without contributing to effective energy output. Pre-drying the fuel and selecting fuels with lower moisture content or alternative sources can mitigate this issue.

Additionally, air preheating and dehumidification systems can reduce moisture content in combustion air. Surface radiation loss happens when heat is emitted from the boiler's surfaces as electromagnetic radiation. Enhanced insulation and refractory materials can decrease radiation loss. Surface convection loss occurs when heat is carried away from the boiler's surfaces by circulating gases or liquids. Enhancing heat transfer surfaces within the boiler and applying heat-resistant coatings can lessen convective heat losses. Boiler blowdown loss occurs during the blowdown process, leading to considerable heat energy wastage. Implementing efficient blowdown control strategies and heat recovery systems can reduce these losses and enhance boiler efficiency. To reduce losses, it is advisable to enhance insulation and implement heat recovery systems like economizers or condensing heat exchangers.

4 Conclusion

Based on the analysis of the data, the indirect method's value for the boiler efficiency is 81.64%. The moisture from burning hydrogen in the fuel sources is the main source of losses, this result is caused by the higher content of hydrogen in the fuel. Hydrogen in the fuel, when burned, reacts with oxygen to produce water vapor. This water vapor absorbs a significant amount of latent heat during the phase change from liquid to gas. Then it is followed by losses due to dry flue gas, this loss occurs when the heat in the flue gas is not fully transferred to the water or steam in the boiler. It is recommended to implement heat recovery systems, such as economizers or air preheaters, to capture waste heat from the flue gas and utilize it for the preheating of feed water or combustion air.

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