Evaluation of Slagging and Fouling Indices in Boilers, for Steam Power Plant

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Abstract

Coal acts as the primary fuel for the boiler at PLTU to support the combustion process. The boiler serves as the main steam generator in this coal-fired power plant. During combustion, coal produces ash that deposits and leads to slagging and fouling, two conditions that reduce boiler efficiency and performance[4]. This study analyses how slagging and fouling affect the performance of Boiler at PLTU. Using a quantitative approach, the research evaluates coal quality data (proximate and ultimate analyses), ash compound content, sulphur levels, and calculates slagging and fouling indices in relation to boiler performance [1]. The results show that the slagging index ranges from 0.15 to 0.77 and the fouling index from 0.19 to 0.48, indicating a low to moderate tendency. When these indices are at their lowest, boiler efficiency reaches 88.05% (direct method) and 86.09% (indirect method). At their highest, efficiency drops to 78.25% and 78.65%, respectively. This decline increases coal consumption for electricity generation [5]. These findings highlight the need for regular inspection of ash content and coal quality to reduce the negative effects of slagging and fouling on overall boiler performance.

Keywords: *Boiler Efficiency, Coal, Fouling, Power Plant, Slagging.*

1. Introduction

Coal remains the primary source of electricity generation in Indonesia. This is reflected in the fact that approximately 67% of Indonesia's electricity supply comes from coal-fired steam generators. Fuel standardization is necessary because a suitable energy source will ensure optimal combustion [2]. Therefore, coal quality is a primary concern for steam power plant. One component of the power plant is the boiler [4]. The boiler functions as a device that converts the chemical energy of coal into heat energy in steam. Coal requirements for power generation are determined by boiler capacity and coal quality. When coal is burning in a boiler, it produces ash [3]. This ash content reduces the heat absorption capacity. The accumulation of ash in the boiler area is commonly referred to as slagging and fouling. The presence of slagging and fouling is closely related to the heat transfer process in the boiler tube and is feared to reduce boiler performance.

1.1. Purpose of the Evaluation

The objectives of evaluating slagging and fouling indices are as follows:

a. Identify the potential for coal adhesion on the boiler to prevent damage.
b. Maintain heat transfer efficiency to prevent damage to boiler components.
c. Ensure safe and stable power plant operations.

1.2. Significant of the Research

Slagging evaluation is of critical importance because the accumulation of coal ash deposits has severe consequences for the boiler; buildup on the radiant furnace walls can impede the rate of heat transfer to the fluid within the water wall tubes [10]. This results in suboptimal energy absorption and a drastic decline in boiler thermal efficiency, leading to increased coal consumption to meet power demands [11]. Furthermore, fuel wastage poses safety and financial risks if this issue is not evaluated.

1.3. Literature Review

1.3.1 Coal Specifications for PLN

Coal serves as the primary fuel for the boiler for steam Power plant; however, the coal specifications must align with the boiler design to prevent corrosion or slagging issues. Generally, PLN boilers utilize coal ranging from sub-bituminous to bituminous grades, with a calorific value of 4,200–6,000 kcal/kg (Gross As Received/GAR), a moisture content of 25–40%, and low ash and sulfur levels. While the coal's calorific value does not directly influence slagging formation, the primary factors driving slagging are the chemical composition of the ash and the Ash Fusion Temperature (AFT) [**12**]. In general, the technical coal specifications established for power plant operations include:

a. Calorific Value (Gross Calorific Value - GCV): Typically ranges from 4,200 to 6,000 kcal/kg (GAR), depending on the power plant boiler's original design.
b. Moisture Content (Total Moisture - TM): Usually capped within the 25–40% range to maintain combustion efficiency. Volatile Matter (VM): The ideal range is 30–45% to ensure ease of ignition within the furnace.
c. Ash Content: Generally limited to below 10–15% to minimize deposit formation (slagging and fouling) on boiler tube walls.
d. Sulfur Content (Total Sulfur): Required to be low (ranging from below 1% up to a maximum of 3%) to prevent acid corrosion and suppress flue gas emissions.

1.3.2. Determining the slagging index

The slagging potential of power plant boilers is determined using several empirical indices based on the chemical analysis of coal ash. The primary indices most frequently used are the Base-to-Acid Slagging Index (Rs), the Sulfur Slagging Index (Rs*), and the Silica Ratio (SR). The formulas and assessment categories for each index are as follows [**8**]:

a. Base-to-Acid Ratio (B/A)

The ratio of basic components (metal oxides) to acidic components (silica and alumina) in the ash:

$$\mathbf{B/A} = \frac{\%Fe_2O_3+\%CaO+\%MgO+\%Na_2O+\%K_2O}{\%SiO_2+\%Al_2O_3+\%TiO_2} \quad (1)$$

b. Sulfur-Based Slagging Index (Rs)

This index multiplies the B/A ratio by the total sulfur content of the coal on a dry basis. This formula is highly accurate for bituminous coal refer to:

$$R_s = (B/A)\ x\ \%Sulfur_{dry} \quad (2)$$

Slagging category (Rs)

- low : Rs < 0,6
- medium : 0,6 ≤ Rs ≤ 2,0
- High : 2,0 ≤ Rs ≤ 2,6
- Severe : Rs > 2,6

c. Silica Ratio (SR)

This ratio is used to assess the viscosity of the ash in its molten state. The lower the SR value, the more fluid the ash becomes, making it easier for it to adhere strongly to boiler pipes.

d. Slagging Index Based on Ash Melting Temperature (Ash Fusion Index)

This index compares the ash softening temperature (ST) with the ash fluid temperature (FT) under reducing atmosphere conditions [7]:

$$Temperature\ Index = \frac{4\ x\ ST + FT}{5} \tag{3}$$

1.3.3. Relationship between Coal Quality and Ash Characteristics

To analyze potential boiler issues, coal quality is further evaluated through two specific tests:

a. Ash Composition Analysis (Ash Analysis)

Measuring the percentage of metal oxides in the ash. Ash properties are divided into two broad categories:

1. **Acid Oxide (SiO_2, Al_2O_3, TiO_2):** It maintains the structure of the ash so that it does not melt easily.
2. **Basic Oxide (Fe_2O_3, CaO, MgO, Na_2O, K_2O):** It lowers the ash melting point (acting as a fluxing agent). If the concentration is high, the risk of slagging increases drastically.

b. Ash Melting Point (Ash Fusion Temperature / AFT)

Test the change in shape of the ash when heated gradually. There are 4 important temperature phases:

1. **Initial Deformation Temperature (IDT):** The ash began to soften, and its surface became sticky.
2. **Softening Temperature (ST):** The ash changes shape into spheres or rounded cubes. This temperature serves as a critical parameter for the onset of slagging.
3. **Hemispherical Temperature (HT):** The ash melts to form a half ball.
4. **Fluid Temperature (FT):** The ash has completely melted and is ready to flow, forming a solid crust as it cools.

2. Method

This study utilized bituminous coal and involved analyzing the ash composition—specifically the percentages of oxides such as SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, and K_2O—as well as conducting proximate analysis and Ash Fusion Temperature (AFT) testing to measure the ash's phase-change points during heating (ranging from Initial Deformation Temperature/IT and Hemispherical Temperature/HT to Fluid Temperature/FT). The slagging index parameter was calculated by multiplying the base-to-acid ratio by the coal's sulfur content (on a dry basis). Finally, the calculated value was compared against standard criteria to classify the slagging potential as low, medium, or high.

3. Results and Discussion

This section presents the research results together with their discussion. Tables or graphs may be added to facilitate the interpretation of the results, Coal Quality Analysis [9].

a. Proximate Analysis

Proximate analysis of coal is used to determine the moisture percentage of coal. Proximate analysis of coal can also be used to determine the gross calorific value of coal. The proximate analysis values in this study are as follows:

Table 1. Proximate Analysis Data in Coal Utilization according to

Parameter Analysis						
Sample	TM (Ar)	AC (Adb)	VM (Adb)	FC (Ar)	GCV (Ar)	TM : Total Moisture AC : Ash Content
A	34,32	5,3	38,77	29,53	4167	VM : Volatile Mater
B	36,03	5,96	38,87	27,44	4002	FC : Fixed Carbon
C	32,97	4,25	39,96	30,14	4244	GCV: Gross Calorific Value
D	35,09	4,18	40,12	27,97	4104	Ar : As received
A	34,33	5,56	39,63	29,59	4170	Adb : Air Dried Basisi

The results of the proximate analysis in the study showed that coal samples from PT. PLN Nusantara Power UP Paiton 9 had a moisture content (TM) ranging from 32.97% to 36.03% (Ar), ash content (AC) ranging from 4.18% to 5.96% (adb), volatile matter (VM) content ranging from 38.77% to 40.62% (adb), and a calorific value (GCV) ranging from 4002 Kcal/kg to 4244 Kcal/kg.

b. *Ultimate Analysis*

Ultimate analysis is useful for describing the reactions that occur between elements in coal. The values of ultimate analysis in this study are as follows:

Table 4.2 Ultimate Data Analysis

Parameter Analysis						
Sample	**C (db)**	**H (db)**	**N (db)**	**S (db)**	**O (db)**	O : Oxygen C : Carbon
A	72,87	4,12	1,12	0,32	13,88	H : Hydrogen
B	68,21	5,03	1,11	0,8	24,53	N : Nitrogen
C	72,95	3,48	0,97	0,24	14,39	S : Sulfur
D	72,24	4,62	1,1	0,15	18,11	db : Dried Basisi
A	72,61	4,16	1,05	0,29	14,02	

The ultimate analysis results showed that the sample had a carbon (C) content ranging from 68.21% to 72.95% (db), hydrogen (H) content ranging from 3.48% to 5.03% (adb), nitrogen (N) content ranging from 0.97% to 1.12% (db), sulfur (S) content ranging from 0.15% to 0.8% (db), and oxygen content ranging from 13.88% to 24.53%.

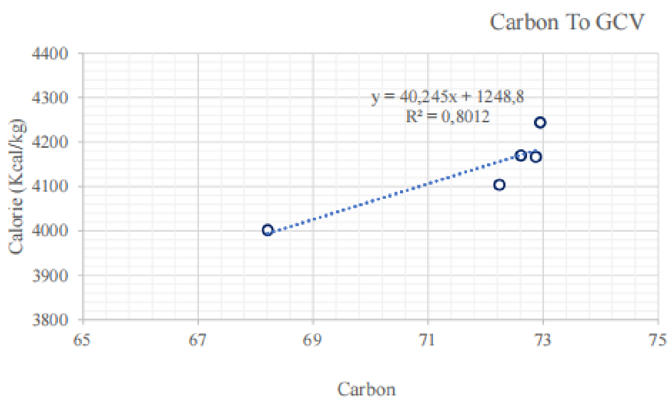

Figure 1. Relationship between Carbon and GCV

Figure 1 shows a good correlation (R2 = 0.8012) between carbon content (and calorific value (GCV)), which explains that carbon content and calorific value (GCV) are directly proportional, in accordance with existing theory. Carbon content is the most abundant element burned in the coal combustion process, so the carbon content increases as the calorific value of the coal increases [**9**].

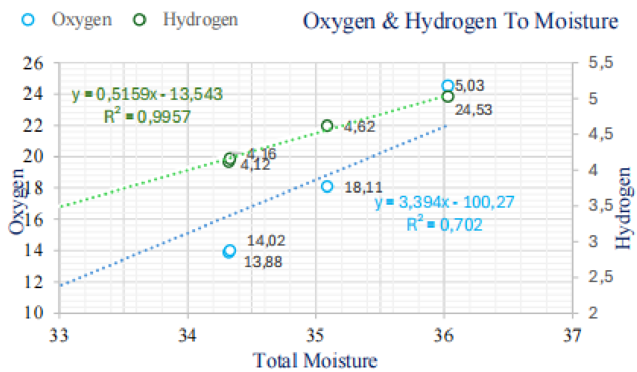

Figure 2. Relationship between Oxygen and Hydrogen and Moisture

Figure 2 shows a fairly good correlation (R2 = 0.702) between oxygen content and total moisture, indicating that the higher the oxygen content, the higher the moisture content. Figure 4.2 also shows a good correlation (R2 = 0.9957) between hydrogen content and moisture. Like oxygen, high hydrogen content has the potential to increase the moisture content of coal, as oxygen and hydrogen contribute to increasing the amount of water (moisture) in coal. High humidity reduces combustion energy due to the increased moisture content, diverting energy that should be used for combustion to evaporate the water (moisture) in the coal.

3.1 Ash content and slagging analysis – Fouling Index

The ash composition in the form of chemical compounds (oxides) is required for calculating and determining the slagging-fouling index. This compound composition results from coal combustion. This compound data is obtained from testing incoming coal samples from suppliers and recorded on the certificate of sampling and analysis (CoA) in a moisture-free or dry condition.

Table 3. Ash Analysis

Parameter (%)	Ash Analysis Sample				
	A	B	C	D	A
SiO_2	28,49	28,01	37,56	34,25	27,54
Al_2O_3	16,25	13,56	12,25	13,51	14,12
Fe_2O_3	24,98	22,17	22,51	29,85	27,36
CaO	15,23	12,36	10,36	10,87	15,41
MgO	8,76	4,29	5,62	5,68	10,02
TiO_2	0,25	0,45	0,65	0,77	0,36
Na_2O	0,28	0,5	0,28	0,2	0,25
K_2O	0,4	0,89	0,96	0,65	0,51
Mn_3O_4	0,27	0,37	0,9	0,43	0,22
P_2O_5	0,09	0,47	0,32	0,11	0,16
SO_3	4,53	16,17	8,14	2,79	0,89
Sulfur	28,49	28,01	37,56	34,25	27,54

The comparative data of Fe2O3 with CaO and MgO obtained from table 3 is used to determine the type of coal ash used, whether bituminous or lignitic ash.

Table 4. Ash Classification

Sample	Ash Classification	
A	Bituminous	Fe_2O_3 > CaO + MgO 24,98 > 15,23 + 8,76
B	Bituminous	Fe_2O_3 > CaO + MgO 22,17 > 12,36 + 4,29
C	Bituminous	Fe_2O_3 > CaO + MgO 22,51 > 10,36 + 5,62

Sample	Ash Classification	
D	Bituminous	Fe_2O_3 > CaO + MgO 29,85 > 10,87 + 5,68
A	Bituminous	Fe_2O_3 > CaO + MgO 27,36 > 15,41 + 10,02

The results in Table 4 indicate that the Slagging-Fouling Index calculation in this study did not include the ash fusion temperature (AFT) or ash melting point because the coal used in this study was bituminous.

3.2 Slagging Index

To calculate the slagging index, the data used are the acid-base ratio and sulfur content. The slagging-base value is obtained from the ratio of basic compounds (CaO, MgO, Fe2O3, Na2O, and K2O) to acidic compounds (SiO2, Al2O3, and TiO2).

Table 5. Slagging Calculation

Sample	Base Acid Ratio (B/A)	Slagging Index (Rs)
A	1,10	0,35
B	0,96	0,77
C	0,79	0,19
D	0,97	0,15
A	1,27	0,37

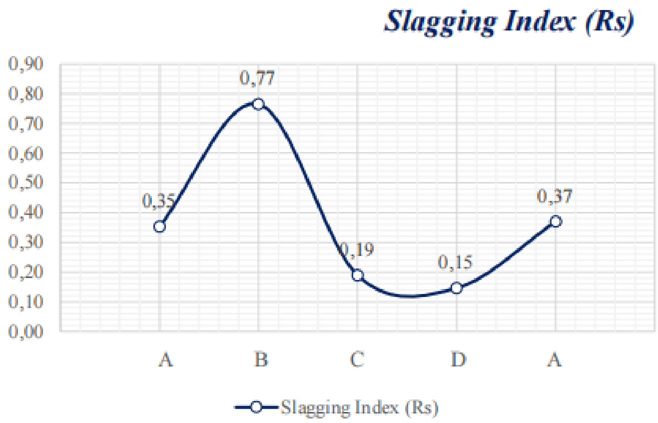

Figure 3. Slagging Index

Figure 3 illustrates the relationship between the calculated slagging index results and the coal combustion process. The graph shows that the highest slagging index result was found in the coal sample from supplier B, with a value of 0.77. The 0.77 value indicates a classification based on slagging inclinations for bituminous coal, which falls into the medium severity range (0.6 < Rs < 2.0), while the lowest slagging index was found in the coal sample from supplier D, with a value of 0.15. The 0.15 value indicates a classification based on slagging inclinations for bituminous coal, which falls into the low severity range (Rs < 0.6).

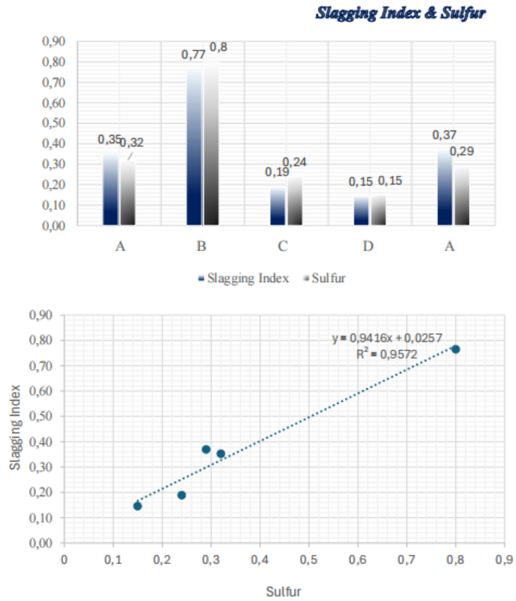

Figure 4. Relationship between Sulfur and Slagging Index

Figure 4 shows the correlation (R2 = 0.9572) between sulfur content and the slagging index. Figure 4 explains that, despite not having the highest acid-base ratio, the slagging index value from supplier B is due to the sulfur content in supplier B's coal. This is intended to determine which supplier has the highest slagging index value among other suppliers. Similarly, supplier D's coal has the lowest slagging index value. t can be said that the higher the sulfur content of coal, the greater the potential for slagging to form in the boiler. High levels of slagging will impact boiler efficiency because slagging inhibits heat transfer and potentially increases flue gas pressure due to heat loss.

3.3 *Fouling Index*

The data required to calculate the slagging index are the acid-base ratio and sodium oxide (Na2O) content. The slagging-base value is obtained from the ratio of basic compounds (CaO, MgO, Fe2O3, Na2O, and K2O) to acidic compounds (SiO2, Al2O3, and TiO2).

Sample	Base Acid Ratio (B/A)	Fouling Index (Rs)
A	1,10	0,31
B	0,96	0,48
C	0,79	0,22
D	0,97	0,19
A	1,27	0,32

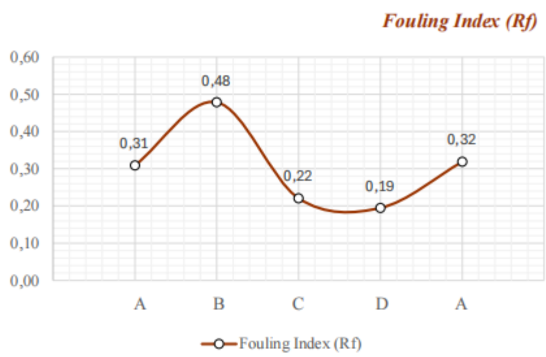

Figure 5. Fouling Calculation

Figure 5 explains the relationship between the fouling index calculations and the coal combustion process. The graph shows that the highest fouling index was found in the coal sample from supplier B, with a value of 0.48. The value of 0.48 refers to the classification based on slagging inclinations for bituminous coal, which is classified as medium (0.2 < Rf < 0.5), while the lowest fouling index was found in the coal sample from supplier D, with a value of 0.19.

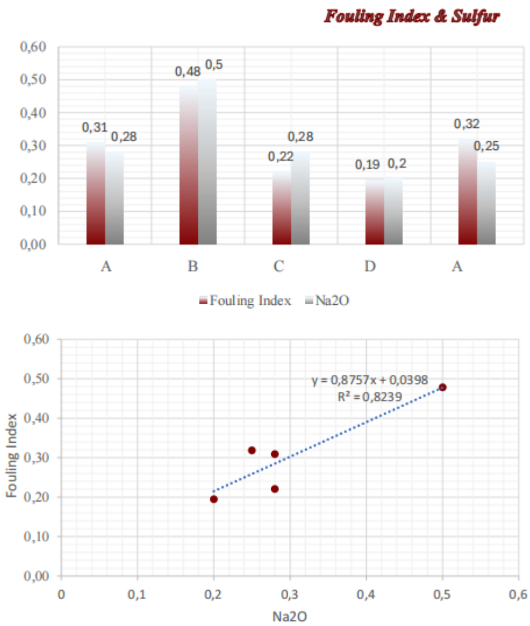

Figure 6. Relationship between Na2O and Fouling Index

Figure 6 shows the correlation (R2 = 0.8027) between sulfur content and the slagging index. Figure 6 explains that, despite not having the highest acid-base ratio, the high fouling index value from supplier B is due to the sodium oxide (Na2O) content in supplier B's coal, which is the highest among the other suppliers, and the same is true for supplier D's coal, which has the lowest fouling index.

3.4. Boiler Performance

The calculation data is divided into two types: the direct method and the indirect method. The purpose of this calculation is to determine the boiler efficiency value based on the energy from the coal fuel compared to the energy generated by the steam. Meanwhile, the indirect method calculation data is used to determine the extent of efficiency loss based on the source of the energy loss (heat) [7].

1. Based on technical data collected from the field, boiler efficiency calculations were obtained using the direct method. Boiler efficiency calculations using the direct method on coal sample C yielded a value of 87.30%. The same calculation (direct method) was also applied to the other samples, yielding the following results: 88.05.
2. The boiler efficiency calculation using the indirect method on coal sample C yielded a value of 86.09%.
3. The results of the direct method analysis of boiler efficiency showed the highest efficiency in coal sample C, which was used for the combustion process.
4. The boiler plant heat rate calculation for coal sample C yielded a value of 2268.26 Kcal/kWh for the gross value and 2472.29 Kcal/kWh for the net value.
5. The boiler thermal efficiency calculation for coal sample C yielded a value of 37.92.
6. The specific coal consumption calculation for coal sample C yielded a value of 0.534 Kg/kWh for the gross value and 0.583 Kg/kWh for the net value.

3.5. Effect of Slagging and Fouling Indices on Boiler Performance

The results of the direct method calculations were used as a comparison with the slagging and fouling index to determine the significant influence of the slagging and fouling index on boiler performance. The direct method was chosen as a comparison because it uses input (energy used) and output (energy produced), thus more accurately representing the actual situation. While the indirect method was used as a guide to identify the sources and magnitude of potential energy (heat) losses due to slagging and fouling.

Supplier	Efficiency (Direct Method)	Slagging Index	Fouling Index
A	85,36%	0,35	0,30
B	78,25%	0,77	0,48
C	88,05%	0,19	0,22
D	86,66%	0,15	0,19

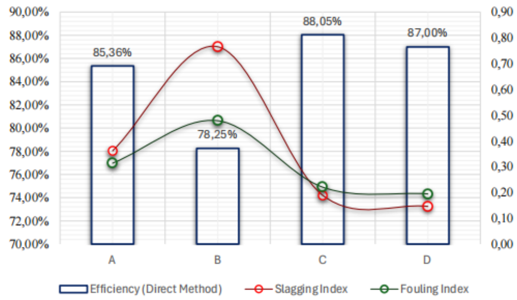

Figure 6. The Relationship Between Slagging & Fouling and Boiler Efficiency

The calculation and analysis results in Figure 6 show that the highest efficiency was found in supplier C's coal sample, with an efficiency value of 88.05% at a low slagging index (0.19) and a medium fouling index (0.22). The lowest efficiency was found in supplier B's coal sample, with an efficiency value of 78.25% at a medium slagging index (0.77) and a medium fouling index (0.48).

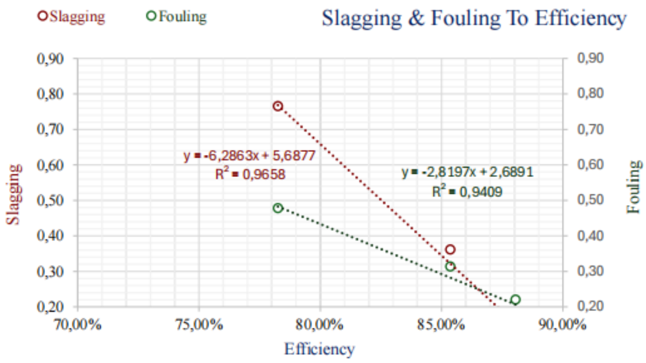

Figure 7. Slagging & Fouling on Boiler Efficiency

Figure 7 shows the correlation between the slagging and fouling index and boiler efficiency. The higher the slagging and fouling index, the lower the boiler efficiency, and vice versa.

Table 6. Indirect Method (Heat Losses)

	Heat Loss Parameter									
Supplier	L1	L2	L3	L4	L5	L6	L7	L8	Total Losses	Efficiency (%)
A	5,19	4,34	4,97	0,349	0,110	0,180	0,018	0,106	15,15	84,85
B	9,35	5,19	6,08	0,280	0,105	0,180	0,023	0,136	21,35	78,65
C	4,89	3,59	4,82	0,244	0,109	0,180	0,010	0,069	13,91	86,09
D	3,76	4,45	5,63	0,233	0,104	0,180	0,011	0,067	14,43	85,57

Table 6 shows that the greater the amount of heat loss, the lower the boiler's efficiency because the heat from combustion that should be absorbed to generate energy (electricity) must be lost under certain conditions. The most influential parameters in calculating heat loss using the indirect method are heat loss in dry flue gas (L1), heat loss due to water formation by H2 in the fuel (L2), and heat loss due to moisture in the fuel (L3).

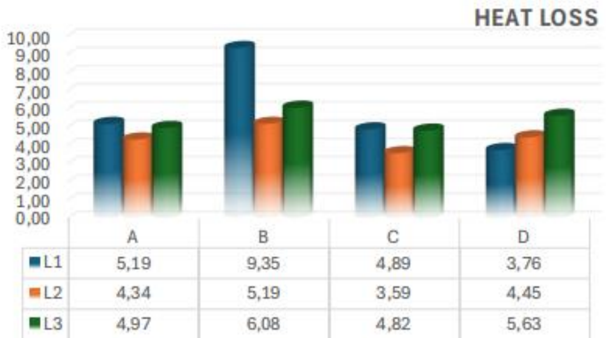

Figure 8. Heat Loss

4. Conclusion

The coal used in this study was bituminous, with the highest slagging index of 0.77 and the lowest slagging index of 0.15. The highest fouling index was 0.48 and the lowest fouling index was 0.19. The potential for slagging and fouling indexes is in the low to medium range. The results of the boiler efficiency calculation obtained the highest efficiency value of 88.05% for the direct method and 86.09% for the indirect method at a slagging index of 0.19 and a fouling index of 0.22, while the lowest efficiency value was 78.25% for the direct method and 78.65% for the indirect method at a slagging index of 0.77 and a fouling index of 0.48. The results of the calculation of heat absorption performance obtained the most optimal value of 2256.15 Kcal/kWh (gross), 2459 Kcal/kWh (net) for PHR and 38.12% for thermal efficiency at slagging index conditions of 0.15 and fouling index of 0.19 while the worst value in heat absorption was at 2332.72 Kcal/kWh (gross), 2542 Kcal/kWh for PHR and 36.87 for thermal efficiency at slagging index conditions of 0.77 and fouling index of 0.48. The difference in efficiency values affects fuel consumption (SFC) the highest coal consumption is at a value of 0.635 kg/kWh (gross), 0.583 kg/kWh (net) in the condition of slagging index 0.19 and fouling index 0.22 and the lowest consumption is at a value of 0.534 kg/kWh (gross), 0.583 kg/kWh (net) in the condition of slagging index 0.77 and fouling index 0.48. This explains that in addition to the magnitude of the calorific value and moisture content of coal, the presence of slagging & fouling can affect boiler performance.

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