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Comparative Analysis Of The Effect Of Sawdust And Coal Combustion On Fouling Formation

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Abstract

The utilization of biomass in the form of sawdust as a co-firing fuel in boilers has increasingly been implemented to reduce coal consumption and carbon emissions. Sawdust has a high volatile matter content and is readily available; however, its ash characteristics, which contain alkali elements such as potassium (K) and sodium (Na), as well as its relatively low ash melting point, have the potential to increase fouling formation on boiler heat transfer surfaces. Fouling refers to the accumulation of deposits on the economizer, superheater, reheater, and air preheater, which can reduce heat transfer efficiency, increase flue gas temperature and differential pressure (DP), increase induced draft fan load, decrease main steam temperature, and increase sootblower operating frequency. This study aims to analyze the effect of sawdust combustion on fouling formation using boiler operational data obtained from the Distributed Control System (DCS). The parameters analyzed include coal flow rate, sawdust flow rate, total fuel flow, co-firing percentage, primary air flow, secondary air flow, flue gas O_2 content, furnace exit gas temperature (FEGT), flue gas temperature to the stack, economizer differential pressure, air preheater differential pressure, main steam temperature, and sootblower operating frequency. Data were collected at fuel mixture variations of approximately ±3% sawdust relative to the total fuel flow, with hourly intervals for a minimum of 24 hours for each operating condition. The analysis was conducted by comparing changes in temperature, differential pressure, and boiler performance at each variation of sawdust percentage. Indications of increased fouling were identified by rising flue gas temperatures and differential pressure, reduced heat transfer effectiveness, and increased sootblower operation requirements. The results of this study are expected to show that increasing the percentage of sawdust tends to increase fouling formation; however, there is still an optimum limit for sawdust utilization that can be applied without significantly reducing boiler efficiency and reliability.

Keywords: Sawdust, Co-Firing, Fouling, Boiler, Differential Pressure, Economizer, Air Preheater, Flue Gas Temperature, Dcs, Biomass.

INTRODUCTION

The increasing demand for energy has led to a significant rise in the consumption of fossil fuels, particularly coal. Continuous coal utilization causes various problems, such as increased carbon dioxide (CO_2) emissions, environmental pollution, and the depletion of fossil energy reserves (IEA, 2022). Therefore, alternative fuels that can be used together with coal are required to reduce fossil fuel consumption and minimize environmental impacts. One of the most widely used alternatives in industrial boilers and power plants is biomass.

Biomass is a renewable energy source derived from organic materials such as agricultural waste, plantation waste, and wood industry waste (IRENA, 2021). One type of biomass that is easily obtained and abundantly available is sawdust. Sawdust has a high volatile matter content, making it highly combustible and suitable for co-firing fuel with coal (Rahman et al., 2021). The use of sawdust as a supplementary fuel offers several advantages, including reducing coal consumption, lowering greenhouse gas emissions, and utilizing wood industry waste that was previously underutilized.

However, the use of sawdust in boilers also creates several operational challenges. The characteristics of sawdust differ from coal, particularly in terms of ash content, alkali element content, and ash melting point. Sawdust ash generally contains potassium (K), sodium (Na), calcium (Ca), and silica (SiO_2), which can react to form low-melting-point compounds (Wang et al., 2020). During the combustion process, these compounds can adhere to boiler heat transfer surfaces and form deposits. This deposit accumulation is known as fouling.

Fouling in boilers occurs on heat transfer components such as the economizer, superheater, reheater, and air preheater. The formation of fouling causes heat transfer surfaces to be covered by ash layers, reducing the rate of heat transfer. As a result, flue gas temperature increases, steam temperature decreases, and boiler efficiency declines (Li et al., 2022). In addition, fouling obstructs flue gas flow, causing an increase in differential pressure (DP) and increasing the workload of the induced draft fan. If this condition continues, the sootblower operating frequency will increase, leading to higher operating costs and a greater risk of boiler disturbances.

In modern boiler systems, operating conditions can be monitored through a Distributed Control System (DCS). Data stored in the DCS, such as fuel flow rate, furnace exit gas temperature, flue gas temperature, O_2 content, economizer and air preheater differential pressure, main steam temperature, and sootblower operating frequency, can be used to analyze fouling formation tendencies. By comparing operational data when the boiler uses 100% coal and when sawdust co-firing is applied, the effect of sawdust addition on fouling formation can be identified.

Research on the effect of sawdust combustion on fouling formation is important because biomass utilization in boilers still faces challenges in maintaining operational efficiency and reliability. Furthermore, each type of biomass has different ash characteristics, which may result in different fouling tendencies (Zhang et al., 2023). Therefore, a more in-depth analysis is required to determine the extent of the effect of sawdust utilization on fouling formation and to identify the safe limit of co-firing percentage that can still be applied.

Based on these problems, this study was conducted to analyze the effect of sawdust fuel combustion on fouling formation in boilers using operational data obtained from the DCS. The results of this study are expected to provide a reference for determining the optimum sawdust co-firing composition so that coal consumption can be reduced without causing excessive fouling formation or significantly decreasing boiler efficiency.

RESEARCH METHODS

Flow Chart

A research flowchart is used to systematically illustrate the stages of the research process, from problem identification to drawing conclusions. The research process began with the identification of operational problems in the boiler related to the use of sawdust as a co-firing fuel, particularly its potential to increase fouling formation on heat transfer surfaces. Next, a literature review was conducted to establish the theoretical foundation related to biomass co-firing, boiler combustion processes, ash characteristics, and fouling mechanisms.

The next stage involved field observations and the collection of operational data from the boiler through the Distributed Control System (DCS), including measurements of coal flow rate, sawdust flow rate, flue gas temperature, O_2 content, differential pressure, main steam temperature, and sootblower operating frequency. The collected data were then processed and analyzed to determine the effect of sawdust combustion on fouling formation and overall boiler performance. After the analysis was completed, an evaluation of boiler operating conditions was carried out, and the research findings were compiled into discussions, conclusions, and recommendations regarding the optimum co-firing percentage and preventive actions to minimize fouling while maintaining boiler efficiency and reliability.

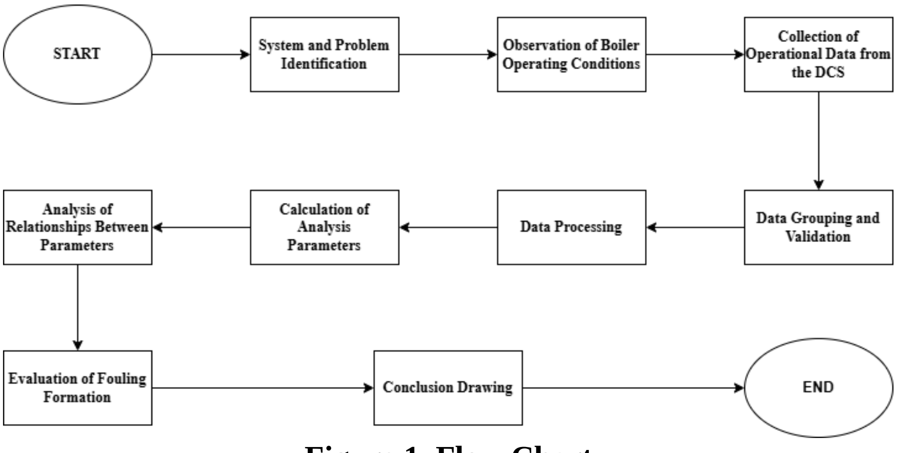

Figure 1. Flow Chart

System and Problem Identification

The initial stage was carried out by studying the boiler operating system, combustion flow process, and main components such as the economizer and air preheater. At this stage, problems related to the potential formation of fouling due to the use of sawdust in the co-firing system were also identified.

Observation of Boiler Operating Conditions

Observations were conducted on boiler operating conditions directly in the field and through the DCS display to understand operational characteristics during sawdust utilization, including patterns of changes in temperature, pressure, and fuel flow.

Collection of Operational Data from the DCS

Historical data were collected from the Distributed Control System (DCS) during the sawdust co-firing operation period. The collected data included main parameters such as FEGT, Stack Temperature, Economizer DP, APH DP, O_2 Flue Gas, Main Steam Temperature, MW Gross, and sootblower operating frequency.

Data Grouping and Validation

The obtained data were grouped based on parameters and observation time. Furthermore, data verification was conducted to ensure that the data used were valid, consistent, and free from anomalies that could affect the analysis results.

Data Processing

The validated data were processed using Microsoft Excel in the form of tables

Calculation of Analysis Parameters

Calculations were performed to strengthen the analysis, including:

• Percentage increase or decrease of parameters
• Temperature difference between flue gas and ambient conditions (ΔT) as an indicator of heat loss

Analysis of Relationships Between Parameters

The relationships between parameters such as FEGT, Stack Temperature, Economizer DP, APH DP, and Main Steam Temperature were analyzed to determine the effect of fouling formation on boiler performance.

Evaluation of Fouling Formation

The fouling level was determined based on changes in operational parameters, particularly increases in differential pressure and flue gas temperature, as well as increased sootblower operating frequency.

Conclusion Drawing

Conclusions were prepared based on the results of the data analysis to answer the research objectives and explain the effect of sawdust utilization on fouling formation.

Data Analysis Techniques

The boiler at PT. PLN Nusantara Power UP Paiton Unit 9 uses coal as the primary fuel with additional biomass in the form of sawdust in a co-firing system. The utilization of sawdust aims to reduce coal consumption and increase the use of renewable energy. However, the use of sawdust can also affect combustion conditions and increase the potential for fouling formation on boiler heat transfer surfaces.

Fouling occurs when ash produced from sawdust combustion, which contains alkali elements, adheres to the surfaces of economizer and air preheater tubes. As a result, heat transfer performance decreases, flue gas temperature increases, gas flow becomes more restricted, and the sootblower operating frequency increases.

Fouling Indicator Approach Based on Stack Temperature

In this study, fouling analysis was conducted using the Stack Temperature parameter as the main indicator because the available data only consisted of flue gas temperature measurements. This parameter is considered sufficiently representative for evaluating changes in boiler heat transfer performance. Stack Temperature represents the flue gas temperature after passing through the economizer and air preheater. Under normal conditions, this temperature remains relatively low because a significant amount of heat has been absorbed by the heat transfer surfaces. However, when fouling occurs, heat transfer efficiency decreases, causing the flue gas temperature to increase (Shi & Wang, 2015). To quantify this condition, a Fouling Indicator (FI) was used with the following equation:

$$FI = \frac{T_{stack} - T_{baseline}}{T_{baseline}} \times 100\% \qquad (1)$$

Explanation:

- $FI = Fouling\ Indicator$ (%)
- $T\_stack = Exhaust\ gas\ temperature\ (°C)$
- $T\_baseline = Reference\ temperature\ (°C)$

where T_{stack} is the stack temperature during co-firing operation and $T_{baseline}$ is the stack temperature under baseline or normal operating conditions. A higher FI value indicates a greater tendency for fouling formation because more heat escapes through the flue gas instead of being absorbed by the boiler heat transfer surfaces (Shi & Wang, 2015).

Comparison of Economizer DP and APH DP when Co-firing and not Co-firing

In this study, differential pressure (DP) was also used as an indicator to evaluate fouling formation in the boiler during sawdust co-firing operation. Differential pressure represents the resistance of flue gas flow through heat transfer equipment such as the economizer and air preheater. Under normal operating conditions, the gas flow passes smoothly with relatively stable pressure differences. However, when fouling occurs, ash deposits accumulate on the heat transfer surfaces and gas flow passages, causing higher flow resistance and an increase in differential pressure (Li et al., 2022).

The increase in differential pressure indicates that the flue gas path is becoming more obstructed due to deposit formation. Therefore, comparing the differential pressure during co-firing operation with the normal operating condition can provide an indication of fouling severity and its impact on boiler performance. To quantify this condition, the differential pressure ratio was calculated using the following equation:

$$Ratio = DP_{co-firing} / DP_{non\ co-firing} \qquad (2)$$

Explanation:

- $DP_{co-firing}$ = Differential pressure during sawdust co-firing operation
- $DP_{non\ co-firing}$ = Differential pressure during normal operation without sawdust co-firing

A higher ratio value indicates a greater tendency for fouling formation because the accumulation of deposits causes higher resistance to flue gas flow through the boiler heat transfer components (Zhang et al., 2021).

In addition, different DP values were calculated to assess the stability of fouling formation:

$$\%variation = \frac{maksimum\ value - minimum\ value}{minimum\ value} \times 100\% \quad (3)$$

Heat Loss Calculation Based on Stack Temperature during co-firing and non-co-firing

In this study, heat loss through flue gas was analyzed to evaluate the effect of fouling formation on boiler thermal performance during sawdust co-firing operation. Heat loss occurs when a portion of the combustion heat energy is carried away by the flue gas and released to the environment through the stack. Under normal conditions, the boiler heat transfer surfaces absorb most of the combustion heat efficiently. However, when fouling occurs, ash deposits reduce heat transfer effectiveness, causing the flue gas temperature to increase and resulting in higher heat loss (Incropera et al., 2019).

The amount of heat loss can be estimated using the relationship between flue gas mass flow rate, specific heat capacity, and the temperature difference between stack gas and ambient conditions. Therefore, the heat loss parameter was calculated using the following equation:

$$q_{loss=}m \times C_p \times (T_{stack} - T_{ambient}) \quad (4)$$

Explanation:

- q_{loss}= Heat loss through flue gas (kJ/s or kW)
- m= Mass flow rate of flue gas (kg/s)
- C_p= Specific heat capacity of flue gas (kJ/kg·K)
- T_{stack}= Stack gas temperature (°C or K)
- $T_{ambient}$= Ambient temperature (°C or K)

A higher q_{loss}value indicates that more heat energy escapes through the flue gas, which reflects lower boiler heat transfer efficiency and a higher tendency of fouling formation on the heat transfer surfaces (Çengel & Boles, 2019).

Determination of Mixed Calorific Value (GCVmix)

In this study, the calorific value of the fuel mixture was analyzed to determine the effect of sawdust co-firing on the overall energy input to the boiler. The calorific value is an important parameter because it represents the amount of heat energy released during the combustion process. Since coal and sawdust have different Gross Calorific Values (GCV), the total calorific value of the mixed fuel depends on the composition ratio of each fuel used in the co-firing process (Basu, 2018).

The mixed fuel calorific value was calculated using the weighted average method based on the fraction of each fuel component in the mixture. This calculation is useful for evaluating combustion performance, boiler efficiency, and the influence of fuel composition on operational parameters during co-firing. The mixed Gross Calorific Value (GCV_{mix}) was determined using the following equation:

$$GCV_{mix} = x_1 \times GCV_{v1} + x_2 \times GCV_{v2} \quad (5)$$

Explanation:

- GCV_{mix}= Gross calorific value of the fuel mixture
- x_1= Mass fraction of coal in the fuel mixture
- x_2= Mass fraction of sawdust in the fuel mixture
- GCV_{v1}= Gross calorific value of coal
- GCV_{v2}= Gross calorific value of sawdust

A lower GCV_{mix}value generally indicates that the addition of sawdust reduces the total heating value of the fuel mixture because biomass typically has a lower calorific value compared to coal. This condition may influence combustion stability, boiler efficiency, and flue gas characteristics during co-firing operation (Vassilev et al., 2020).

Calculation of Heat Loss in Exhaust Gas (Stack Loss)

In this study, the percentage of heat loss through flue gas was analyzed to evaluate the effect of sawdust co-firing on boiler thermal efficiency. Heat loss through the stack occurs when a portion of the combustion energy is carried away by hot flue gas and released to the environment instead of being absorbed by the boiler heat transfer surfaces. The occurrence of fouling can increase stack temperature, resulting in greater heat loss and reduced boiler efficiency (Çengel & Boles, 2019).

To determine the proportion of heat energy lost compared to the total fuel energy input, the heat loss percentage (L_1) was calculated using the following equation:

$$L_1 = \frac{m \times C_p \times (T_{stack} - T_{ambient})}{GCV_{mix}} \times 100\% \quad (6)$$

Explanation:

- L_1= Percentage of heat loss through flue gas (%)
- m= Mass flow rate of flue gas (kg/s)
- C_p= Specific heat capacity of flue gas (kJ/kg·K)
- T_{stack}= Stack gas temperature (°C or K)
- $T_{ambient}$= Ambient temperature (°C or K)
- GCV_{mix}= Gross calorific value of the fuel mixture

A higher L_1value indicates that more combustion heat is lost through the stack gas, reflecting lower heat transfer effectiveness and reduced boiler efficiency due to fouling formation on the heat transfer surfaces (Miller, 2017).

Relationship between FEGT and Main Steam Temperature

In this study, the temperature difference between the Furnace Exit Gas Temperature (FEGT) and the main steam temperature was analyzed to evaluate the effectiveness of heat transfer inside the boiler during sawdust co-firing operation. FEGT represents the temperature of combustion gas leaving the furnace area before entering the convective heat transfer sections, while steam temperature indicates the amount of heat successfully absorbed by the boiler heating surfaces. Under normal operating conditions, efficient heat transfer allows a significant portion of the combustion heat to be absorbed for steam generation. However, when fouling occurs, ash deposits on the heat transfer surfaces reduce heat absorption effectiveness, causing the gas temperature to remain high while steam temperature tends to decrease (Babcock & Wilcox, 2018).

To evaluate this condition, the temperature difference (ΔT) between FEGT and steam temperature was calculated using the following equation:

$$\Delta T = T_{FEGT} - T_{steam} \quad (7)$$

Explanation:

- ΔT = Temperature difference between flue gas and steam (°C)
- T_{FEGT}= Furnace Exit Gas Temperature (°C)
- T_{steam}= Main steam temperature (°C)

A larger ΔTvalue indicates lower heat transfer effectiveness because more heat remains in the flue gas instead of being absorbed by the steam generation system. This condition can be associated with fouling formation on boiler heat transfer surfaces during co-firing operation (Yin et al., 2021).

RESULTS AND DISCUSSION

Observation data during (co-firing) and comparative data (when not co-firing)

Bas Observation data were obtained from the Distributed Control System (DCS) on boiler conditions when using a sawdust co-firing system. All data used in this study were taken when sawdust was being injected into the boiler along with coal with a co-firing volume of approximately 200–250 tons per day. Therefore, all observed parameter changes in FEGT, Stack Temperature, Economizer DP, APH DP, Main Steam Temperature, and other parameters represent boiler conditions during sawdust use. Based on historical DCS data, average values of boiler operating parameters were obtained, such as.

Data from Co-Firing of Sawdust

Tabel 1. Data from the DCS Co-Firing of Sawdust

Parameter	Mininimum value	Maksimum value	Average value	Unit
MW Gross	382,29	513,65	448,92	MW
Total Fuel Flow	5794	7520	6720	Ton/Days
Coal	5594	7269	6581	Ton/Days
Sawdust flow	200	250	225	Ton/Days
FEGT	869,33	1007,95	938,07	°C
Stack temperature	131,75	146,57	139,38	°C
Economizers DP	1,38	1,73	1,56	kPa
Air pre Heater DP	7,55	10,07	8,97	kPa
O2 Flue Gas	4,61	7,07	5,87	%
Main Steam Temperature	532,51	536,11	534,83	°C

Data When Not Co-Firing

Tabel 2. Data from the DCS When Not Co-Firing

Parameter	Mininimum value	Maksimum value	Average value	Unit
MW Gross	382,29	513,65	448,92	MW
Total Fuel Flow	5287,87	5842,18	5558,30	Ton/Days
Coal	5594	7269	6582	Ton/Days
Sawdust flow	-	-	-	-
FEGT	975,40	1086,95	1020,57	°C
Stack temperature	132,27	141,77	136,80	°C
Economizers DP	0,81	1,45	1,07	kPa
Air pre Heater DP	6,68	7,95	7,39	kPa
O2 Flue Gas	4,61	7,42	6,57	%
Main Steam Temperature	520,96	535,08	530,55	°C
Frekuensi sootblower	-	-	-	-

Based The operational data presented in Tables 1 and 2 were obtained from the Distributed Control System (DCS) of the boiler during co-firing and non-co-firing operating conditions. The data were collected to evaluate the effect of sawdust utilization on boiler operating performance and fouling formation characteristics. Several important operational parameters were analyzed, including MW Gross, total fuel flow, coal flow, sawdust flow, Furnace Exit Gas Temperature (FEGT), stack temperature, economizer differential pressure (DP), air preheater (APH) differential pressure, O_2 flue gas content, and main steam temperature.

Table 1 shows the boiler operating data during sawdust co-firing operation, while Table 2 presents the boiler operating data under normal conditions without sawdust addition. The comparison between these two operating conditions was conducted to identify changes in heat transfer performance, flue gas flow resistance, combustion characteristics, and thermal efficiency associated with the use of sawdust as a co-firing fuel.

The minimum, maximum, and average values of each parameter were used to observe operational trends and evaluate the tendency of fouling formation. Parameters such as stack temperature, economizer DP, and APH DP were considered important indicators because increases in these values may indicate deposit accumulation on boiler heat transfer surfaces. Meanwhile, changes in FEGT, O_2 flue gas content, and main steam temperature were analyzed to determine the impact of fouling on combustion performance and boiler efficiency during co-firing operation.

Fouling Indicator Approach Based on Stack Temperature

The fouling analysis was conducted using the Stack Temperature parameter as the main indicator because the available operational data primarily consisted of flue gas temperature measurements. Stack Temperature represents the flue gas temperature after passing through the economizer and air preheater sections. Under normal conditions, the stack temperature remains relatively low because most of the combustion heat has been absorbed by the boiler heat transfer surfaces. However, when fouling occurs, ash deposits reduce the effectiveness of heat transfer, causing more heat to escape through the flue gas and increasing the stack temperature (Shi & Wang, 2015).

Based on the operational data, the stack temperature during co-firing operation ranged from 131.75 °C to 146.57 °C, with an average value of 139.38 °C. The baseline temperature used in this analysis was the minimum observed stack temperature of 135.76 °C, which was assumed to represent the cleanest operating condition during the observation period. The Fouling Indicator (FI) was calculated using the following equation:

$$FI = \frac{146{,}57 - 135{,}76}{135{,}76} \times 100\% = \mathbf{7{,}96\%} \qquad (8)$$

The calculation result showed that the maximum FI value reached approximately 7.96%. This result indicates that heat transfer performance had decreased due to deposit accumulation on the boiler heat transfer surfaces. However, since the FI value remained below 10%, the fouling condition can still be categorized as an early-stage fouling condition and has not yet caused severe thermal performance degradation.

The fluctuation of FI values during the observation period indicates that deposit formation did not occur constantly but was influenced by operating conditions and fuel characteristics, especially during sawdust co-firing. In general, the increase in stack temperature reflected by the FI value indicates that the heat that should have been absorbed by the economizer and air preheater was not utilized optimally. Therefore, periodic monitoring of the FI value can be used as an early indicator for fouling detection and as a basis for maintenance actions such as sootblowing to maintain boiler heat transfer performance.

Economizer and Air Preheater Differential Pressure Analysis

Temperature Differential pressure (DP) in the economizer and air preheater was analyzed to evaluate the increase in flue gas flow resistance caused by deposit accumulation. Higher DP values generally indicate greater resistance to gas flow due to the buildup of fly ash and combustion particles on heat transfer surfaces (Li et al., 2022).

Based on the operational data, during co-firing operation with approximately 3% sawdust, the economizer DP ranged from 1.38 to 1.73 kPa, while the APH DP ranged from 7.55 to 10.22 kPa. Under non-co-firing conditions, the economizer DP ranged from 0.96 to 1.48 kPa, and the APH DP ranged from 6.93 to 7.97 kPa. These results indicate that both DP values tended to increase during co-firing operation, showing an increase in flue gas flow resistance.

To quantify the increase in resistance, a DP ratio was calculated using the average values of each condition:

Economizer

$$Ratio = \frac{(1{,}38+1{,}73)/2}{(0{,}96+1{,}48)/2} = \frac{1{,}56}{1{,}22} = 1{,}28 \qquad (9)$$

Air Preheater

$$Rasio = \frac{(7{,}55+10{,}22\,)/2}{(6{,}93+7{,}97\,)/2} = \frac{8{,}89}{7{,}45} = 1{,}19 \qquad (10)$$

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The calculation results showed that the economizer DP increased by approximately 1.28 times during co-firing operation, while the APH DP increased by approximately 1.19 times compared to non-co-firing conditions. This indicates that co-firing operation increased the tendency of fouling formation, although the increase was still within a moderate range.

From the variation analysis, the economizer DP during co-firing showed a smaller variation of 25.36% compared to 54.17% during non-co-firing operation, indicating a relatively more stable condition. In contrast, the APH DP variation increased from 15.01% during non-co-firing to 35.36% during co-firing, indicating more fluctuating operational conditions in the air preheater section. Overall, co-firing operation increased DP values, with the economizer condition remaining relatively stable while the air preheater experienced more dynamic variations.

Heat Loss Analysis Based on Stack Temperature During Co-firing and Non-co-firing

Heat loss analysis was conducted to determine the amount of thermal energy lost through the flue gas during boiler operation. The stack temperature was used as the primary parameter because it reflects the amount of heat energy not absorbed by the boiler heat transfer system. Higher stack temperatures generally indicate greater heat loss and lower thermal efficiency (Çengel & Boles, 2019).

The heat loss was calculated using the following equation:

During Co-Firing Operation

Temperature Difference

$$\Delta T = 139{,}38 - 29{,}31 = 110{,}07°C \quad (11)$$

Fuel Mass Flow Rate

Total fuel consumption:

Coal + sawdust = **6720 tons/day**

Conversion:

$$\mathrm{m_{fuel}} = 6720 \times 1000 = 6.720.000\mathrm{kg/days} \quad (12)$$

In this analysis, the fuel composition was assumed to consist of 97% coal and 3% sawdust, resulting in the following fuel distribution:

- Coal = 6518.4 tons/day
- Sawdust = 200 tons/day

Estimation of Flue Gas Mass Flow Rate

Assumption:

- 1 kg of fuel produces approximately ±11 kg of flue gas

$$m_{gas} = 11 \times 6.720.000 = 73.920.000 kg/hari \ = 73920\, Tons/day \quad (13)$$

Heat Loss Calculation

With : $C_p = 1{,}0\ kJ/kg°C$

$$q_{loss} = 73.920.000 \times 1{,}0 \times 110{,}07 = 8.136.374.400 kJ/hari \quad (14)$$

Conversion to GJ/day

$$q_{loss} = \frac{8.136.374.400}{1.000.000} = \approx 8.136\ GJ/hari \quad (15)$$

- When not Co-Firing

Temperature Difference

$$\Delta T = 135{,}76 - 29{,}31 = 106{,}45°C \quad (16)$$

Fuel Mass Flow Rate

Total fuel consumption:

Coal = **5,354 tons/day**

Conversion:

$$m_{fuel} = 5354 \times 1000 = 5.354.000 kg/hari \quad (17)$$

Estimation of Flue Gas Mass Flow Rate

Assumption:

- 1 kg of fuel produces approximately ±11 kg of flue gas

$$m_{gas} = 11 \times 5.354.000 = 58.894.000 kg/hari \ = 58.894\, Ton/hari \quad (18)$$

Heat Loss Calculation

With : $C_p = 1{,}0\ kJ/kg°C$

$$q_{loss} = 58.894.000 \times 1{,}0 \times 135{,}76 = 7.995.449.440 kJ/hari \quad (19)$$

Conversion to GJ/day

$$q_{loss} = \frac{7.995.449.440}{1.000.000} = \approx 7995\ GJ/hari \quad (20)$$

Based on the calculation results, the heat loss during co-firing operation was approximately 8,136 GJ/day, while the heat loss during non-co-firing operation was approximately 7,995 GJ/day. This indicates that the use of sawdust in the co-firing system slightly increased the amount of heat energy released through the flue gas. The increase in heat loss was mainly influenced by the higher stack temperature during co-firing operation, which reflects that part of the combustion heat was not optimally absorbed by the boiler heat transfer surfaces.

In addition, the higher stack temperature and increased differential pressure values in the economizer and air preheater during co-firing operation indicate the tendency of fouling formation caused by ash deposits from sawdust combustion. The alkali content and ash characteristics of sawdust potentially accelerate deposit accumulation on heat transfer surfaces, reducing heat absorption effectiveness and increasing flue gas flow resistance. As a result, more thermal energy escapes through the stack gas.

However, although the absolute heat loss during co-firing was slightly higher, the boiler system was still able to maintain relatively stable operating performance. The increase in heat loss and fouling indicators remained within a moderate range, indicating that the co-firing implementation with approximately 3% sawdust had not yet caused severe operational disturbances or significant decreases in boiler reliability.

Overall, the comparison results show that co-firing operation slightly increased fouling tendency and heat loss compared to non-co-firing conditions. Nevertheless, the boiler still operated within acceptable operational limits, meaning that sawdust utilization at the observed percentage can still be applied effectively, provided that proper monitoring and maintenance such as sootblowing are performed regularly to control deposit accumulation and maintain optimal heat transfer performance.

Mixed Fuel Gross Calorific Value (GCVmix) Analysis

Since the boiler used a combination of coal and sawdust during co-firing operation, the mixed fuel calorific value (GCV_{mix}) was calculated to represent the total energy content of the fuel mixture. The calculation was based on the weighted average of each fuel component according to its mass fraction (Basu, 2018).

$$GCV_{mix} = 0{,}97 \times 4200 + 0{,}03 \times 3000 = 4164\ \text{kcal/kg} \quad (21)$$

Using a fuel composition of 97% coal and 3% sawdust, with calorific values of 4200 kcal/kg and 3000 kcal/kg respectively, the calculated mixed fuel calorific value was approximately 4164 kcal/kg. This value was then used as the basis for heat loss and combustion performance calculations.

Calculation of Heat Loss Based on Stack Temperature During Co-firing and Non-co-firing

The percentage of heat loss through the stack gas was calculated to compare thermal performance between co-firing and non-co-firing conditions. The stack loss percentage was determined using the following equation:

- **During Co-Firing Operation**

Input energy

1 kcal = 4,184 kJ

$$Convert\ \text{kcal} > \text{kJ} = 4.164\ \text{kcal/kg} \times 4{,}184\ \text{kJ} = \approx \mathbf{17.422\ kJ/kg} \quad (11)$$

$$\boldsymbol{E}_{input} = 6.720.000 \times 17.422 = 117.075.840.000\ kJ/day \quad (11)$$

$\boldsymbol{L_1\ During\ Co-Firing}$

$$L_1 = \frac{8.136.374.400}{117.075.840.000} \times 100\% = \approx\ 6{,}95\% \quad (12)$$

- When not Co-Firing

Input energy

1 kcal = 4,184 kJ

$$Convert\ \text{kcal} > \text{kJ} = 4.200\ \text{kcal/kg} \times 4{,}184\ \text{kJ} =\approx \mathbf{17.572\ kJ/kg} \quad (11)$$

$$\boldsymbol{E_{input}} = 6.720.000 \times 17.422 = 94.086.088.000\ kJ/day \quad (11)$$

$\boldsymbol{L_1\ When\ not\ \ Co - Firing}$

$$L_1 = \frac{7.995.449.440}{94.086.088.000} \times 100\% =\approx\ 8{,}50\% \quad (12)$$

Based on the calculation results, the heat loss percentage during co-firing operation was approximately 6.95%, while the heat loss percentage during non-co-firing operation was approximately 8.50%. The lower heat loss value during co-firing indicates that the boiler was able to utilize combustion heat relatively more effectively compared to the condition without co-firing.

During co-firing operation, the fuel mixture consisting of coal and sawdust produced a total energy input of approximately 117,075,840,000 kJ/day, while the calculated heat loss through the stack gas was approximately 8,136,374,400 kJ/day. Meanwhile, under non-co-firing conditions, the total energy input was approximately 94,086,088,000 kJ/day with a heat loss of approximately 7,995,449,440 kJ/day. Although the absolute heat loss during co-firing was slightly higher, the percentage relative to the total input energy was lower.

This result indicates that the addition of sawdust in small proportions did not significantly decrease boiler thermal performance. The high volatile matter content in sawdust may contribute to improved combustion characteristics, resulting in relatively better heat utilization inside the boiler. However, the increase in stack temperature and differential pressure during co-firing still indicates the presence of fouling tendencies caused by ash deposition on the economizer and air preheater surfaces.

In general, the comparison results show that co-firing operation with approximately 3% sawdust was still capable of maintaining relatively good boiler efficiency while only causing a moderate increase in fouling tendency. Therefore, the implementation of co-firing can still be considered operationally acceptable as long as proper monitoring and maintenance are continuously performed.

Relationship Between FEGT and Main Steam Temperature

The relationship between Furnace Exit Gas Temperature (FEGT) and Main Steam Temperature was analyzed to evaluate the effectiveness of heat transfer inside the boiler during co-firing and non-co-firing operations. FEGT represents the temperature of combustion gas leaving the furnace, while Main Steam Temperature represents the temperature of steam produced after the heat absorption process in the superheater section. A smaller temperature difference between these parameters indicates better heat transfer effectiveness because more combustion heat is absorbed by the steam system.

During Co-Firing Operation

$$\Delta T = 938{,}07 - 534{,}83 = 403{,}24°C \quad (12)$$

When not Co-Firing

$$\Delta T = 1020{,}57\ -\ 530{,}55 = 490{,}02°C \quad (12)$$

Based on the operational data, during co-firing operation the average FEGT was 938.07 °C and the average Main Steam Temperature was 534.83 °C, resulting in a temperature difference of 403.24 °C. Meanwhile, during non-co-firing operation, the average FEGT was 1020.57 °C and the average Main Steam Temperature was 530.55 °C, resulting in a larger temperature difference of 490.02 °C.

The smaller temperature difference during co-firing operation indicates that heat transfer inside the boiler was relatively more effective compared to non-co-firing conditions. This means that more combustion heat was successfully absorbed by the steam system. However, the increase in stack temperature and differential pressure during co-firing still indicates the presence of fouling tendencies caused by ash deposits from sawdust combustion. Overall, the boiler was still able to maintain stable heat transfer performance under both operating conditions, although co-firing showed slightly better thermal performance.

CONCLUSIONS

Based on the analysis of boiler operational data obtained from the Distributed Control System (DCS), the use of sawdust as a co-firing fuel showed an influence on fouling formation and boiler thermal performance. During co-firing operation, the Stack Temperature, Economizer Differential Pressure (DP), and Air Preheater (APH) DP values tended to increase compared to non-co-firing conditions, indicating an increase in flue gas flow resistance and the tendency of deposit accumulation on heat transfer surfaces.

The Fouling Indicator (FI) analysis produced a maximum value of approximately 7.96%, indicating that fouling had started to occur but was still within a moderate and acceptable operational range. In addition, the economizer DP increased by approximately 28% and the APH DP increased by approximately 19% during co-firing operation, showing that sawdust combustion contributed to increased fouling tendency due to its ash characteristics.

Heat loss analysis showed that the percentage of heat loss during co-firing operation was approximately 6.95%, lower than the non-co-firing condition of approximately 8.50%. This indicates that the co-firing system was still able to maintain relatively good thermal efficiency despite the increase in fouling tendency. Furthermore, the relationship between FEGT and Main Steam Temperature showed a smaller temperature difference during co-firing operation, indicating relatively better heat transfer effectiveness compared to non-co-firing conditions.

Overall, the implementation of co-firing using approximately 3% sawdust was still considered operationally feasible because it did not cause significant decreases in boiler performance or severe fouling conditions. However, continuous monitoring of stack temperature, differential pressure, and sootblower operation remains important to prevent excessive deposit accumulation and maintain optimal boiler efficiency and reliability.

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