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Research Article

The Effect of Biomass & Coal Co-firing on The Flue Gas Temperature Profile in a 350 MW Class Pulverized Coal-Fired Power Plant

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Abstract: PT PLN (Persero) as the Indonesian state electricity supply company must carry out an energy transition **Abstract:** Direct biomass co-firing within pulverized coal-fired power plants involves the integration of biomass into the existing coal consumption process, enabling utilization by the power plant's established equipment. Typically, biomass co-firing accounts for up to 5% of the total coal consumption. This paper examines the impact of co-firing fractions on the flue gas temperature, specifically focusing on the regenerative air preheater hot side outlet temperature. Among the various operational parameters requiring compliance with acceptable limits, maintaining the flue gas temperature above the sulfur dew point is critical to prevent sulfur dioxide condensation. Such condensation risks corrosion of the flue gas duct and other downstream components. Empirical studies reveal a linear reduction in flue gas temperature as power plant load decreases, with the temperature eventually reaching the sulfur dew point threshold. This study further explores the influence of biomass co-firing fractions on the part-load temperature profile of flue gas, demonstrating an additional decline in temperature with the inclusion of biomass in the combustion process. Findings indicate that through modest adjustments in operational management and logic control systems, sustainable operation of the flue gas pathway can be maintained. These modifications ensure operational flexibility remains close to the original design specifications. Additionally, an economic assessment of the fuel mixture comprising coal, biomass, and fuel oil across the operational range of the power plant is essential. Optimization of the fuel mix is required to identify the optimal operating range for coal-fired power plants (CFPPs) while simultaneously minimizing fuel costs.

Keywords: Renewable Energy, Biomass Co-firing, PC Boiler, Flue Gas Temperature, Sulfur Dew Point

1. Introduction

The Indonesian Ministry of Energy and Mineral Resources has established a target for the New and Renewable Energy (NRE) share in electricity generation to reach 23% by 2025, aiming to mitigate the dominance of fossil fuels as the primary energy source [1]. In 2024, Indonesia's total electricity production was approximately 300 terawatt-hours. Coal remained the dominant energy source, accounting for 66% of the total production, followed by natural gas at 14%, oil at 6%, and renewable energy sources contributing around 14%. Within the renewable energy category, the share of New and Renewable Energy (NRE) further supplemented the energy mix. Given that coal-fired power plants (CFPPs) remain the predominant method of electricity generation, integrating NRE through biomass fuel substitution offers a swift approach to enhancing the NRE share in the energy mix. Similar to coal combustion, biomass combustion emits carbon dioxide (CO_2) as its primary byproduct. However, it is considered "carbon neutral" under the assumption that the CO_2 released during combustion equals the amount absorbed by the biomass throughout its lifecycle [2], [3], [4].

Despite its potential benefits, the substitution of coal with biomass introduces several technical challenges for large-scale firing in existing CFPPs. These challenges arise from the lower combustion efficiency of biomass compared to coal, as well as the underdeveloped biomass supply chain relative to coal [5], [6]. Numerous operational parameters in biomass co-firing must be meticulously managed to avoid efficiency losses or even a de-rating of maximum power output. Consequently, analyzing the potential impact of biomass co-firing on critical power plant parameters becomes essential.

Yan Xu et al. (2020) investigated several CFPPs employing biomass co-firing through direct or indirect firing methods. Their findings highlighted several adverse effects on boiler performance, including reductions in furnace temperature, combustion efficiency, and increased risks of slagging and corrosion. Additionally, biomass co-firing led to a slight increase in the levelized cost of electricity (LCOE) [7]. Similarly, Miroslav Variny et al. (2021) conducted a comprehensive study of biomass co-firing and offered significant insights [8]. Their study concluded that biomass co-firing effectively reduces emissions of Sulfur Oxides (SOx) and Nitrogen Oxides (NOx) in the flue gas. However, it also underscored the necessity of addressing other challenges such as slagging, fouling, chlorine-induced corrosion, and the accelerated deterioration of Selective Catalytic Reduction (SCR) catalysts due to alkali and alkaline metal entrainment in the flue gas [8].

In addition to the aforementioned effects, biomass co-firing is anticipated to lower flue gas temperatures, posing a risk of sulfur dew point infringement and subsequent corrosion [9]. Through theoretical analysis and software-based simulations, this study aims to assist power plant engineers in evaluating and revising operational parameters before and during the implementation of biomass co-firing.

To estimate the flue gas temperature profile, the Steam Master 30.0 software is utilized to simulate the power plant's heat balance based on CFPP design parameters and various input variables. The resulting flue gas temperature profile is analyzed in conjunction with the sulfur dew point, which is derived from the combustion mass balance. This sulfur dew point serves as a critical limiting parameter, determining the feasible extent of biomass co-firing.

2. POWER PLANT OVERVIEW

The coal-fired power plant (CFPP) analyzed in this study utilizes a subcritical single-reheat pulverized coal boiler, with a gross rated power output of 350 megawatts. The design specifications of the power plant, excluding the implementation of a Flue Gas Desulfurizer (FGD), are summarized in Table 1.

Tabel 1. Spesifikasi Substrat yang Digunakan

No	Parameter	Value	Unit
1.	Gross Output	350.00	MW
2.	Net Plant Heat Rate (HHV)	2264.90	kCal/kWh
3.	Combustion Excess Air	24.03	%
4.	Main Steam Temperature	561.50	Celsius
5.	Main Steam Pressure	190.50	Bar
6.	Reheated Steam Pressure	46.12	Bar
7.	Auxiliary Power	12713.00	kW

The parameters used in this study are representative of those typically applied in 350 MW net output subcritical coal-fired power plants in Indonesia. The initial assumption considers the X CFPP as designed for full coal consumption, with no prior utilization of biomass as a primary fuel or for co-firing purposes.

Since power plants do not consistently operate at full load, this study incorporates off-design simulations to better approximate real-world CFPP operational conditions. These simulations were performed using the Steam Master 30.0 software. Based on the design parameters outlined in Table 1, the simulation was conducted under full coal combustion, and the resulting operational parameters are presented in Table 2.

Tabel 2. Full coal combustion heat rate vs load

Load (%)	MW (Gross)	Net Plant Heat Rate
100	350.00	2296.00
90	315.00	2303.00
75	262.50	2330.00
60	210.00	2379.00

3. COAL AND BIOMASS CHARACTERISTICS

As outlined in the title, this study examines the effects of biomass co-firing on various aspects of desulfurizer operation. The characteristics of both fuel types utilized in the analysis are presented in Table 3.

Tabel 3. Fuel Composition

Component	Coal	Sawdust
C - Carbon	60.10%	28.06%
H - Hydrogen	4.49%	3.17%
O - Oxygen	13.41%	24.80%
S - Sulphur	0.64%	0.07%
N - Nitrogen	1.36%	0.42%
Total Moisture	16.00%	41.47%
Ash	4.00%	2.01%

The coal used in this study was sourced from Tanjung Jati B and selected due to its relatively high sulfur content. This type of coal is commonly utilized in coal-fired power plants (CFPPs) equipped with Flue Gas Desulfurization (FGD) systems to mitigate sulfur dioxide (SO_2) emissions.

In contrast, the biomass fuel data was derived from PT. Pembangkitan Jawa Bali's presentation, which outlined the typical composition of Indonesia's sawdust.

Using the Dulong equation [10], the calculated high heating value (HHV) for Tanjung Jati B coal was 5,862.28 kCal/kg, while the HHV for sawdust was significantly lower at 2,303.20 kCal/kg. This calculation highlights the considerably lower calorific value of sawdust compared to Tanjung Jati B coal.

For this analysis, the coal-to-biomass ratios of 100:0, 97.5:2.5, and 95:5 were selected to evaluate the effects of biomass co-firing at varying proportions. The 5% upper limit for biomass co-firing was determined based on prior analyses of Indonesia's pulverized coal-fired power plants (PC CFPPs), which demonstrated that this level did not compromise boiler operation [2], [3].

Two key variable options were considered in the application of biomass co-firing ratios: the mass input ratio and the energy input ratio. This study primarily adopts the fuel mass flow ratio as the base calculation, with power output treated as the variable parameter.

4. TECHNICAL SIMULATION ON BIOMASS CO-FIRING

4.1. Effect on Flue Gas

The primary burners in pulverized coal-fired power plants (PC CFPPs) typically operate at a flame temperature range of 1200–1600°C at the burner nozzle [11]. Within the furnace, flue gas generated during combustion flows through the system, transferring heat upon interaction with the boiler's heat exchangers. This process results in a progressive reduction in flue gas temperature, as illustrated in Figure 1.

The furnace exit gas temperature refers to the temperature of the flue gas as it exits the final steam superheater. This gas is subsequently directed to the economizer heat exchanger for further heat recovery and energy efficiency optimization.

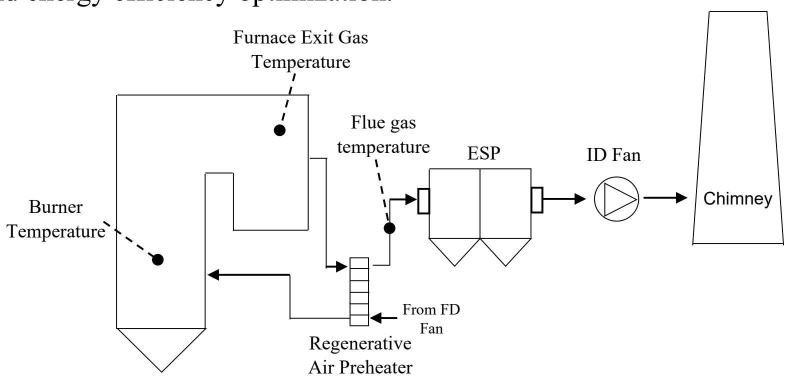

Figure 1. PC boiler flue gas stream

Various studies conducted under actual operating conditions of pulverized coal-fired power plants (PC CFPPs) have demonstrated that biomass co-firing in PC-type boilers, at substitution levels of up to 5% of the coal flow, reduces the Furnace Exit Gas Temperature (FEGT) by approximately 10°C[12]. This decrease in the furnace temperature profile subsequently lowers the flue gas temperature.

A 350 MW-class CFPP utilizing a PC-type boiler and its associated heat exchangers was modeled using the Steam Pro and Steam Master 30.0 software. The simulation results indicate a reduction in flue gas temperature during part-load operation, declining from 155°C under 100% load conditions to 131°C during 60% part-load operation. From an operational perspective, PC CFPPs can operate at loads as low as 25%. However, at such reduced loads, the activation of an additional fuel oil burner is required to sustain the burner and flue gas temperatures.

The primary focus of this discussion is the flue gas temperature at the exit of the regenerative air preheater (RAPH), which serves as a critical parameter for evaluating the operational efficiency and stability of the system.

The flue gas temperature distribution in various load and biomass composition can be seen in Table 4.

Tabel 4. Co-firing effect on power output and flue gas temperature

Composition	Load	Power Output	RAPH Out
0% wt biomass	100	350.00	156.90
	90	315.00	150.90
	75	262.50	141.70
	60	210.00	130.60
2,5% wt biomass	100	344.31	155.10
	90	309.87	149.00
	75	257.97	139.80
	60	206.32	128.70
5% wt biomass	100	338.53	152.90
	90	304.64	147.00
	75	253.54	137.80
	60	202.63	126.70

4.2. SULFUR DEW POINT

In coal-fired power plant (CFPP) operations, maintaining the flue gas temperature above a critical threshold, known as the sulfur dew point, is essential [13]. The sulfur dew point, also referred to as the acid dew point, represents the temperature at which SO_3 in the flue gas condenses to form H_2SO_4 (sulfuric acid), posing significant risks of material corrosion. This threshold is directly influenced by the flue gas moisture content and the concentration of SO_3, which is formed through the oxidation of SO_2. The oxidation ratio of SO_2 to SO_3 is a critical consideration, as it determines the minimum allowable outlet temperature for the air heater [10].

In this study, the sulfur dew point was calculated using the Okkes equation [9], incorporating the moisture and SO_3 content of the flue gas. The conversion of SO_2 to SO_3 was assumed to be 2%, based on standard preliminary design estimates [14]. The actual moisture and SO_3 content in the flue gas were derived from combustion mass balance calculations, referencing the findings of Reza (2020) [15]. For coal with a calorific value in the 5850 kCal/kg range, the sulfur dew point temperature was generally estimated, as depicted in Figure 2.

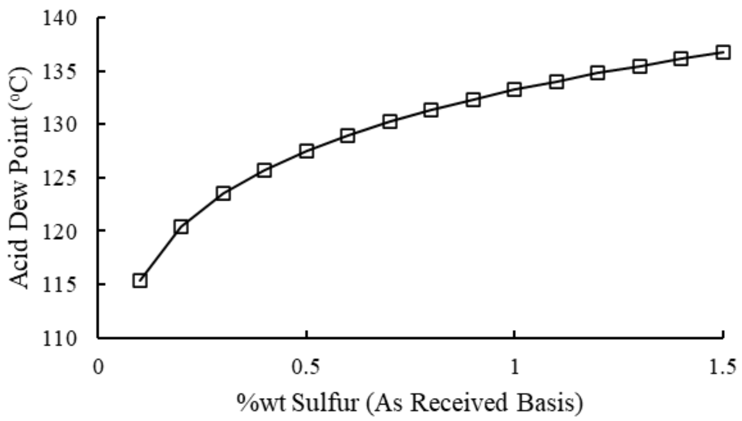

Figure 2. Sulfur dew point as function of coal sulfur content for 5850 kCal/kg HHV coal.

With a combustion excess air level of 24.03% and using coal properties as outlined in Table 3, the designed flue gas sulfur dew point for X CFPP is estimated at 128.9°C. Consequently, the flue gas temperature at the exit of the Regenerative Air Preheater (RAPH) must be maintained above this threshold to prevent acid corrosion resulting from sulfur condensation.

Based on the simulated flue gas temperature profiles presented in Table 4 and constrained by the calculated sulfur dew point, the distribution of flue gas temperature is illustrated in Figure 3. The introduction of biomass co-firing at up to 5% of the coal mass flow results in the flue gas temperature approaching the sulfur dew point at lower operational loads, reaching the critical threshold at approximately 65% load. This scenario is not advisable for long-term operation due to the corrosive effects of sulfur condensation. In contrast, with 2.5% biomass co-firing, the flue gas temperature is estimated to reach the sulfur dew point at a 60% load condition.

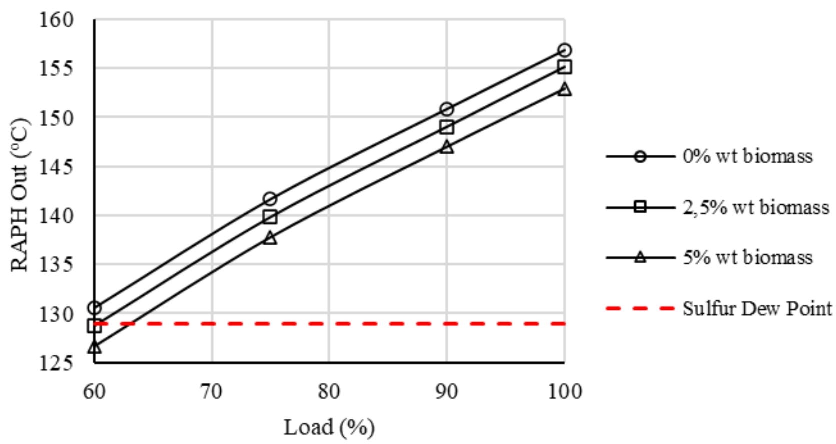

Figure 3. Flue gas temperature as a function of CFPP load and co-firing fraction

The utilization of sawdust as biomass fuel in a 350 MW-class coal-fired power plant (CFPP), with fuel properties outlined in Table 3, contributes to a reduction in the flue gas temperature profile as the biomass composition increases. Under conditions of full coal combustion, even during lower-load operations, the flue gas temperature remains above the designed sulfur dew point. However, simulations indicate that in biomass co-firing applications, the flue gas temperature decreases below the sulfur dew point during lower-load operations as the biomass composition increases. This behavior underscores potential risks of sulfur condensation and associated corrosion in lower-load scenarios of biomass co-firing.

5. OPERATIONAL CONSIDERATION IN LONG-TERM OPERATION OF BIOMASS CO-FIRING

Several considerations arise from the long-term operation of coal-fired power plants (CFPPs) utilizing biomass co-firing, particularly concerning corrosion risks to critical components such as the air preheater, flue gas duct, electrostatic precipitator (ESP), and chimney lining. To address these challenges, CFPP operation management and procedures should account for the parameters influenced by biomass co-firing, as outlined below:

a. Biomass Co-firing Load Limit
   In continuous biomass co-firing, part-load operation must not fall below a specific threshold to maintain the flue gas temperature above the sulfur dew point and prevent sulfur condensation. Although biomass mixing in the coal yard may result in a relatively homogeneous mixture in the coal bunker, potential inconsistencies in the biomass blend should be taken into account. Consequently, the load limit for biomass co-firing should be determined through continuous monitoring and measurement of actual flue gas temperatures.
b. Provision of a Dedicated Coal Bunker for Low-Load Operation
   The management of coal and biomass supply in CFPP operations typically occurs at the coal yard and coal bunker. In scenarios requiring unavoidable part-load operation, as dictated by electrical grid requirements, a dedicated bunker containing 100% coal with no biomass should be made available. This approach ensures that part-load operation can maintain the required flue gas temperature to avoid sulfur condensation, safeguarding the operational integrity of the system.
c. Early Deployment of Fuel Oil Burners
   In standard CFPP operations, additional fuel oil burners are typically employed during part-load excursions when the load decreases below typical operating ranges of 70–90%, especially at loads below 60%. These burners can be activated to sustain flue gas temperatures and adhere to load limits. For biomass co-firing scenarios, modifications to burner control logic may be required due to the lower flue gas temperature characteristics of biomass. These adjustments would ensure proper flue gas temperature maintenance, albeit at the cost of increased fuel oil consumption.

For higher fractions of biomass co-firing, minor modifications to the power plant can be explored to ensure optimal flue gas temperature by adjusting the heat exchange rate within the Regenerative Air Pre-Heater (RAPH). Given the flue gas temperature profile and flow rate as a function of unit load, the heat exchange rate can be reduced during low-load operations to maintain higher flue gas temperatures. Conversely, during high-load operations, increasing the heat exchange rate can sustain boiler efficiency.

The RAPH, a multi-stacked Ljungström-type heat exchanger, offers the possibility of modifying heat exchange variables through partial operation of its modules during part-load conditions. Under full-load operation, all rotating units of the RAPH are engaged. However, in low-load scenarios, selective disengagement of one or more rotating units can reduce the heat exchange rate, helping to maintain the flue gas temperature above critical limits.

Achieving this adjustment may require several modifications, including mechanical upgrades, electrical system adjustments, and enhancements to control logic systems. These measures could ensure the plant's operational flexibility while accommodating the specific requirements of higher biomass co-firing fractions.

6. CONCLUSION

Direct biomass co-firing in pulverized coal-fired power plants (PC CFPPs) designed primarily for coal firing can be implemented with careful consideration of operating parameter deviations, as compared to 100% coal firing operations. The findings indicate that with minor modifications to the plant's operational management and control logic, sustainable operation of the flue gas flow path can be achieved, while maintaining operational flexibility closely aligned with the original design specifications.

Furthermore, an economic assessment of the fuel mix, including coal, biomass, and fuel oil, across the operational range of the CFPP should be conducted. This analysis is critical to identify and optimize the most cost-effective operational range, ensuring both efficiency and reduced fuel expenses.

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It is our hope that this research inspires power plant engineers to undertake further studies and innovations in biomass co-firing technology for coal-fired power plants, contributing not only to advancements in energy efficiency but also to Indonesia's broader goals for renewable energy adoption. Through continued collaboration and scientific inquiry, such studies will pave the way for a cleaner, more sustainable energy future.

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