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Potential for Slagging, Fouling, and Abrasion during Co-firing of Indonesian Bituminous Coal and Hardwood Waste Pellet.

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Abstract. Indonesia has started co-firing in Coal-Fired Power Plant, reducing carbon emissions. However, co-firing can cause slagging, fouling, and abrasion in practice. The potential for slagging, fouling, and abrasion of the blend of hardwood waste pellet and Indonesian bituminous coal from two different regions (A Coal and B Coal) is evaluated based on the analysis of the material characteristics. The A Coal and B Coal were blended with a ratio of 25:75 (X Coal), 50:50 (Y Coal), and 75:25 (Z Coal), then coal was blended with hardwood waste pellet with a composition of 5, 10, and 15 percent, respectively. Based on the calculation, B coal with high alkaline content has a higher risk than others. The score of slagging decreased with the blending of 5%-15% of the wood pellet for B Coal but increased for Y Coal. The score of fouling decreased with the blending of 15% of the wood pellet for X Coal and 5%-15% of the wood pellet for Y Coal. Blending wood pellets up to 15% does not affect the risk of slagging and fouling of Z Coal. The abrasion risk for all samples is low. Overall, blending wood pellets up to 15% with coal with a high alkali content can reduce the risk of slagging, fouling, and abrasion.

INTRODUCTION

Most energy sectors, especially in Indonesia, are currently supported by fossil fuels [1]. This prompted the creation of the Paris Agreement in 2016, which contained restrictions on fossil fuels to decrease carbon emissions. In line with that, Indonesia's government had committed to increasing new and renewable energy use through Presidential Regulation No. 22 of 2017 on the National Energy General Plan [2]. National power plant company of Indonesia, as known as PT. PLN, also support the government through Regulation of the President Director of PT. PLN No. 001.P/DIR/2020 regarding Guidelines for Co-firing Coal-Fired Power Plants with Biomass [3]. As an agricultural country, Indonesia benefits from the abundance of biomass raw materials such as trees and forest wastes that can be used in co-firing [4][5]. The application of biomass co-firing can reduce carbon emissions because the carbon emission from fossil fuel is replaced by biomass. Moreover, biomass contains lower sulfur and nitrogen than coal [6][7].

Co-firing is combustion that uses two or more fuels simultaneously in one furnace. In the practice of coal co-firing, common problems such as slagging and fouling still need more attention. Slagging and fouling occur when the ash particles melt and stick to the surface of the boiler [6][7]. Both slagging and fouling may influence the lifetime and working capacity of the boiler. In addition, there is also the risk of abrasion and corrosion, which can reduce the combustion efficiency [8].

Some studies regarding potential slagging and fouling in hardwood biomass, which can be generated from tress of Indonesian forest [9], has been conducted by researchers. The study from Mack et al. (2021) [10] showed hardwood has a higher slagging risk than softwood. Meanwhile, Lachmant et al. (2021) [11] showed hardwood chips have a lower risk of slagging and fouling than softwood chips. That different result may occur due to the influence of the ash content of the fuel [12][13]. In a previous study, slag formation was contributed by the high content of CaO and fouling was influenced by high Na2O [14]. Meanwhile, high SiO2 could decrease the risk of slagging and fouling [14][15][16]. Moreover, Rebbling et al. (2020) [17] found that slagging was influenced by ash content and the fuel parameters.

Biomass from forest resources such as hardwood can be converted into a wood pellet to increase the value of that biomass [9]. Currently, wood pellet is a type of biomass that is often used as fuel in co-firing [18]. Some researchers have carried out various kinds of research on wood pellets. Guo et al. (2018) [19] said that co-firing with coal can reduce the slagging ratio of wood pellets ash. Another research from Cahyo et al. (2021) [20] showed that the use of wood pellets could reduce the temperature of the furnace. Ohman et al. (2004) [21] found that the temperature of critical slagging from wood pellets was higher than 1100°C based on the deposits produced, which means the potential slagging is low. Another research that used thermogravimetric analysis (TGA) and drop tube furnaces (DTF) showed that particle size, environmental conditions and blending ratio of wood pellets in co-firing had a significant effect on combustion characteristics [22].

The blending of coal and biomass has been applied in some coal-fired power plants with a ratio of 5% of the biomass. Previous research in biomass and coal co-firing showed that 10% of the biomass in coal co-firing had no significant effect than single coal in the DTF combustion test [23] and TGA- differential scanning calorimetry (DSC) analysis [24]. The study from other researchers was also conducted using biomass up to 15% in the co-firing system and gave good results in the emission [25]. The result from Jeong et al. (2019) [26] showed that from x-ray fluorescence (XRF) analysis, an increase in the ratio of the blending of empty fruit bunch (EFB) and wood pellets would increase the amount of ash deposition. It was mentioned that combustion using DTF showed the optimal blending for wood pellets was 10%, and the slagging potential of the wood pellet blending was lower than that of the EFB blending.

However, the interaction between wood pellet and coal into slagging, fouling, and abrasion was not clearly investigated. This study aims to obtain a comparison of the predictions of the potential for slagging, fouling and abrasion of wood pellet biomass from hardwood waste blended into two bituminous coals from two different regions in Indonesia with various ratios. The calculation of the prediction of the potential for slagging, fouling and abrasion is based on the results of the initial characteristics test.

METHOD

The flow diagram of this study can be seen in Fig. 1. The coals used were bituminous coal from East Kalimantan (A Coal) and South Sumatera (B Coal), Indonesia. The wood pellet (HWP) from East Java, Indonesia, was used as biomass processed from hardwood waste.

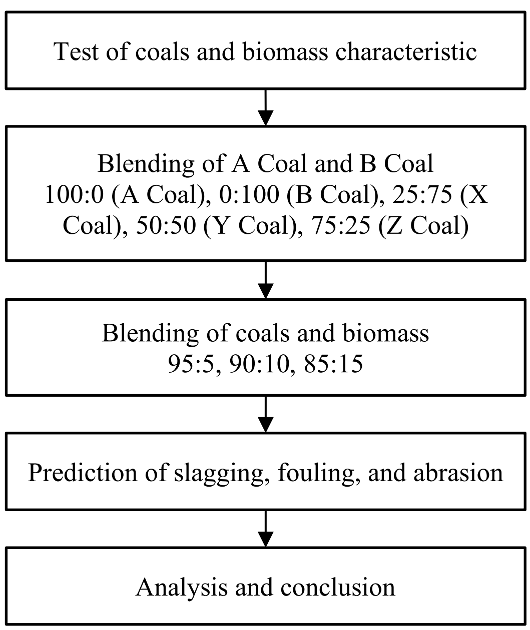

FIGURE 1. Flow diagram of study

Figure 2 shows the materials used in this study. Fig. 2(a) is A Coal, Fig. 2(b) presents B Coal, and Fig. 2(c) is hardwood waste pellet biomass (HWP). The test of Proximate, Ultimate, AFT, and Ash Analysis was carried out to find the characteristics of materials. After that, A Coal and B Coal were blended with the ratio of 100:0 for A Coal, 0:100 for B Coal, 25:75 for X Coal, 50:50 for Y Coal and 75:25 for Z Coal. It was conducted to find the optimal composition of A Coal and B Coal Blended. Then, coals and wood pellets were blended with the ratio of 95:5, 90:10 and 85:15. It was conducted to determine the impact of using wood pellets in co-firing. Furthermore, the predictions of slagging, fouling, and abrasion were calculated based on a dry basis.

(a) (b) (c)

FIGURE 2. Photographs of the material used, (a) A Coal; (b) B Coal; (c) Hardwood Waste Pellet Biomass (HWP)

TABLE 1. Parameters and risk criteria of slagging, fouling, and abrasion calculation

No	Indices		Low	Moderate	High	Severe
	Slagging Indices					
1	B/A ratio [13]		< 0.4 or > 0.7		0.4 – 0.7	
2	Silica ratio [28]		72 – 80	65 – 72	50 – 65	-
3	Slagging index [13]		< 0.6	0.6 – 2.0	2.0 – 2.6	> 2.6
4	Fusibility [27]		> 1343	1232–1343	1149-1232	< 1149
5	Fe/Ca [33]		< 0.3 or > 3.0		0.3 – 3.0	
6	Fe [28]		3 – 8	8 – 15	15 – 23	> 23
7	Fe+Ca [33]		< 10 %		> 12%	
8	Si/Al [34]		< 0.7 or > 3.5		0.7 – 3.5	
	Fouling Indices					
9	Fouling index [13]		< 0.2	0.2 – 0.5	0.5 – 1.0	> 1.0
10	Na_2O in ash [13]	CaO+MgO+ Fe_2O_3 < 20%	< 1.2		1.2 – 3.0	> 3.0
		CaO+MgO+ Fe_2O_3 > 20%	< 3.0		3.0 – 6.0	> 6.0
11	Total alkali [29]		< 0.3	0.3 – 0.45	0.45 – 0.6	> 0.6
	Abrasion Indices					
12	Abrasion index [28]		< 4.0	4.0 – 8.0	8.0 – 12.0	> 12.0

Note : B/A = Base/Acid

The calculation was conducted based on formulas of commonly predictive indices used, such as Base Acid Ratio [13], Slagging Index [13], Fouling Index [13], Fusibility [27], Silica Ratio [28], Abrasion Index [28], and Total Alkali [29]. For fusibility, the calculation used was softening temperature (ST) because its melting begins at that temperature [27]. After the calculation, risk criteria were determined based on TABLE 1, which shows slagging, fouling, and abrasion parameters. After it was determined, then quantified with a score of 0.00 for low risk, 0.50 for moderate risk, and 1.00 for high risk [12][30][31]. TABLE 2 shows the risk of slagging and fouling based on the total score from the parameters in TABLE 1. For slagging prediction with 8 parameters, if the score is below or equal to 3.5, the risk is low; if the score is between 4 to 5, the risk is moderate; and if the score is above 5, the risk is high. For fouling prediction with 3 parameters, if the score is below 1, the risk is low; if the score is between 1 to 1.5, the risk is moderate; and if the score is above or equal to 2, the risk is high. And for abrasion prediction with one parameter, the low risk if the score is 0, moderate risk's score is 0.5 and high risk's score is 1 [32].

TABLE 2. The score of slagging, fouling, and abrasion indices

Risk	Low	Moderate	High
Slagging	≤ 3.5	4 – 5	> 5
Fouling	< 1	1 – 1.5	≥ 2
Abrasion	0	0.5	1

RESULT AND DISCUSSION

Prediction of slagging, fouling, and abrasion were calculated based on the results of the characteristics test in TABLE 3. It was found that A Coal, Y Coal, and Z Coal are included in bituminous ash type, which has more Fe_2O_3 than CaO + MgO [13]. Meanwhile, B Coal, X Coal, and HWP Biomass are classified as lignitic ash, where the percentage of Fe_2O_3 is smaller than CaO + MgO [13]. As shown in TABLE 3, as bituminous ash, A Coal contained higher SiO_2 than others. Then, CaO and Na_2O of B Coal were higher than others. The higher content of CaO and Na_2O decreases the ash fusion temperature (AFT), increasing the potential of slagging and fouling [12][35]. For the comparison between coal and wood pellet, the content of CaO in the wood pellet is much higher than coals. Otherwise, The SiO_2 of the wood pellet is lower than all coal samples.

TABLE 3. Characteristics of coals and wood pellet

Sample	AC (%)	TS (%)	Ash Analysis (%)										
			SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	Na_2O	K_2O	Mn_3O_4	P_2O_5	SO_3
A	7.59	0.66	53.46	21.16	9.66	3.88	3.14	0.78	1.96	1.92	0.07	0.26	3.40
B	6.59	0.27	44.47	21.66	10.23	10.70	1.16	0.70	5.22	0.62	0.15	0.10	4.70
X	7.12	0.48	49.56	21.38	9.91	6.84	2.28	0.75	3.37	1.36	0.11	0.19	3.96
Y	6.86	0.38	47.20	21.51	10.06	8.63	1.76	0.72	4.23	1.01	0.13	0.15	4.31
Z	7.36	0.57	51.63	21.26	9.78	5.27	2.74	0.76	2.62	1.66	0.09	0.23	3.66
HWP	0.51	0.10	7.34	1.40	3.27	67.89	8.21	0.24	0.73	5.12	0.00	0.51	0.00

AC = Ash Content (dry basis); TS = Total Sulfur (dry basis)

Predicted results of slagging, fouling, and abrasion are shown in TABLE 4. B Coal has a high slagging risk while the others have a moderate slagging risk. For fouling, a high risk was found for coal, but the fouling scores on A Coal and Z Coal were lower than the others. Meanwhile, low abrasion risk was found for all samples. The risk of slagging and fouling is influenced by the high content of CaO and Na_2O in the sample [12][35].

TABLE 4. Slagging, fouling, and abrasion prediction of coals

Parameter		B/A Rat	Sil Rat	Slag Ind	Fus	Fe/ Ca	% Fe	Fe + Ca	Si/ Al	Slag Total	Foul Ind	Na_2O	Alk Ind	Foul Total	Abr Ind
A	calc	0.27	76.22	0.18	1256	2.49	9.66	13.54	2.53		0.53	1.96	0.24		3.40
	score	0.00	0.00	0.00	0.50	1.00	0.50	1.00	1.00	4.00	1.00	1.00	0.00	2.00	0.00
B	calc	0.42	66.81	0.11	1228	0.96	10.23	20.93	2.05		2.18	5.22	0.37		2.09
	score	1.00	0.50	0.00	1.00	1.00	0.50	1.00	1.00	6.00	1.00	1.00	0.50	2.50	0.00
X	calc	0.33	72.26	0.16	1304	1.45	9.91	16.74	2.32		1.12	3.37	0.30		2,79
	score	0.00	0.00	0.00	0.50	1.00	0.50	1.00	1.00	4.00	1.00	1.00	0.50	2.50	0.00
Y	calc	0.37	69.77	0.14	1293	1.17	10.06	18.69	2.20		1.57	4.23	0.34		2.45
	score	0.00	0.50	0.00	0.50	1.00	0.50	1.00	1.00	4.50	1.00	1.00	0.50	2.50	0.00
Z	calc	0.30	74.39	0.17	1314	1.86	9.78	15.04	2.43		0.79	2.62	0.27		3.10
	score	0.00	0.00	0.00	0.50	1.00	0.50	1.00	1.00	4.00	1.00	1.00	0.00	2.00	0.00

B/A Rat = B/A Ratio; Sil Rat = Silica Ratio; Slag Ind = Slagging Index; Fus = Fusibility; Slag Total = Slagging Total; Alk Ind =

Alkali Index; Foul Ind = Fouling Index; Foul Total = Fouling Total; Abr Ind = Abrasion Index

Low Risk Moderate Risk High Risk

According to TABLE 5, the same results were obtained with a blend of 5%, 10%, and 15% wood pellets in coal. All samples have a high risk of fouling and a low risk of abrasion. B Coal has a high risk for slagging, while the other samples have a moderate risk. The blend with wood pellets can reduce slagging tendency in B Coal.

TABLE 5. Slagging, fouling, and abrasion prediction for the blending of coals and wood pellet

Parameter		A	B	X	Y	Z
Wood Pellet 5%	Slagging	4.00	5.50	4.50	4.50	4.00
	Fouling	2.00	2.50	2.50	2.00	2.00
	Abrasion	0.00	0.00	0.00	0.00	0.00
Wood Pellet 10%	Slagging	4.00	5.50	4.50	4.50	4.00
	Fouling	2.00	2.50	2.50	2.00	2.00
	Abrasion	0.00	0.00	0.00	0.00	0.00
Wood Pellet 15%	Slagging	4.00	5.50	4.50	4.50	4.00
	Fouling	2.00	2.50	2.00	2.00	2.00
	Abrasion	0.00	0.00	0.00	0.00	0.00

Figure 3 presents the total risk value of samples which is an accumulation of slagging, fouling and abrasion score. B Coal had the highest total risk value with 8.5 for a single condition and the value of 8 for other conditions. The lowest total risk value was both A Coal and Z Coal which had an identical result with 6 for all parameters. B Coal contained high CaO and Na_2O that increased slagging and fouling scores [12]. Meanwhile, the high content of SiO_2 decreased the score of slagging and fouling of A Coal and Z Coal [12][13][14].

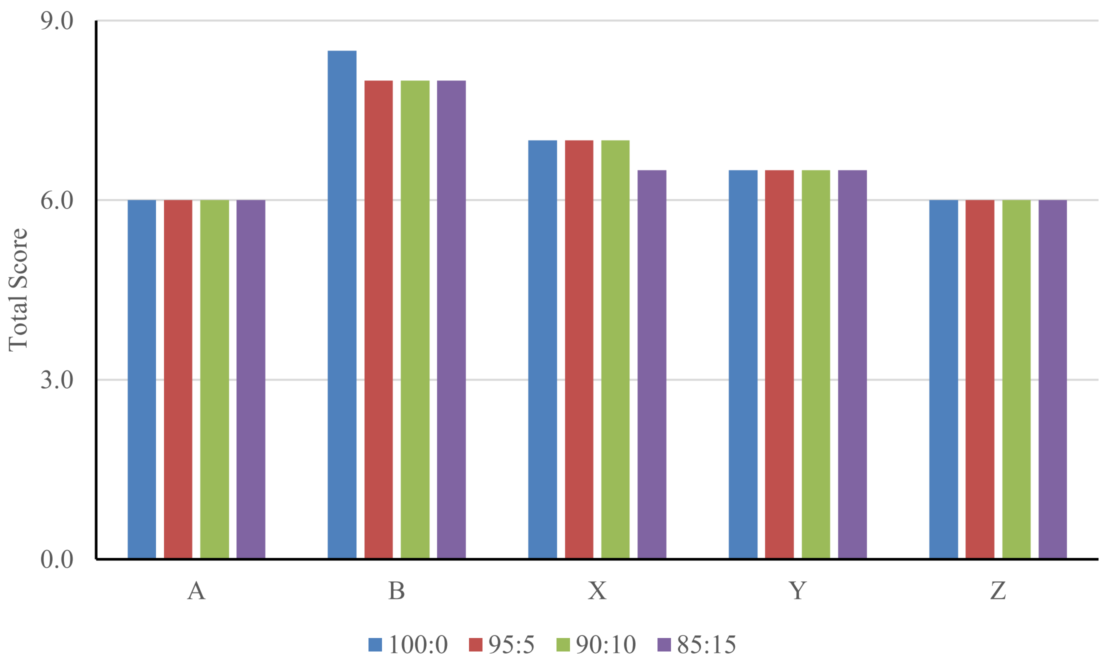

FIGURE 3. Total risk value

The effect of wood pellet blended was compared with the risk of slagging and fouling for single coals. A decrease of slagging was found for B Coal with 5%-15% of wood pellet blended. The fouling risk of X Coal was reduced with 15% of wood pellet blended. For Y Coal, the effect of 5%-15% of wood pellet blended decreased fouling and increased slagging. For Z Coal, blending wood pellets up to 15% does not affect the risk of slagging and fouling. The abrasion risk for all samples is low. Overall, the effect of wood pellet blended was not significant for the potential risk of slagging, fouling, and abrasion. Blending wood pellets up to 15% with coal with a high alkali content can reduce the risk of slagging, fouling, and abrasion.

CONCLUSION

Prediction of the potential of slagging, fouling, and abrasion in co-firing has been conducted using Indonesian bituminous coals and hardwood waste pellets. For slagging and fouling potential, B Coal has a high risk for both slagging and fouling, while A Coal, X Coal, Y Coal, and Z Coal have a moderate risk for slagging and high-risk fouling. However, A Coal and Z Coal have the lowest total risk value. Then, the effect of the use of wood pellet is not significant in slagging and fouling potential risk of samples. The score of slagging decreased with the blending of 5%-15% of the wood pellet for B Coal but increased for Y Coal. The score of fouling decreased with the blending of 15% of the wood pellet for X Coal and 5%-15% of the wood pellet for Y Coal. Blending wood pellets up to 15% does not affect the risk of slagging and fouling of Z Coal. The abrasion risk for all samples is low. From the prediction calculation, blending wood pellets up to 15% with coal with a high alkali content can reduce the risk of slagging, fouling, and abrasion. Further combustion test using Drop Tube Furnace is needed to determine the characteristics of combustion ash deposition.

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