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Utilization of agricultural waste biomass for co-firing fuel for coal-fired power plant with consideration of the potential of slagging, fouling, and abrasion in pulverized coal (PC) boilers

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KEYWORDS

Agricultural waste
Biomass blending
Biomass co-firing
Slagging fouling

ABSTRACT

The world is moving towards clean energy, especially since the Paris Agreement in 2016. Indonesia is no exception, which must reach 23% of its total energy mix usage from renewable energy sources by 2025, as stated in President Regulation No. 22/2017. Biomass as a renewable energy source can be used as a co-firing fuel for power plants based on its calorific value. This study discusses some of the most important characteristics needed in co-firing fuels, including slagging, fouling, and abrasion, using palm empty fruit bunch (EFB), rice husk (RH), and EFB-RH blended with the composition of 5%, 15%, 25%, and 35% on low-rank coal (LRC) and bituminous coal (BTC). The results showed that the addition of biomass on BTC has no significant effect on the slagging and fouling potential. Conversely, the addition of biomass to LRC significantly reduced the potential of slagging and fouling with the composition of up to 35% biomass which has EFB up to 20%. For blends with 75% of LRC and 25% of biomass blends, only biomass blends with 100% RH can be considered from the aspect of slagging and fouling risk. From potential abrasion characteristics, the addition of biomass on two types of coals did not show any problem for all compositions studied.

Introduction

Since the signing of the Paris Agreement in 2016, the world moves to clean energy in the form of new and renewable energies. To support reducing the GHG effect, the co-firing method is one of the most feasible programs to be applied in power plants. Co-firing is the combustion of two or more different fuel types during operation, such as coal and biomass (Ogaji and Probert, 2008). Co-firing program is in line with the government policy to achieve 23% of the total energy mix from new and renewable energy by 2025 (Perpres, 2017). In general, biomass which has lower nitrogen and sulphur content than coal can reduce nitrogen oxides and sulphur oxides emissions from power plants, thus making it environmentally friendly (Mehmood et al., 2012).

Indonesia’s co-firing program is supported by an abundant supply of biomass because of high production in the agricultural sector. Palm oil plantation, as the largest plantation sector, estimated to have a total area of 14.99 million hectares with the main product is crude palm oil (CPO) with 49.12 million tons in 2020. The waste byproducts of CPO production (i.e. empty fruit bunch/EFB, shells, and fronds) can be used as biomass for co-firing. With this amount of CPO production, it can be estimated that EFB produced is around 50.46 million tons (Ambarita and Kawai, 2021). From the food crop sector, rice has the largest production with a potential harvest of 10.79 million hectares in 2020, making 55.16 million tons of dry milled grain. With normally 64% (or 35.31 million tons) of dried grain is produced into edible rice, 9.84 million tons of rice husk (RH) as a byproduct is potentially used as biomass co-firing (Indonesian Statistics, 2020).

One of the problems of using low-rank coal (LRC) and biomass for power plant fuel is the tendency of slagging and fouling. Slagging and fouling are mainly caused by their mineral content (Li et al., 2017). Slagging and fouling affect boiler

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efficiency and operation cost, thus fuel composition became a critical thing to be considered (Akiyama et al., 2011). EFB has high potassium content (K_2O), which causes ash deformation for its low-temperature melting point. Research by Jeong et al. (2019) showed that increasing the portion of EFB in coal increase the ash deposition tendency analyzed by the thermomechanical analyzer and X-ray fluorescence, whereas in the same study by using drop tube furnace showed that composition EFB up to 15% have no significant effect. Rice husk has high ash content, mainly silica (SiO_2), but is low in alkali (Du et al., 2014; Wang et al., 2014; Vassilev et al., 2017). Ash content and quartz (SiO_2) are essential variables that cause abrasion in the power plant tubing (Bureska, 2021). Research by Wang et al. (2014), using a drop tube furnace, found that the addition of rice husk as a blending material can cause slagging in the ash formed at low temperature). Meanwhile, a previous study by Oladejo et al. (2020) shows that adding rice husk can mitigate the risk of slagging from fusibility.

This study used rice husk and EFB as additional biomass materials on LRC and bituminous coal (BTC). Based on the potential risk of slagging, fouling, and abrasion, the blending composition is studied to obtain the acceptable parameters for fuel blending for the power plant.

Research Methods

Materials

The coal used in this study are two different types of coal, low-rank coal (LRC) with a heating value of 4129 kcal/kg and bituminous coal (BTC) with a heating value of 5100 kcal/kg (Hariana et al., 2020) The biomass used is empty fruit bunch (EFB) and rice husk (RH) with characteristic data such as ash content, total sulphur, and ash analysis obtained from the average of several previous studies (Jeong et al., 2019; Vassilev et al., 2017; Umamaheswaran and Batra, 2008; Ninduangede and Kuprianov, 2016).

Flow Diagram

Figure 1 shows the flow diagram used in this study. EFB and RH are blended from 0% EFB with 100% RH, 10% EFB with 90% RH, until 100% EFB with 0% RH. Furthermore, these biomasses are blended with LRC and BTC then the risk predictions of slagging, fouling, and abrasion is calculated.

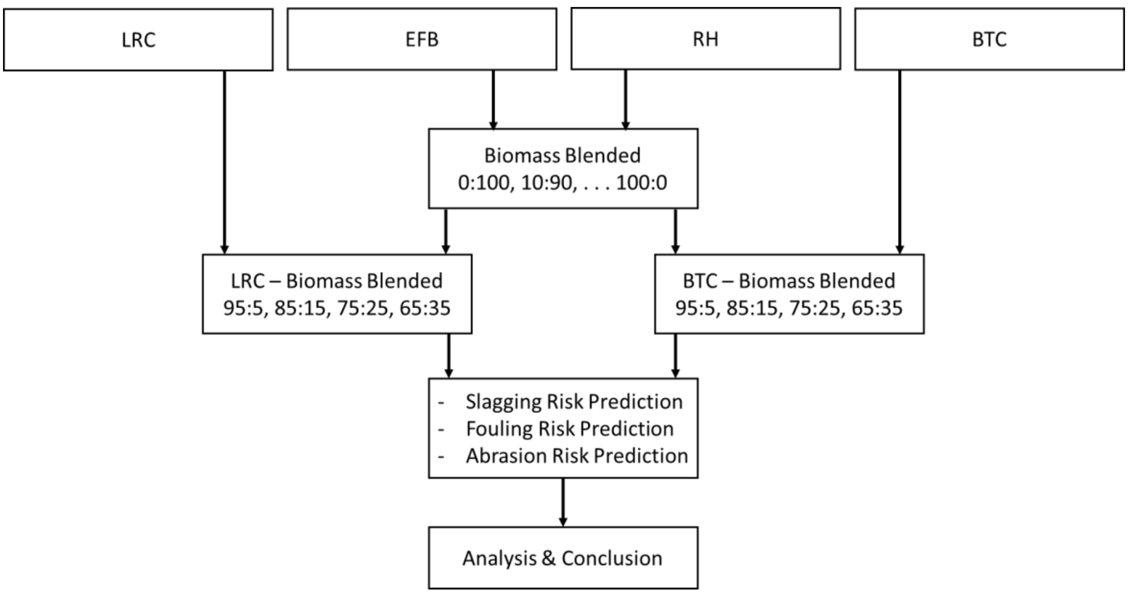

Figure 1. Flow diagram of study

Risk Prediction Calculation

Prediction of slagging can be calculated as follows:

Base acid ratio (Stultz and Kitto, 2005)

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

Slagging index (Stultz and Kitto, 2005)

$$R_s = \frac{B}{A} \cdot S \quad \text{.. (2)}$$

Silica ratio (Raask, 1985)

$$Si_R = \frac{SiO_2}{SiO_2 + Fe_2O_3 + CaO + MgO} \cdot 100 \quad \text{.................... (3)}$$

Fusibility (Yin et al., 1998)

If SiO_2 is less than or equal to 60% and Al_2O_3 is more than 30%,

$$T_{AFI} = 69.94SiO_2 + 71.01Al_2O_3 + 65.23Fe_2O_3 + 12.16CaO + 68.31MgO + 67.19a - 5485.7 \quad \text{............ (4)}$$

If SiO_2 is less than or equal to 60%, Al_2O_3 is less than or equal to 30%, and Fe_2O_3 is less than or equal to 15%,

$$T_{AFI} = 92.55SiO_2 + 97.83Al_2O_3 + 84.52Fe_2O_3 + 83.67CaO + 81.04MgO + 91.92a - 7891 \quad \text{............ (5)}$$

If SiO_2 is less than or equal to 60%, Al_2O_3 is less than or equal to 30%, and Fe_2O_3 is more than 15%,

$$T_{AFI} = 1531 - 3.01SiO_2 + 5.08Al_2O_3 - 8.02Fe_2O_3 - 9.69CaO - 5.86MgO - 3.99a \quad \text{............ (6)}$$

If SiO_2 is more than 60%,

$$T_{AFI} = 10.75SiO_2 + 13.03Al_2O_3 - 5.28Fe_2O_3 - 5.88CaO - 10.28MgO + 3.75a + 453 \quad \text{............ (7)}$$

Prediction of fouling can be calculated as follow,
Fouling index (Stultz and Kitto, 2005)

$$R_f = \frac{B}{A} \cdot (Na_2O) \quad \text{.. (8)}$$

Total alkali (Winegartner, 1974)

$$\text{Total alk.} = \frac{(Na_2O + 0.6589\ K_2O) \times \%\ ash}{100} \quad \text{.................. (9)}$$

For prediction of abrasion can be calculated as follows:

Abrasion index (Raask, 1985)

$$AI = qc + 0.5pc + 0.2\ Ac \quad \text{.............................. (10)}$$

After risk criteria in accordance with Table 2 are determined, the variables are quantified with the value of 0.00 for low risk, 0.50 for medium risk, and 1.00 for high risk (Hariana et al., 2020; Sophia and Hasini, 2017; Zaid et al., 2019). From Table 2, number 1 to 8 are the slagging parameter, number 9 to 12 are the fouling parameter, and number 13 is the abrasion parameter. For slagging prediction with 8 calculation parameters, it is determined that a total score of $\leq$ 3.5 is low risk, 4 – 5 is medium risk, and > 5 is high risk. For fouling prediction, a total score of < 1 is low risk, 1 – 1.5 is medium risk, and $\geq$ 2 is high risk. For abrasion prediction, 0 is low risk, 0.5 is medium risk, and 1 is high risk.

Results and Discussion

Table 1 shows the sample characteristics for risk predictions of slagging, fouling, and abrasion calculation. The value of LRC characteristics is obtained from laboratory analysis according to ASTM standards. The analysis results show that LRC has low SiO_2 and high SO_3, which causes a high tendency of slagging (Li et al., 2017; Akiyama et al., 2011). In EFB, other than having low SiO_2, it also has a very high content of K_2O, which causes a high tendency of fouling (Du et al., 2014). For RH, the concerned parameter is its high ash content and silica value, which may result in a high tendency of abrasion (Maskur and Nugroho, 2021). After calculating each parameter for slagging, fouling, and abrasion, the obtained value is compared to the value in Table 2. Table 2 contains the criteria to determine the risk potential for each parameter (i.e. slagging, fouling, and abrasion). The parameters are slagging index, fusibility, and fouling index by Stultz and Kitto (2005); silica index and abrasion index by Raask (1985); base acid ratio and iron calcium in ash by Płaza (2013); and total alkali from Winegartner (1974).

The results of the calculation of coals are shown in Table 3. The LRC score of 6.0 for the total slagging parameter is included in the high-risk category of slagging, while a score of 1.0 for the total fouling parameter is in the medium-risk category of fouling. For BTC, a score of 2.0 for the total slagging parameter is included in low risk, while a score of 0.0 for fouling is included in low risk. For abrasion, both coals are in the low-risk category with a value of abrasion index of 0.0.

Table 1. Coal and biomass characteristics

	AC adb %	TS adb %	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 %
LRC	5.11	0.44	29.26	15.65	17.23	17.35	7.78	0.61	0.64	0.86	0.17	0.58	9.21
BTC	4.98	0.25	63.94	29.42	2.55	1.14	0.25	1.82	0.07	0.14	0.01	0.16	0.28
EFB	4.05	0.61	19.36	1.15	3.17	9.96	2.96	0.22	0.27	50.54	0.12	2.99	1.51
RH	15.97	0.16	86.58	0.95	1.01	1.27	1.03	0.04	0.19	3.24	0.00	2.66	0.52

Table 2. Slagging, fouling, and abrasion risk criteria

No	Criteria	Low	Medium	High	Severe	Reference
1	B/A ratio	< 0.4 or > 0.7		0.4 – 0.7		(Plaza, 2013)
2	Silica ratio	72 – 80	65 – 72	50 – 65	-	(Rassk, 1985)
3	Slagging index	< 0.6	0.6 – 2.0	2.0 – 2.6	> 2.6	(Stultz and Kitto, 2005)
4	Fusibility	> 1343	1232–1343	1149-1232	< 1149	(Stultz and Kitto, 2005)
5	Fe/Ca	< 0.3 or > 3.0		0.3 – 3.0		(Bryers, 1996)
6	Fe	3 – 8	8 – 15	15 – 23	> 23	(Rassk, 1985)
7	Fe+Ca	< 10 %		> 12%		(Plaza, 2013)
8	Si/Al	< 0.7 or > 3.5		0.7 – 3.5		(Yan et al., 2017)
9	Fouling index	< 0.2	0.2 – 0.5	0.5 – 1.0	> 1.0	(Stultz and Kitto, 2005)
10	Na_2O in ash, if $CaO+MgO+Fe_2O_3 < 20\%$	< 1.2		1.2 – 3.0	> 3.0	(Stultz and Kitto, 2005)
11	Na_2O in ash, if $CaO+MgO+Fe_2O_3 > 20\%$	< 3.0		3.0 – 6.0	> 6.0	(Stultz and Kitto, 2005)
12	Total alkali	< 0.3	0.3 – 0.45	0.45 – 0.6	> 0.6	(Winegartner, 1974)
13	Abrasion index	< 4.0	4.0 – 8.0	8.0 – 12.0	> 12.0	(Rassk, 1985)

Table 3. Slagging, fouling, and abrasion risk prediction calculations of coal

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
LRC	calc	0.96	40.86	0.42	1120	0.99	17.23	34.58	1.87		0.62	0.64	0.06		1.41
	score	0.00	1.00	0.00	1.00	1.00	1.00	1.00	1.00	6.00	1.00	0.00	0.00	1.00	0.00
BTC	calc	0.04	94.20	0.01	1511	2.24	2.55	3.69	2.17		0.00	0.07	0.01		1.95
	score	0.00	0.00	0.00	0.00	1.00	0.00	0.00	1.00	2.00	0.00	0.00	0.00	0.00	0.00

A study by Hariana et al. (2020) stated that the combustion test of the BTC coal is indeed very satisfying in case of slagging and fouling tendency. From the combustion test series such as probe observation, SEM-EDS analysis, and XRD analysis, BTC has a low tendency for slagging and fouling, which is similar to the result of slagging and fouling prediction calculation conducted before the test. On the other hand, Table 3 shows that LRC has a high risk of slagging and a medium risk of fouling, which will be a good comparison to BTC for biomass blending.

LRC and BTC were blended with biomass with the composition of 5%, 15%, 25%, and 35%. Then, the risk potential of slagging, fouling, and abrasion are calculated. Table 4 shows the results of slagging, fouling, and abrasion risk prediction calculations from LRC-biomass blended. It is seen that for the risk of slagging between pure LRC and 5% biomass blended, there is no significant change. However, the risk of fouling is increased. For 15% biomass blend, the risk of slagging was reduced to 5.5 with the composition of 0:100 to 90:10 (EFB to RH). For 25% biomass blend, the risk of slagging was reduced even more significantly (3.5) with the composition of 0:100 (EFB to RH). For 35% biomass blend, the risk of slagging tends to decrease to a value under 3.5 for the composition of 0:100 to 20:80 (EFB to RH).

Table 4. Quantification of slagging, fouling, and abrasion risk prediction calculations on LRC blended with biomass

Blending Parameter		Composition of EFB : RH in Biomass Blended in Blending with LRC										
		0:100	10:90	20:80	30:70	40:60	50:50	60:40	70:30	80:20	90:10	100:0
Biomass 5%	slagging	5.50	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00	6.00
	fouling	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00	1.00	1.00	1.00
	abrasion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass 15%	slagging	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	6.00
	fouling	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	1.00	1.00	1.00
	abrasion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass 25%	slagging	3.50	5.00	5.00	5.00	5.50	5.50	5.50	4.50	5.50	5.50	5.50
	fouling	0.00	0.00	0.00	0.50	0.50	0.50	0.50	1.00	1.00	1.50	1.50
	abrasion	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass 35%	slagging	3.00	3.00	3.00	4.50	5.00	5.00	5.00	5.50	4.50	5.50	6.00
	fouling	0.00	0.00	0.00	0.00	0.50	1.00	1.00	1.00	1.00	2.00	2.00
	abrasion	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00

Table 5. Quantification of slagging, fouling, and abrasion risk prediction calculations on BTC blended with biomass

Blending Parameter		Composition of EFB : RH in Biomass Blended in Blending with BTC										
		0:100	10:90	20:80	30:70	40:60	50:50	60:40	70:30	80:20	90:10	100:0
Biomass 5%	slagging	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	fouling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abrasion	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass 15%	slagging	1.00	1.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	fouling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	abrasion	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Biomass 25%	slagging	1.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00
	fouling	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50
	abrasion	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00
Biomass 35%	slagging	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00
	fouling	0.00	0.00	0.00	0.00	0.00	0.50	0.50	0.50	0.50	0.50	1.00
	abrasion	0.50	0.50	0.50	0.50	0.50	0.50	0.00	0.00	0.00	0.00	0.00

This calculation shows that adding biomass has a good effect on reducing the risk of slagging on LRC. On the other hand, adding biomass composition higher than 15% increases the risk of fouling. The higher RH composition in biomass blend generally reduces the risk of slagging and fouling compared to pure LRC as single coal.

This result is similar to the study from Oladejo et al. (2020), RH with high silica content can reduce the risk of slagging and fouling if the material is blended with coal, specifically with low silica and high calcium content as LRC, for up to 30% composition of RH. RH enables the mineral transformation in combustion that favours higher melting point compound like silica, calcite, and mullite. A study from Wu et al. (2017) also stated that RH composition of 10% and 20% is not causing a significant effect when blended with coal containing low silica and aluminium but high potassium. The research shows that a better fouling tendency happened during the drop tube furnace test and higher RH composition. The value of AFT increased and the ash deposit was decreased. Different from RH, the higher composition of EFB increases the risk of fouling, and this result is similar to the study by Jeong et al. (2019) who used the drop tube furnace and thermo-mechanical analyzer. The study showed an increase risk of slagging and fouling with the increase of biomass composition in the coal. From a previous study about blending EFB into coal blended, the addition of EFB in coal with high iron and calcium content increases the risk of slagging (Hariana et al., 2020). Table 5 shows the result of slagging, fouling, and abrasion risk prediction calculations from BTC-biomass blended. For biomass blend up to 15%, there are no significant changes in the risk of slagging and fouling compared to pure BTC. For 25% biomass blend, the risk of fouling increased at EFB to RH ratio from 80:20 to 100:0. For 35% biomass blend, the risk of fouling increased at EFB to RH ratio from 50:50 to 100:0. However, overall, the risk of slagging and fouling for BTC-biomass blend are in the low-risk category. For abrasion, a study by Maskur and Nugroho (2021) showed that stand-alone RH has a high risk of abrasion. However, in this study, concern about abrasion due to the addition RH, which high of silica content (SiO_2) in BTC apparently is still in the range of low and medium risk until 35% of biomass blend is present. From risk prediction, BTC-biomass blended can be carried out without any problem.

Conclusion

In this study, LRC has a high risk of slagging, medium risk of fouling, and low risk of abrasion while BTC has a low risk of slagging, fouling, and abrasion. For the LRC-biomass blend, an additional 25% biomass can improve the slagging and fouling aspect with the composition of 100% RH. While adding 35% biomass can improve the slagging and fouling aspect with the composition of at least 70% RH. For the BTC-biomass blend, there are no significant effects for slagging and fouling potential risk, but abrasion increased to medium, starting from 15% of biomass composition, with composition of 100% RH. Overall, abrasion potential is in the range of low to medium for both blends. For further research, it is better to add medium ash coal (sub-bituminous) and test the sample using a drop tube furnace for more accurate results.

Declarations

Conflict of interests The authors declare no competing interests.

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