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STUDY ON CHEMICAL CHARACTERISTICS OF COAL AND BIOMASS BLEND AND THE TENDENCY OF ITS ASH DEPOSITION

STUDI SIFAT KIMIA DAN KECENDERUNGAN DEPOSISI ABU CAMPURAN BATUBARA DAN BIOMASSA

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ABSTRACT

A coal and biomasses of empty fruit bunch (EFB), mesocarp fiber (MF) and palm kernel shell (PKS) were characterized in terms of its proximate, ultimate, calorific value and ash chemical composition. Ash fusion temperature (AFT) was carried out on coal and biomass blends with a composition in weight % of 95-5; 90-10 and 85-15. The coal used in this research has high calorific value of 6,106 cal/g. Results indicate that based on the AFT, the coal-biomass blends at some composition shows a medium tendency to ash deposition. While based on the chemical composition, generally the coal-biomass blends have a low tendency to slagging but have a high tendency to fouling. Coal-biomass blend at the coal composition of 85 wt% and PKS of 15 wt% (85-15) is recommended to be applied. The less the coal is used, the less the CO_2 emission, so it is expected to reduce the GHG significantly.

Keywords: biomass, proximate, ultimate, slagging, fouling.

ABSTRAK

Batubara dan biomassa berupa tandan kosong kelapa sawit (TKKS), serat sawit dan cangkang sawit dianalisis terhadap proksimat, ultimat, nilai kalor dan komposisi kimia abu. Uji titik leleh abu dilakukan dengan mencampurkan batubara dan biomassa dengan komposisi persen berat 95-5; 90-10 dan 85-15. Batubara yang digunakan dalam penelitian ini memiliki nilai kalor yang tinggi yaitu 6.106 cal/g. Hasil menunjukkan bahwa berdasarkan AFT, campuran batubara-biomassa pada beberapa komposisi menunjukkan kecenderungan deposisi abu yang sedang. Sedangkan berdasarkan komposisi kimianya, umumnya campuran batubara-biomassa memiliki kecenderungan slagging *yang rendah tetapi memiliki kecenderungan* fouling *yang tinggi. Campuran batubara-biomassa pada komposisi batubara 85 wt% dan PKS 15% wt (85-15) direkomendasikan untuk diterapkan. Semakin sedikit batubara yang digunakan, semakin sedikit emisi CO_2 yang dihasilkan, sehingga diharapkan dapat mengurangi gas rumah kaca secara signifikan.*

Kata kunci: biomassa, proksimat, ultimat, slagging, fouling.

INTRODUCTION

The need of energy, especially electricity increases year by year along with the increasing standard of the Indonesian living. Coal-fired power plants are likely to dominate electricity generation for at least the next few decades. The energy produced from coal fired plants is cheaper and more affordable than other energy sources. Since coal is abundant, it is definitely cheap to generate electricity using this fuel. Moreover, it is not expensive to extract and mine from coal deposits. On the other hand, there are also some significant disadvantages of coal-fired plants including greenhouse gas (GHG) emissions, mining destruction, generating millions of tons of waste, and emission of harmful substances

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(Bhattacharya and Datta, 2013). Despite the shortcomings, coal-fired power plant is still important for the power generation, the traditional fuel combustion technology will be improved with a better performance to overcome the contradiction between industry development and environment.

One of the major operational concerns in coal-fired power plants is ash deposition of slagging and fouling. Ash deposition will reduce the boiler efficiency and increase the maintenance cost. Slag is molten ash and incombustible by-products that remain after coal combustion and can stick to furnace components. Fouling refers to deposits that occur in the convection pass after the gases exit the furnace, and is generally caused by ash cinders and accumulations that form on the leading edges of the superheater and reheater tubes (Qi *et al.*, 2018; Clark, Zucker and Urpelainen, 2020).

Ash with low melting temperature causes the ash deposition problems in pulverized combustion boilers. Ash deposition on the heat exchanger tubes affects the decrease in the overall heat transfer coefficient due to the thermal conductivity of the ash as well as several other operation problems. Ultimately, deposits in the high-temperature zone led to corrosion, reduced heat transfer, and shortened equipment life (Song *et al.*, 2017; Umar, Monika and Handoko, 2021).

In order to reduce the GHG,Indonesian Government implements the use of biomass as a substitute for coal in the co-firing system in several coal-fired power plants. Due to their short life cycle, biomass fuels are often considered to be carbon neutral in nature. Biomass co-firing with coal is recognized as a particularly attractive proposition for electricity generation as it provides an immediate and practical means of greducing coal consumption. Madanayake *et al.* (2017), pointed out that the major shortcomings of biomass as a resource are its distributed nature and low energy and mass densities. Consumption of biomass as the sole fuel resource for a large power station may not be an attractive alternative either economically or logistically. However, biomass can be used as a supplementary fuel along with the conventional fossil fuel in the plant, either in a co-firing mode or as a re-burning fuel (Mun *et al.*, 2016). Coal-biomass co-firing power generation technology has provent to be an effective way to reduce the CO_2 emission and other pollutants.

Three ways in which biomass co-firing plants can be configured (Dai *et al.*, 2008) as shown in Figure 1. Direct co-firing systems use a single common boiler (a). This boiler can be powered by burners using a blend of coal and biomass or coal and biomass separately. The common boiler means that existing conventional coal power plants can start co-firing biomass with minimal modifications, making it an attractive proposition economically. As the result, direct co-firing is the predominant configuration in the power generation industry. Parallel co-firing systems have separate boilers for coal and biomass (b).

The last option, indirect co-firing, relies on gasification of the biomass component (c). This method has the potential to utilize a high biomass: coal ratio during the co-firing, and also provides great fuel flexibility. Problems arising from biomass combustion, such as slagging, are also avoided. However, it is expensive and rarely used at present (Madanayake *et al.*, 2017). In this paper, discussion focuses on issues related to direct co-firing.

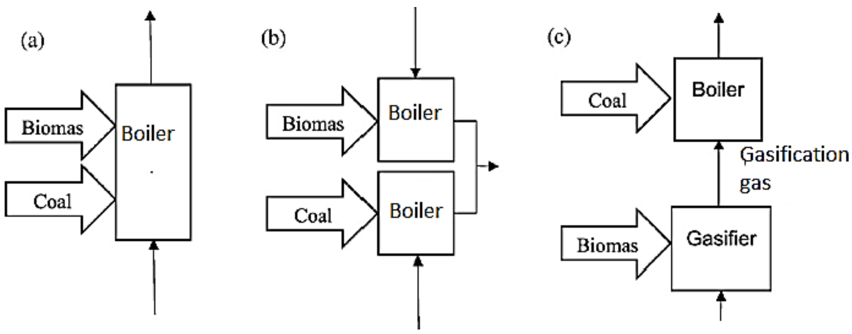

Figure 1. Configuration of biomass co-firing plants (Dai *et al.*, 2008)

Some biomass can be used as blending material with coal. Indonesia produces about 3 million tons of crude palm oil (CPO), making it the largest CPO producer in the world with a total production of 32 million tons or about 46.6% of the total world CPO production. The world market demand for CPO continue increase. The world demand for CPO in 2020 is estimated to reach 95.7 million tons. Meanwhile, the development of Indonesian palm oil industry shows a positive trend with an increase in production every year. This shows that Indonesian palm oil industry will continue to grow in the future to meet global CPO demand. Therefore, it is important to recognize the potential of palm oil waste as an added value for the Indonesian palm oil industry (Awalludin *et al.*, 2015).

The raw material of CPO is fresh fruit bunch (FFB). In a palm oil mill, FFB is processed to produce CPO and palm kernel oil (PKO). The processing of FFB into CPO involves cooking, threshing, digestion, pressing, settling, purification, and drying. Pressing process produces a waste product, namely nut/fibre. Further process is the separation of nut and fibre followed by drying, nut cracking, kernel/shell separation, drying, pressing, and filtering until PKO is produced (Hambali and Rivai, 2017).

In palm oil mills, during the conversion process of FFB into CPO and PKO, several types of waste including empty fruit bunch (EFB), mesocarp fiber (MF), palm kernel shell (PKS), palm kernel meal (PKM), and palm oil mills effluent (POME) are produced. CPO and waste production is affected by the production efficiency of the mills. Mill production efficiency is influenced by mills capacity, technical efficiency, labour, capital, machines, methods, and materials (Azman, 2014; Foong *et al.*, 2019). The percentage of that waste of about 21 – 26% EFB, 5 – 7% PKS, about 27% washing water and condensate, 12 – 18% MF, and 50 – 70% liquid waste. The mass balance of FFB processing can be seen in Figure 2 (Kramanandita *et al.*, 2014; Hambali and Rivai, 2017; Kurniawan *et al.*, 2020).

The main objective of this paper is to study the ash deposition of fouling and slagging tendencies of the coal and biomass blend in coal-fired power plant. The fouling and slagging tendencies was studied based on the ash chemical composition and ash fusion temperature (AFT). Slagging is dominant in the high-temperature radiative sections of the boiler and occurs due to molten ashes, while fouling is primarily found in the low-temperature convective sections and is related to ash deposits during cooling (Teixeira *et al.*, 2012). Slag and fouling deposits consist primarily of chlorides, sulphates, hydroxides and silicates of alkali and alkaline earth metals. The slag is formed when ash is fused or partially-fused. This requires high temperatures, typically exceeding 1,000 °C. Fouling occurs when alkali compounds condense on the metal surfaces, and also when fly ash is quenched below its melting temperature and gets deposited. Both these phenomena occur due to the falling temperatures in the heat-recovery sections, where heat transfer is by convection (Madanayake *et al.*, 2017).

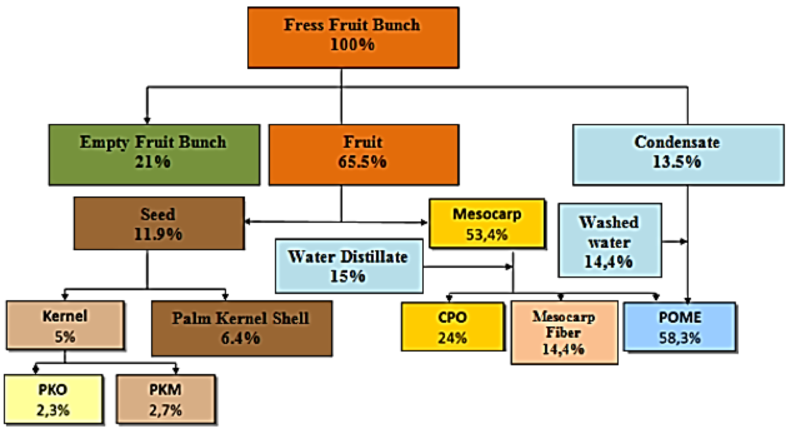

Figure 2. Mass balance of FFB processing (Kramanandita *et al.*, 2014; Hambali and Rivai, 2017; Kurniawan *et al.*, 2020)

METHOD

In some cases, the biomass co-firing in large coal fired utility boilers is associated with a relatively low co-firing ratios up to 20% by mass (Kleinhans *et al.*, 2018). Therefore, in this research the composition of blended coal-biomass was designed limited up to 85% of coal and 15% of biomass. The composition of coal and biomasses in this study is shown in Table 1.

Table 1. Composition of coal and biomass

Sample mark	Coal, weight %	EFB, weight %
C-EFB-1	95	5
C-EFB-2	90	10
C -EFB-3	85	15
		MF, weight %
C -MF-1	95	5
C -MF-2	90	10
C -MF-3	85	15
		MF, weight %
C -PKS-1	95	5
C -PKS -2	90	10
C -PKS -3	85	15

A coal sample from South Kalimantan as a blended material with biomass was used in this research. Three biomasses of EFB, MF and PKS used in this study were collected from a palm oil plantation of PT Perkebunan Nusantara VIII, in Pandeglang, Banten, Indonesia. Figure 3 shows the EFB, MF and PKS in this research.

EFB is the main waste from palm oil mills (Ninduangdee and Kuprianov, 2016) amounting 21-25% (w/w) of FFB. EFB generally becomes waste or can be used as organic fertilizer on oil palm plantations. The properties of EFB have the potential to generate heat which is quite good given the presence of fibres or shells as boiler fuel. Apart from the caloric value shown by EFB, it is almost the same as fibre under various waste conditions. But the impact that occurs during combustion in boilers is quite potential. EFB can be used as boiler fuel because of the considerable availability in Indonesia with a higher calorie-burning value.

The composition of EFB has a fairly high mineral content such as Ca, Fe, Na, K, and P. High ash content in EFB can cause secondary reactions in thermochemical processes. Hence, EFB is not widely used as a fuel in local power plants, mainly due to the high potassium content in biomass. Fluidized-bed combustion technology is the most preferred technology for heat and power production from biomass (Ninduangdee and Kuprianov, 2016).

PKS is a by-product in palm oil mills which is commonly used in the natural biomass energy industry. PKS is the shell fractions that remain after the nut is removed after being crushed in the palm oil mill (Figure 2). It is a fibrous material, brownish-yellow in colour and can be easily handled in bulk directly from the product line to the end use. Generally, the PKS contains moisture content of 15-25% (As received) or 8 – 11% (air dried base), has a minimum ash content, approximately 1-3% and more than 4,200 cal/g calories.

MF is obtained from the husk of FFB. It is a fibrous material found between the internal shell and the outer coat of the FFB. This material can be used for the manufacture of bio composites. MF bio composites can be used in automotive, electronics and building materials.

Figure 3. EFB, MF and PKS samples

To support this research, the coals and biomasses of EFB, PKS and MF were analysed for the proximate, ultimate, calorific value, ash composition and ash fusion temperature. The analysis of proximate consisted of inherent moisture, ash and volatile matter according to ASTM D 3176, ASTM D 3175 and ASTM D 3175 respectively. While fixed carbon is calculated by: 100% - % (IM + ash + volatile matter) in air dried base (adb), ultimate analysis consisting of: carbon (C), hydrogen (H), according to ASTM D 3179-89, nitrogen (N) according to ASTM D 3179 , total sulfur (S) using the infrared method, and oxygen (O) based on the calculation of 100% - % (C + H + N + S + ash). The calorific value according to the ASTM standard 5865-04. Ash chemical composition analysis covering SiO_2 was determined by gravimetry, spectrophotometry for TiO_2 and P_2O_5, turbidimetry for SO_3 and AAS for Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, and MnO_2 (Speight, 2005).

Ash fusion temperature (AFT) was conducted to determine the suitability and efficiency of the boiler. The AFT test provides information on the softening and melting behaviour of fuel ash at high temperatures in the boiler. Blended coal-biomass for co-firing system, the AFT cannot be calculated directly according to the weight ratio of each material used. AFT was determined according to the ASTM D1857-04 (2013) by viewing a moulded specimen of the coal ash through an observation window in a high-temperature furnace under both reduction and oxidation conditions. The ash, in the form of a cone, was steadily heated past 1,000°C to a highest possible temperature, preferably 1,600°C (2,910°F). The following temperatures in either reduction or oxidation condition were recorded:

a. Initial Deformation temperature (IDT): This is reached when the corners of the mold first become rounded.
b. Softening (sphere) temperature (ST): This is reached when the top of the mold takes on a spherical shape (h=w)
c. Hemisphere temperature (HT): This is reached when the entire mold takes on a hemisphere shape (h=1/4 w).
d. Flow (fluid) temperature (FT): This is reached when the molten ash collapses to a flattened button on the furnace floor.

The shapes of the DT, ST, HT and FT are shown in Figure 4.

RESULT AND DISCUSSION

Proximate and Calorific Value Analyses

The analysis results of proximate and calorific value of coal and three typical biomasses of EFB, PKS and MF are shown in Table 2. The coal and biomasses blends are presented according to the ratio as shown in Table 1.

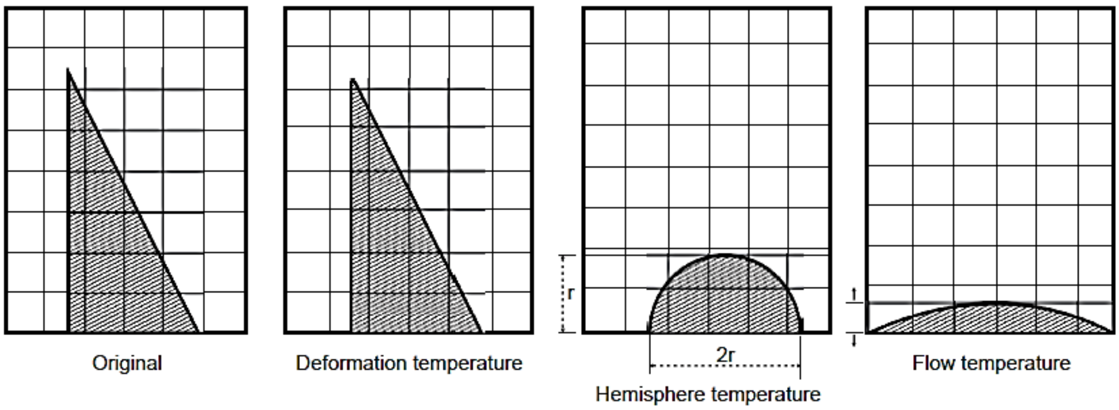

Figure 4. Shape characterisitcs of AFT (ASTM D1857-04, 2013)

Table 2. Results of proximate and calorific value analyses (air dried base)

	Inherent Moisture %	Ash %	Volatile matter %	Fixed Carbon %	Calorific Value cal/g
Coal	7.49	3.43	32.95	56.13	6,109
EFB	10.86	5.41	72.86	10.87	4,098
MF	11.19	6.11	65.26	17.44	4,187
PKS	11.77	1.51	68.14	18.58	4,447
C-EFB 1	7.66	3.53	34.95	53.87	6,008
C-EFB 2	7.83	3.63	36.94	51.60	5,908
C-EFB 3	8.00	3.73	38.94	49.34	5,807
C-MF 1	7.68	3.56	34.57	54.20	6,013
C-MF 2	7.86	3.70	36.18	52.26	5,917
C-MF 3	8.05	3.83	37.80	50.33	5,821
C-PKS 1	7.70	3.33	34.71	54.25	6,026
C-PKS 2	7.92	3.24	36.47	52.38	5,943
C-PKS 3	8.13	3.14	38.23	50.50	5,860

Moisture is an important issue related to the combustion of coal and biomass as fuel. High moisture content makes the fuel combustion less profitable, not only because of the process itself, but also due to high transportation costs (Rao *et al.*, 2015). As in the case of all combustion fuels, moisture significantly affects the lower calorific value and plays an important role in the combustion process. Combustion of fuels with a high moisture content increases the volume of exhaust gases and, consequently lowers the combustion temperature (Mierzwa-Hersztek *et al.*, 2019). Additionally, an increase in losses related to partial and incomplete combustions can be observed, since the temperature in the combustion chamber will not be sufficient to combust all flammable substances in flue gases (Tsai *et al.*, 2018). The inherent moisture of coal and biomasses were relatively low (as shown in Table 2). Biomass usually has high total moisture. In this case, inherent moisture of the biomasses is low, it means the surface moisture is high. Surface moisture is relatively easy to be removed either by mechanical or thermal.

As in the case of coal, combustion of biomass generates solid waste, mostly in the form of the bottom ash. The amount of that waste depends mainly on the type of biomass used (He *et al.*, 2018). One factor can be influence ash content is solid contamination. As can be seen in Table 2, the ash content of the coal and biomasses is low, the lowest is achieved by PKS (1.51%). As a fuel, low moisture and ash contents is desirable because it increases the calorific value.

Volatile matter (VM) is the percentage loss of mass, adjusted for moisture, when coal is heated without contact with air under standard conditions. Volatile matter content is an important parameter that significantly affects the combustion process (Holtmeyer *et al.*, 2013). Table 2 shows that the VM of biomasses are high. Literature data indicate that biomass contains up to 2.5 times more volatile matter than coal, which has a major influence on ignition and combustion (He *et al.*, 2018). During combustion of high volatile fuels, large number of flammable substances (mainly CO, low hydrocarbons, and monocyclic aromatic hydrocarbons) is released, which manifests itself with a higher flames. This requires the supply of additional air to ensure complete burnout of these products (Sadiku, Oluyege and Sadiku, 2016).

The higher the volatile matter content in the fuel, the more high-pressure secondary air is required for effective combustion. On the other hand, incomplete combustion of volatile matter result in dark smoke, heat loss, pollution hazard, and soot deposition on boiler surfaces. The biomass after being mixed with coal at a certain ratio as shown in Table 4 has volatile matter which is well accepted as a fuel in the range of 34.57-38.94% on an air-dried base.

Fixed carbon is the solid combustible residue that remains after coal/biomass is heated and volatile matter is expelled excluding the ash and moisture content (Brewer *et al.*, 2014). Fixed carbon content represents the amount of matter which will form coke during combustion. Sadiku, Oluyege and Sadiku (2016) stated that the fixed carbon of any material gives a rough estimate of the heating value of a fuel and acts as the main heat generator during the combustion. For the analysed fuels, fixed carbon of the biomasses was low, due to the high of volatile matter. The fixed carbon of the blended biomass with coal is in the range of 49.34 to 54.25%. the highest fixed carbon is achieved by the blended coal with PKS in the ratio of 95:5 (C-PKS 1).

Calorific value is one of the most important thermo-physical parameters that describe energy potential of materials. This parameter forms a basis for assessing the quality of fuel as an energy source. Calorific value is associated with moisture and depends strongly on the fuel chemical composition. In this study, calorific value of the coal is relatively high. The coal is classified as medium calorific coal with the calorific value of 6,109 cal/g. While the calorific value of the biomass ranges from 4,098 to 4,447 cal/g. The highest calorific value of the blended coal-biomass is achieved by coal-PKS blends by 6,026 kcal/kg comparing coal and PKS 95 and 5 respectively (C-PKS 1). This result consistent with the result of the fixed carbon, the higher the fixed carbon, the higher the calorific value.

Ultimate Analysis

The ultimate analysis results in air dried base are shown in Table 3. The carbon content in coal and biomasses ranges from 45.67 to 65.39%. The coal has higher carbon content compared to the biomasses. While the EFB has the lowest carbon content. However, the highest carbon values of blended coal and biomass (64.53% of the C content) was reached by the composition of coal and PKS 95 and 5% (C-PKS 1).

According to Tripathi, Sahu and Ganesan (2016), the proportions in which carbon, hydrogen, and oxygen occur in biomass have a decisive effect on its calorific value. The hydrogen content is practically the same as the nitrogen content in each biomass, only PKS shows very low nitrogen content of about 0.38%. The high content of N can result in the formation of high-energy C–N, H–N, C–S, and H–S bonds. On the other hand, the low content of sulphur in biomass is more environmentally friendly when the biomass is combusted, because it does not contribute to the formation of acid rains and GHG emissions (Singh, Mahanta and Bora, 2017).

Ash Chemical Composition

Absorption Spectroscopy (AAS) and X-ray fluorescence spectroscopy were used to analyze the ash chemical composition of the coal and biomass ashes. Ash comprises a wide variety of inorganic matter. The elements found in ash are reported as the weight percentage of their stable oxides of SiO_2, CaO, K_2O, P_2O_5, Al_2O_3, MgO, Fe_2O_3, Na_2O, SO_3 and TiO_2. The result can be seen in Table 4.

Table 3. Results of ultimate analysis (air dried base)

	C %	H %	N %	S %	O %
Coal	65.39	5.93	1.79	1.01	22.84
EFB	45.67	6.27	0.95	0.09	41.61
MF	45.89	6.04	1.12	0.13	40.71
PKS	48.24	6.32	0.38	0.04	43.51
C-EFB 1	64.40	5.95	1.75	0.96	23.78
C -EFB 2	63.42	5.96	1.71	0.92	24.72
C -EFB 3	62.43	5.98	1.66	0.87	25.66
C -MF 1	64.42	5.94	1.76	0.97	23.73
C -MF 2	63.44	5.94	1.72	0.92	24.63
C -MF 3	62.47	5.95	1.69	0.88	25.52
C -PKS 1	64.53	5.95	1.72	0.96	23.87
C -PKS 2	63.68	5.97	1.65	0.91	24.91
C -PKS 3	62.82	5.99	1.58	0.86	25.94

Table 4. Ash chemical composition

	SiO_2 %	Al_2O_3 %	Fe_2O_3 %	K_2O %	Na_2O %	CaO %	MgO %	TiO_2 %	MnO %	P_2O_5 %	SO_3 %
Coal	37.10	28.30	23.2	0.81	0.69	3.46	1.32	0.92	0.33	0.44	2.05
EFB	27.40	2.49	1.55	35.50	2.15	9.38	7.15	0.018	0.17	4.04	2.64
MF	61.00	7.04	3.83	9.80	1.46	6.6	5.43	0.17	0.18	1.84	1.68
PKS	72.20	2.61	1.06	1.69	0.37	2.46	3.65	0.007	0.15	3.22	1.93
C -EFB 1	36.62	27.01	22.12	2.54	0.76	3.76	1.61	0.87	0.32	0.62	2.08
C -EFB 2	36.13	25.72	21.04	4.28	0.84	4.05	1.90	0.83	0.31	0.80	2.11
C -EFB 3	35.65	24.43	19.95	6.01	0.91	4.35	2.19	0.78	0.31	0.98	2.14
C -MF 1	38.30	27.24	22.23	1.26	0.73	3.62	1.53	0.88	0.32	0.51	2.03
C -MF 2	39.49	26.17	21.26	1.71	0.77	3.77	1.73	0.85	0.32	0.58	2.01
C -MF 3	40.69	25.11	20.29	2.16	0.81	3.93	1.94	0.81	0.31	0.65	1.99
C -PKS 1	38.86	27.02	22.09	0.85	0.67	3.41	1.44	0.87	0.32	0.58	2.04
C -PKS 2	40.61	25.73	20.99	0.90	0.66	3.36	1.55	0.83	0.31	0.72	2.04
C -PKS 3	42.37	24.45	19.88	0.94	0.64	3.31	1.67	0.78	0.30	0.86	2.03

The oxides of SiO_2, Al_2O_3 and TiO_2 are categorized as acidic compound while CaO, K_2O, MgO, Fe_2O_3 and Na_2O are categorized as basic compound. The acidic compounds have been shown to increase the overall melting temperature, while the basic compounds have the opposite effect (Lachman *et al.*, 2021). The coal is dominated by Si, Al and Fe, which mainly originate from mineral grains composed of aluminosilicates, quartz or pyrite depending on the coal seam (Kleinhans *et al.*, 2018). The EFB has high potassium content of 35,50%. However, EFB is not widely used as a fuel in power plants, mainly due to high potassium content in the ash, causing serious operational problems in boilers. The potassium in fuel ends up mainly as KCl, K_2SO_4, K_2CO_3, and KOH. Sodium in the biomasses is much lower compared to potassium. Due to the low sodium content in most biomass, the impact of Na-containing species on the ash-related problems is noticeably lower than the impact of potassium (Ninduangdee and Kuprianov, 2016).

The SiO_2, CaO and K_2O contents of the biomass are higher than the other chemical constituents (Adeleke *et al.*, 2020). The silicate (SiO_2) content of the MF and PKS is 61.00 and 72.20% respectively while the SiO_2 of EFB is 27.40%. It was reported by Vassilev *et al.* (2013), that higher content above 35% of silica minerals such as quartz, tridymite, and cristobalite could increase the wear of the combustion chamber. Hence, the usage of the EFB in this study will have a lower tendency to wear the combustion chamber since the silica mineral present in the samples is lower than 35%. The amount of silica content present in the biomass will also limit the formation of low-temperature alkaline silicates that can rapidly increase slagging and even health risks.

The CaO and MgO contents of fuel ash have also been reported to affect slagging, fouling and corrosion. Biomass with high contents of CaO and MgO exhibits manageable slagging, fouling and corrosion problems. Compared to the coal, the biomass contains lower Al_2O_3. However, the lower content of TiO_2 and Fe_2O_3, could be responsible for lower ash fusion temperature (AFTs) compared to coal (Vassilev, Vassileva and Vassilev, 2015).

Ash Fusion Temperature (AFT)

The AFT test provides information on the softening and melting behaviour of coal ash at high temperatures in the boiler. Blended two types of coal or blended coal-biomass for co-firing system, the AFT cannot be calculated directly according to the weight ratio of each material used. Result of the AFT test can be seen in Table 5 for reduction and oxidation conditions and Figure 5 shows the graphical chart of AFT in reduction condition while Figure 6 in oxidation condition.

Table 5. Results of ash fusion temperature

	Reduction				Oxidation			
	DT °C	ST °C	HT °C	FT °C	DT °C	ST °C	HT °C	FT °C
Coal	1,185	1,250	1,283	1,355	1,343	1,396	1,400	1,410
EFB	1,015	1,135	1,148	1,185	1,050	1,143	1,158	1,195
MF	990	1,195	1,218	1,275	1,080	1,220	1,235	1,280
PKS	1,060	1,198	1,285	1,375	1,075	1,250	1,315	1,423
B-EFB 1	1,335	1,380	1,400	1,460	1,350	1,385	1,405	1,470
B-EFB 2	1,265	1,340	1,400	1,475	1,280	1,355	1,405	1,480
B-EFB 3	1,260	1,325	1,400	1,425	1,260	1,340	1,400	1,450
B-MF 1	1,280	1,375	1,400	1,440	1,280	1,380	1,400	1,445
B-MF 2	1,190	1,285	1,310	1,415	1,260	1,360	1,385	1,415
B-MF 3	1,265	1,360	1,380	1,415	1,265	1,360	1,380	1,420
B-PKS 1	1,220	1,360	1,390	1,450	1,290	1,390	1,410	1,455
B-PKS 2	1,175	1,310	1,380	1,460	1,290	1,365	1,400	1,445
B-PKS 3	1,160	1,300	1,350	1,430	1,280	1,360	1,400	1,425

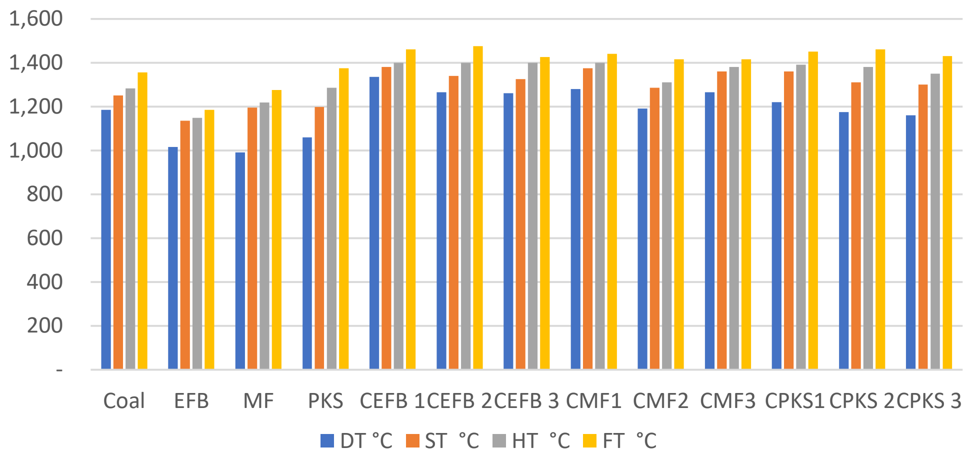

Figure 5. Graphical representation of asf fusion temperature (reduction)

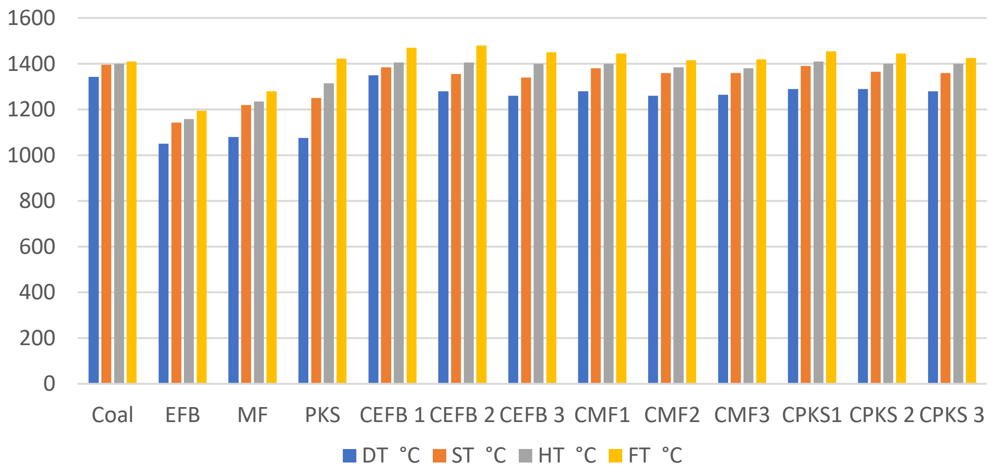

Figure 6. Graphical representation of asf fusion temperature (oxidation)

The AFT of coal is higher than that of the biomass. The lower AFTs of biomass compared to coal are attributed to high alkaline content in biomass ash (Lachman *et al.*, 2021). Another key difference between biomass and coal composition is the increased presence of Ca, Cl, K, Mg, Mn, Na, P, phosphates, carbonates and organically bound inorganic elements. On the other hand, coal tends to be richer in elements such as Al, Fe, N, S, Si, Ti and certain inorganic constituents, e.g. sulphides, sulphates and silicates (Vassilev, Vassileva and Vassilev, 2015). Therefore, the AFTs largely depend on the actual ash composition, the ratio between certain elements and their phase and form. It had been observed that the acidic oxides tend to increase the AFTs while the basic oxides decrease it (Song *et al.*, 2010). It should be considered that during combustion in pulverized (PF) boilers the average furnace temperature at the combustion is about 1,400 to 1,600°C, while in CFBC boilers the furnace bed temperature is 880 to 940°C.

The ash softening temperature (ST) is the temperature at which the ash softens and becomes plastic. This is slightly below the melting point of ash. All biomass showed that the ST were lower than that of the coal. The design of steam generator depends heavily on the ash ST of the fuel. If the furnace temperature is higher than the ash ST, the ash will melt and come out of the furnace bottom continuously as molten slag. For furnace that would discharge ash in the solid form, a high softening temperature is required. A stoker furnace must use coal with a high ash ST otherwise clinkers will form. Clinkers which are large masses of fused ash, cause dischargi problems and also result in inefficient combustion. Therefore the ash ST should be above 1,150°C (Song *et al.*, 2010).

Table 5 shows that the AFT was above 1,000°C for all fuels except MF (the IDT is 990°C). It is important to note that the AFTs obtained under reducing conditions are generally lower (Song *et al.*, 2010) and thus not interchangeable with the AFTs obtained under oxidizing conditions. The coal used in this research had AFT of softening temperature in oxidation condition (ST-ox) of 1,396°C, while the biomasses of EFB, MF and PKS were 1,143; 1,220 and 1,250°C respectively. Blended coal with EFB of 95%-5% (C-EFB 1) had the highest STox of 1,396°C. The blend of coal and MF resulted the highest STox of 1, 380°C at 95%-5% (C-MF 1), while the blend of coal and PKS gave the highest ST-ox of 1,390°C at 95%-5% (C-PKS 1).

Ash Deposition Tendencies

Based on the ash chemical composition, a number of indices has been developed to evaluate the tendency of ash deposition of coal and biomass. They form the basis for acidic ratio (B/A), bed agglomeration index (BAI), fouling index (Fu), slag viscosity index (silica ratio) and alkali index (AI).

Basic to acidic ratio (B/A)

The slagging tendency of the ash increases with increasing the basic to acidic (B/A) compounds ratio. The ash is said to have low slagging inclination when B/A < 0.5, medium one for 0.5 < B/A < 1, a high one for 1 < B/A < 1.75 and a severe one for B/A above 1.75 (Garcia-Maraver *et al.*, 2017). The simplified B/A ratio can be seen in Equation 1.

$B/A = (Fe_2O_3 + CaO + MgO + Na_2O + K_2O) / (SiO_2 + Al_2O_3 + TiO_2)$ ....(1)

Bed agglomeration index (BAI)

The bed agglomeration index has been developed to evaluate operational problems during fluidized bed combustion (Lachman *et al.*, 2021). Bed agglomeration is often caused by low AFT ash, therefore higher coefficient values should indicate higher AFTs. BAI value is calculated based on the Equation 2. Bed agglomeration occurs when BAI is below 0.15.

$BAI = Fe_2O_3 / (Na_2O + K_2O)$ ....(2)

Fouling index (Fu)

The fouling index is based on the B/A ratio. While the sodium content in biomass ash is generally low, potassium has been shown to be one of its major constituents (Garcia-Maraver *et al.*, 2017). The fouling index is calculated according to Equation 3 (Maraver *et al.*, 2017). When potassium condenses on fly ash particles, it increases the surface stickiness and is therefore a major cause of fouling. K_2O to be one of the main constituents (along with SO_3 and CaO) of the ash deposits on superheater tubes. Low fouling inclinations can be expected at Fu <

0.6, high at Fu values up to 40 and extremely high at values above 40.

$Fu = (B/A) \times (Na_2O+K_2O)$ ....(3)

Slag viscosity index (Silica ratio, Sr)

The grate and furnace wall deposits are almost identical to the original ash composition and retain most silica present in the ash. The slag viscosity index is therefore used to evaluate the slagging tendency inside the furnace (Rizvi *et al.*, 2015). High values correspond to high viscosity and therefore low slagging. Low slagging occurs when Sr is above 72, medium at 65 < Sr < 72 and high at values below 65. Equation 4 shows the formula to calculate the slag viscosity index.

$Sr = (SiO_2 /(SiO_2 + CaO + MgO + Fe_2O_3) \times 100$..(4)

Alkali index (AI)

The alkali index expresses the quantity of alkali oxides in the fuel per unit of fuel energy as can be seen in Equation 5 (Garcia-Maraver and Perez-Jimenez, 2015). The fuel energy is commonly expressed as the higher heating value (HHV) in GJ/kg, while Ar represents the ash content in raw fuel (wt%). Fouling may occur above 0.17 kg alkali/GJ and almost certainly occurs above 0.34 kg alkali/GJ.

$AI = [(Na_2O + K_2O) \times Ar] /HHV$ ....(5)

Apart from the ash chemical composition, the following temperature ranges generated from AFT can be used when evaluating the slagging potential of fuels (Yu, Wang and Li, 2014): minor slagging occurs when the ST is above 1390 °C, slight slagging at STs between 1250 °C and 1390 °C, severe slagging at STs below 1250 °C. The indices were applied to predict the ash deposition tendencies as shown in Table 6.

As shown in Table 6, not only the indices predict drastically different tendencies than those observed in the AFTs, but also the predictions for each sample vary based on the index applied. For example, the prediction based on the B/A ratio for MF shows low fouling, while the prediction for the same fuel based on the fouling index shows high fouling, which is more correlated with the observed AFT (severe). According to the AFTs, the coal has low tendency on slagging but high tendency on fouling, while the EFB and MF have severe (very high) tendency on slagging and fouling. All of the coal biomass blends based on AFT show medium tendency on slagging and high tendency on fouling. Bed agglomeration index (BAI) of the investigated fuels was generally low, except for EFB alone, which was due to the high of alkali (K_2O and Na_2O). It means that except EFB, all of investigated fuels can be safely used in power plant using fluidized-bed technology (Lachman *et al.*, 2021). Therefore, Ninduangdee and Kuprianov (2016) burned EFB in a fluidized-bed combustor using alumina sand, limestone, and dolomite as the bed material to prevent bed agglomeration.

Table 6. Ash deposition tendencies of the investigated fuels

	ST-ox	B/A	BAI	Fu	Sr	AI
Coal	Low	Low	Low	High	High	High
EFB	Severe	Severe	High	Severe	High	High
MF	Severe	Low	Low	High	Low	High
PKS	Medium	Low	Low	Low	Low	High
C-EFB 1	Medium	Low	Low	High	High	High
C-EFB 2	Medium	Medium	Low	High	High	High
C -EFB 3	Medium	Medium	Low	High	High	High
C -MF 1	Medium	Low	Low	High	High	High
C -MF 2	Medium	Low	Low	High	High	High
C -MF 3	Medium	Low	Low	High	High	High
C -PKS 1	Medium	Low	Low	High	High	High
C -PKS 2	Medium	Low	Low	High	High	High
C -PKS 3	Medium	Low	Low	High	High	High

CONCLUSION

The coal used in this research has low moisture content of 7.49% and high calorific value of 6,109 cal/g, while the moisture content of the biomass of EFB, MS and PKS were 10.86, 11.19 and 11.77 % with the calorific value of 4,098; 4,187 and 4,447 cal/g respectively. Based on the AFT, the coal-biomass blends show a medium tendency to ash deposition for some composition. While based on the chemical composition, the coal-biomass blends generally have a low tendency to slagging but have a high tendency to fouling. The coal-biomass blend with the coal composition of 95 wt% and PKS of 5 wt% (95:5) has the lowest inherent moisture and the highest calorific value compared to other compositions. However, to reduce the use of coal, a blend of 85 wt% coal and PKS of 15 wt% (95:15) recommended, because it is significantly different from the 95:5 composition in terms of inherent moisture and calorific values. The less the coal is used, the less the CO_2 emission, so it is expected to reduce the GHG significantly.

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