Investigation of Slagging Fouling Aspect of Palm Fiber and Palm Leaves Waste in Drop Tube Furnace

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Abstract. Biomass co-firing is one of alternative way for Coal-Fired Power Plant (CFPP) to achieve green energy. Indonesia as the world's largest producer of palm oil, has the chance to convert palm oil waste into a relatively sustainable biomass for use as co-firing fuel in CFPP. Biomass combustion, on the other hand, can easily lead to ash deposition and corrosion in boilers. It is necessary to predict the slagging and fouling tendency of biomass combustion. This study aims to determine the combustion characteristics of 100% biomass in the form of palm fiber and palm leaves which is still limited study discussed about the comparation of palm fiber and palm leaves. Ash analysis, ash fusion temperature, drop tube furnace test and ash deposition were carried out on 100% palm oil biomass to determine co-firing composition between palm oil waste and coal which is suitable and safe for power plants. The experimental results show that during combustion affects the ash due to various physical and chemical properties. K_2O value of palm fiber is higher than palm leaves, this also makes the AFT value of palm fiber also lower when compared to palm leaves. Both palm fiber and palm leaves samples have a medium risk of slagging and corrosion but relatively low risk in fouling. Probe observation also showed that the probe surface was corroded when combusting single fuel biomass with a drop tube furnace, and the ash deposits on the probe temperature 600 °C have a higher amount than the probe temperature 550 °C.

Keywords: Slagging · Fouling · Palm · Waste

1 Introduction

Global climate change is caused by massive environmental pollution in the world. CO_2 emissions from the combustion of fossil fuels by industry and power plants are major contributors to global warming around the world [1, 2]. Only in terms of electricity generation, developing countries such as Indonesia continue to rely on coal-fired power plants (CFPP) as their primary source of electricity. There are as many as 126 unit of CFPP are still actively used in various regions in Indonesia [3]. Coal combustion

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emits CO_2, which increases the global greenhouse gas effect and raises the Earth's temperature [4]. The world is currently looking for green energy that is environmentally friendly and does not cause significant climate change. Solar cells, wind turbines, and co- firing of coal and biomass are considered as green and renewable energy [5]. Biomass combustion is thought to reduce CO_2 emissions because its ability to absorb CO_2 during the photosynthesis process while being combusted [6–8]. Utilization of biomass as green energy to support government programs through the ministry of energy and mineral resources to achieve net zero emissions by 2060 seems feasible, both as co-firing fuel and single firing in power plants, especially with the legalization of co-firing obligations.

Indonesia has a diverse biomass resource that has the potential to be used as an alternative fuel for power generation, including agricultural and forest waste [9]. Many agricultural plants, such as palm oil, rice husk, sorghum, and rice husks, can be used as alternative fuels. As the most dominating palm oil producer in the world [10], Indonesia's palm oil industry generates far more biomass from plantation and milling activity than any other type of biomass. Palm fiber, leaves, trunks, fronds, wet, shell, and kernel are all examples of palm oil waste that can be used as biomass. Each biomass has different combustion characteristics [11]. However, palm oil waste generally have the characteristics of high value of moisture, so it is quite difficult to control the combustion process. Currently, palm oil biomass can be converted into organic fertilizer or used as the primary fuel in boilers to generate electricity and steam for the palm oil manufacturing process. [12].

Several studies discussed that biomass combustion can potentially cause slagging fouling, corrosion and excessive ash deposition due to its high alkaline and chlorine content [13, 14]. Alkali metals and the presence of KCl in biomass raw materials may react with other materials to generate thermal decomposition compounds with low melting points, way that results in coalescence and sticky ash deposition. [15, 16]. Slagging and fouling may reduce the transmission of heat ability in the boiler, resulting in a decrease in boiler efficiency [17].

In addition, alkaline ash can attack and damage the boiler's refractory layer. This may shorten the boiler service lifetime and require costly repairs [16]. This study will discuss the potential slagging and fouling of palm oil biomass. Even though there are so many studies on palm waste which used as material for co-firing [1, 11, 12], studies on palm fiber and palm leaves are still limited. This study is necessary as a guide for stakeholders to co-firing coal with palm waste, especially palm fiber and palm leaves in CFPP. Lab-scale combustion such as drop tube furnace (DTF) will be carried out to prevent unnecessary damage to the real steam power plant in the field. Previous research [18–20] has made extensive use of DTF to simulate combustion in PC boilers in order to get an accurate representation of the slagging fouling phenomenon that occurs in CFPP. Temperature probes of 550 °C and 600 °C were also tested to represent the super heater and economizer areas on the wall-tube in the boiler.

2 Experimental

2.1 Materials and Methods

The sample for this investigation consists of by products derived from palm oil trees located in two distinct regions, namely palm fiber from the island of Java and palm leaves from the East Kalimantan. The sample that is going to be burned on DTF needs to go through a preparations process such as drying and grinding with a sieve that is at least 60 mesh (250 microns). This is due to the fact that DTF boilers, which are similar to PC boilers, require the coal to be formed into the form of fine dust and must adhere to certain size requirements [21]. Palm fiber and palm leaves that have been prepared according to ASTM D2013 for coal standards are shown in Fig. 2a and 2b respectively. After the sample was prepared; proximate analysis, ultimate analysis, ash analysis and ash fusion temperature were performed for initial characterization of the physical and chemical properties of the samples. Furthermore, initial predictions are made using theoretical calculations that have been used in several studies [13, 22, 23]. To ensure the results of the initial prediction, full combustion was carried out on the DTF to find out the combustion characteristics of the sample. All a series of processes carried out in this study are contained in Fig. 1.

2.2 Equipment

The drop tube furnace consists of an alumina ceramic tube that is 1500 mm in length and has an outer diameter of 76.2 mm [24]. This tube is heated by an electrical heater that utilizes a convection-based heating system and has a temperature range of 1200 to 1250 °C. The solid fuel sample is dropped with a flow rate of 50 kg/h and driven by primary air into a combustion chamber with a temperature of 100–150 degrees Celsius.

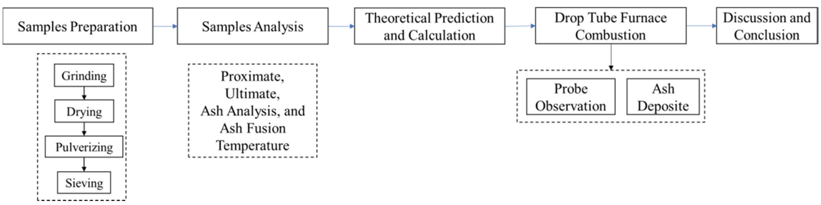

Fig. 1. Experimental Methods

Fig. 2. Powdered Sample of (a) Palm Fiber, (b) Palm Leaves

Secondary air is also added into the combustion chamber as additional air is needed to achieve 3–5% excess oxygen. The samples which are burned in the ceramic tube leaving ash which is then accommodated on a stainless probe in the form of a plate with a diameter of 50 mm at the bottom end of the drop tube furnace. The probe is height-adjusted to reach temperatures of 550 and 600 °C to represent the superheater and economizer areas. After burning for approximately 1 h, the ash on the surface of the probe is brushed for further observations on the surface layer of the probe. After that, the ash that has been brushed is then collected and weighed to get ash deposit weight from DTF combustion.

3 Results and Discussion

3.1 Sample Analysis

The study results of the proximal and ultimate analyses on the characteristics of palm fiber and palm leaves are shown in Table 1. It was discovered that palm fiber has a higher value of 4313 kcal/kg while palm leaves are 3636 kcal/kg. The ash content of palm leaves comes in at a higher 12.89% weight than the ash content of palm fiber, which comes in at 4.75% weight.

The value of chlorine shown in Table 1, that has an impact on corrosion in the boiler, for the two samples used in this study has a relatively high value in comparison to wood-based forestry biomass especially sawdust [25], palm fiber with a chlorine content of 1647 ppm while palm leaves have a chlorine content of 2345 ppm. Chlorides are discharged into the flue gas and have the potential to condense on the surface of the boiler tube or an ash particle while they are moving through the horizontal flue [26].

The occurrence of slagging can be hastened by the presence of a number of chemical components in the ash, including SiO_2, K_2O, CaO, SO_3, and Fe_2O_3. This can cause the ash melting point of palm fiber to be lower [16] than that of palm leaves, which is supported by the AFT value shown in Fig. 3, the value of deformation temperature (DT) in palm fiber is 1140 °C and palm leaves are 1305 °C. The palm fiber has a higher SiO_2 value, which is shown in Table 2 as 60.05%, than palm leaves, which have a value

Table 1. Sample and Ash Characteristics

Sample	Proximate (%weight)				Ultimate (%weight)					Qgr_{ar} (kcal/kg)	$Chlorine_{db}$ (ppm)
	Mt_{db}	As_{db}	Vol_{db}	FC_{db}	C_{db}	H_{db}	N_{db}	O_{db}	S_{db}		
Palm Fiber	6.77	4.75	70.81	17.67	47.94	5.50	0.67	34.24	0.13	4313	1647
Palm Leaves	9.73	12.89	60.90	16.48	41.55	4.91	2.08	28.66	0.18	3636	2345
db: dry-basis Mt: Moisture As: Ash Content	*Vol: Volatile Matter FC: Fixed Carbon*				*C: Carbon H: Hydrogen N: Nitrogen*		*O: Oxygen S: Sulphur*				

Table 2. Ash Analysis of Palm Fiber and Palm Leaves

Samples	Ash Analysis (% weight ash)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	TiO_2	Na_2O	K_2O	Mn_3O_4	P_2O_5	SO_3
Palm Fiber	60.05	10	2.56	9.13	5.91	0.18	0.18	10.02	0.18	0.18	0.12
Palm Leaves	51.93	12.9	11.05	10.22	2.79	0.14	2.83	2.95	0.83	1.78	2.27

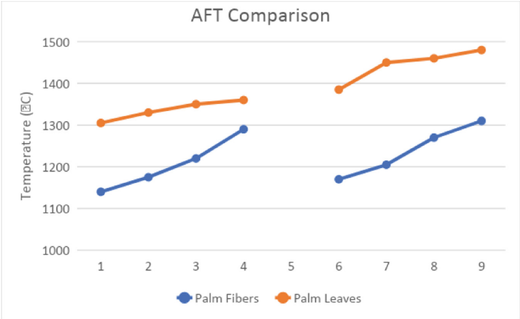

Fig. 3. Palm Fiber and Palm Leaves comparison in Ash Fusion Temperature. *IDT: Initial Deformation Temperature; ST: Softening Temperature; HT: Hemispherical Temperature; FT: Fluid Temperature*

of 51.93%. In addition, the high value of potassium (K_2O), which has a percentage of 10.02%, lends support to palm fiber's low AFT value. This value can be found in palm fiber. The CaO values in both samples are comparable; however, the Fe_2O_3 content of palm leaves with 11.05% higher than that of palm fiber which only contains 2.56%. According to the findings of a study carried out by Shi et al. [27], the effect of the ratio for CaO/Fe_2O_3 can have an impact on the amount of ash deposit that is produced during combustion in the boiler.

One of the ash observation methods widely used to forecast slagging danger is determining AFT. A muffle furnace is used to heat the sample according to ASTM D 3174-2017 for sample preparation. According to the ASTM D1857-2017 standard, the ash is formed into a cone shape using a cone mold with dimensions of 3/4" in height and 1/4" in width. The sample is then placed in an electric furnace and heated at a temperature below 400 °C at a rate of 83 °C/min. For reducing testing, regulated gas consists of 60% CO and 40% CO_2 delivered at a flow rate of 1.3–1.5 furnace liters per minute, whereas regulated air is used for oxidizing tests. As shown in Fig. 3, the ash from biomass was created in a cone and gently heated in a furnace at a high temperature [28], after which the cone shape was checked and the melting temperature was recorded. Figure 3 shows that the AFT value of palm fiber is lower than that of palm leaves. Palm fiber has the lowest DT value of 1140 °C indicates higher slagging risk [23] while compared with palm leaves which only have the DT value of 1300 °C. As demonstrated in Fig. 3, biomass

Table 3. Index Calculation Prediction Palm Fiber and Palm Leaves Sample

Slagging Fouling Parameter	Palm Fibers	Palm Leaves
B/A Ratio	*0.5*	*1*
Silica Ratio	*0*	*0.5*
Fusibility	*1*	*0.5*
Rz	*1*	*1*
Sulfur slagging index	*0*	*0*
Fe	*0*	*0.5*
Fouling Index	*0*	*1*
Na2O in ash	*0*	*0.5*
Total Alkali	*1*	*0*
Abrasion	*0*	*0.5*
Corrosion	*0.5*	*0.5*
0: Low 0.5: Medium 1: High		

ash melts at ST, while palm fiber ash melts at 1175 °C and palm leaves melt at 1330 °C. This ash melt which can result in acceleration of slagging in the superheater area while the operating temperature of the PC Boiler is in the temperature range of 1175–1200. Overall, the DT to FT levels in palm fiber and palm leaves increased. When compared to palm leaves, however, an extremely rise is plainly seen on palm fiber biomass.

3.2 Prediction of Slagging, Fouling, Abrasion, and Corrosion

Other researchers have looked into slagging indices in the past in order to find the correlations that will allow them to accurately predict the collision behavior of the ash [23, 29]. In order to accurately simulate the growth of slag, it is necessary to have a user-defined function. The parameters that were used are parameters that are typically utilized when making predictions regarding coal. Slagging ratio obtained by B/A ratio, silica ratio, fusibility, composite index, sulfur, and Fe. While Fouling using fouling index, Na_2O in ash, and total alkali. Abrasion and corrosion index from Rask [30, 31].

The slagging aspect of palm fibers and palm leaves has relatively medium slagging criteria, as shown in Table 2. Palm fibers present a high risk in terms of the fusibility parameter, whereas palm leaves present a medium risk in this regard. The good news is that palm fiber and palm leaves have low risk criteria in terms of sulfur for the slagging index. When compared to palm leaves, palm fibers have relatively low criteria in terms of both fouling and abrasion. Palm leaves have higher criteria. Palm fibers and palm leaves, on the other hand, have low to medium risk criteria when it comes to corrosion and abrasion.

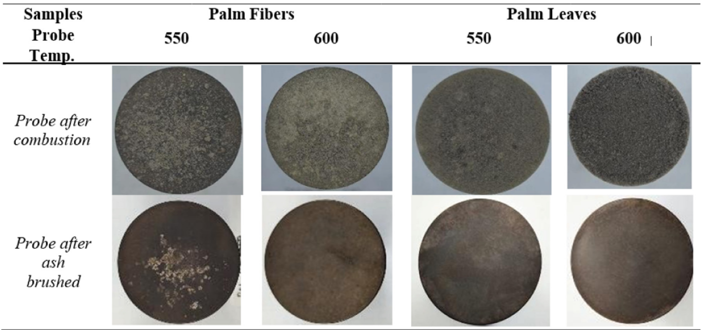

Fig. 4. Probe Observation

Table 4. Ash Deposition

Samples	Weight (in gram)	
	Palm Fiber	**Palm Leaves**
Probe Temperature 550	0.0239	0.0386
Probe Temperature 600	0.0464	0.2965

3.3 Drop Tube Furnace

By the drop tube furnace test carried out for a residence time of 1 h, the temperature probes modeled as economizer (550 °C) and superheater (600 °C) areas on the PC boiler were cooled and photographed as shown in Fig. 4 in the first row for each sample. In the second row of Fig. 4 shows that the ash deposits on the probe surface have been brushed and observed qualitatively [32, 33]. The totally sintered ash category 3 that was proposed by Ohman et al. [32] can be found in the palm fiber sample that was used for the temperature probe 550. The adhering ash deposits actually coalesce into a sticky slag material and is difficult to separate with one's bare hand. As for the other samples, palm fiber probe temperature 600 and palm leaves probe at both temperatures produced non-sintered ash category 1, there was partly sintered ash, but this ash can still be removed with one bare's hand.

The high value of Si and low value of Al causes relatively few ash deposits from combustion [34]. Palm fiber itself produces less ash than palm leaves. However, ash is produced by palm fiber itself at a lower rate than by palm leaves. The high value of Fe_2O_3 that is shown in Table 2 is the cause of the large amount of ash deposits that are found on the palm leaves [27]. As can be seen in Table 3, palm fiber has a lower ash deposit of 0.0239 g at the probe temperature of 550 degrees, in comparison to palm leaves, which have a deposit of 0.0386 g. However, the significant addition of ash deposits was discovered at the probe temperature of 600. Palm fiber had an ash deposit of 0.0464 g, while palm leaves had quite a lot of ash deposit with 0.2965 g (Table 4).

4 Conclusions

Selected biomass from palm oil waste is chosen in this study to determine the behavior of the ash and predicts operational issues during biomass combustion. Palm fiber has a higher calorific value than palm leaves. However, palm leaves have higher moisture, ash content and chlorine values than palm fiber. The AFT value of palm fiber is lower than palm leaves, this makes the fusibility parameter in palm fiber has a higher risk than palm leaves. It is influenced by the amount of SiO_2, K_2O, CaO, and Fe_2O_3 content in the ash analysis which is shown in Table 2. Based on the slagging and fouling parameter calculation, both palm fiber and palm leaves have a medium risk of slagging and corrosion but have a relatively low risk of fouling and abrasion. Observing the sample probe, it was found ash deposit sticking on the surface of probe temperature 550 °C in palm fiber samples and is quite difficult to separate with one's bare hand. While, the palm leaves probe sample was no sintering ash attached. However, all probes from drop tube furnace single fuel combustion, both palm fiber and palm leaves, appear to be corrosive considering the relatively large chlorine values of these two samples. Further studies need to be carried out by combining these two materials with selected coal to determine the blending composition of coal, palm leaves and palm fibers and to conduct a feasibility study on burning biomass as a single fuel.

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