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Additional additives to reduce ash related operation problems of solid biofuel from oil palm biomass upon combustion

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ABSTRACT

Ash related operational problem is one of the most prominent issues in using lignocellulosic biomass as solid biofuel. This study evaluates the effect of kaolin and calcite addition as fuel additives on the ash melting characteristic and heating value of the oil palm biomass (empty fruit bunch and oil palm trunk). Both additives significantly improved the ash melting characteristic of the oil palm biomass. While the concentrations of additives act as a variable to increase the sintering temperature, it also had strong impacts on higher heating value reduction and ash content increment. Kaolin reduced the sintering degree of the ashes with the formation of inorganic elements mixtures mostly detained in the ash sediments. In compare, the presence of calcite helped to increase the ash melting temperature but at the same time induce higher concentration of fly ash in the flue gas. Overall, kaolin is more efficient than calcite to decrease the sintering degree of the ashes from molten to loose with the measure of 0.5 g/g ash while calcite require higher dose (at the dose higher than 0.7 g/g ash) when combusted at 1000 °C.

1. Introduction

The growing interest in lignocellulosic biomass energy in Malaysia creates an entry point for oil palm biomass in energy sector. Oil palm biomass that is steadily generated in huge amount annually may serve as a potential source of biomass solid biofuel for heat and electricity production. The availability of these materials is directly intertwined with activity of the major economic sectors of Malaysia. For the last 40 years, Malaysia has been one of the largest palm oil producers and exporters. As of only 1.5 million hectares in 1985, Malaysia had 5.6 million hectares of oil palm plantations in 2015 (MPOB, 2015). Empty fruit bunches (EFB) and oil palm trunks (OPT) are the two major by-products generated from the palm oil industry. During a replanting programme, 74 tonnes per hectare of dry OPT are available. While in the palm oil mill, the processing of fresh fruit bunch (FFB) generated around 23% of EFB.

Of late, lignocellulosic biomass is utilized as a feedstock in producing renewable energy and bio-based products (Loow et al., 2017; Solarte-Toro et al., 2018). In Malaysia, palm oil industry generates a sustainable huge amount of oil palm biomass which make it an ideal source of lignocellulosic materials for biofuel production. Nonetheless,

the major culprit for the poor handling of oil palm biomass in energy sector may be related to the inferior properties of the material itself. Ash related operational problem is one of the most prominent issues in using lignocellulosic biomass as solid biofuel. It was reported by Chin et al. (2015) that EFB and OPT without proper treatment will create operational problems related to ash effects during combustion. The main cause of these problems is these fuels are rich in alkaline metal (e.g. potassium, sodium, phosphorus and chlorine) which form complex eutectic salts and consequently lower the melting temperature of the ashes during combustion (Bernhardt et al., 2011; Liu and Bi, 2011). These elements have been the major reason on the combustion behavior of lignocellulosic biomass, although it only appear in a minor proportion by weight. Alkali metal such as potassium is essential in every living organism for growth regulation and other various processes, and is taken up by plants in the form of dissolved salts from soil water. Usually, potassium forms as chloride (KCl), sulfates (K_2SO_4), or carbonate (K_2CO_3). All these compounds have low melting points, and some of them melt at common combustion temperatures (700–1000 °C) and form ash deposition in the boiler during combustion (Tobiasen et al., 2007; Ohman et al., 2000).

There are two major categories in ash deposition mechanism in the

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actual combustion which often occur and interact at the same time (Huang et al., 2013). The first is initiated by the ash fragments in the molten or semi-molten state in high temperature combustion region, which flow with the flue gas into the heated surface and bound together, then develop continuously in the heating surface. The second is generated by the volatile alkali material in biomass that gets into the gas phase at high temperature and condense when flowing through the relatively low temperature heating surface. The direct risk is the dramatic decrease of energy conversion efficiency due to the slagging formation on heat exchange components surfaces. On a more serious note is that the fireside corrosion induced by the gaseous alkali deposits accelerated metal wastage of boiler components. Ash related problems in the lignocellulosic biomass hinder the combustion processes and greatly hinder the further application of lignocellulosic biomass as solid biofuels for heat and electricity production. Obviously, seeking an appropriate method to reduce or prevent the heating surface deposition is important to ensure high combustion efficiency and extensive utilization of various types of lignocellulosic biomass as solid biofuel.

One of the ways to prevent problems caused by alkaline metal compounds in biomass fuels is to alter the ash composition by adding a fuel additive (Llorente et al., 2008). Several studies have shown that the use of aluminium based and calcium based fuel additive in combustion of ash rich lignocellulosic biomass can reduce the sintering tendency of ash (Steenari et al., 2009; Bafver et al., 2009; Boman et al., 2008). For instance, the melting point of reacted kaolin and calcite has been reported to have reached 1500 °C and 1100 °C, respectively (Lindström et al., 2007). This combination gives an increase in the melting point of the resulting ash. A few hundred degrees of increment has been reported for straw ash with additional kaolin and calcite (Llorente et al., 2008; Steenari and Lindqvist, 1998). However, no studies have previously been published qualitatively and quantitatively on the effects of kaolin or calcite addition to the problematic ash of oil palm biomass. For further application and selection of the proper fuel additives for a particular process of lignocellulosic biomass combustion, it is essential to gain a better understanding about the effect of additives on the fuel characteristic. The present work aims at studying the effect of additional kaolin and calcite to EFB and OPT on the ash melting characteristic and higher heating value.

2. Materials and methods

2.1. Sample preparation

The oil palm biomass used in this study includes empty fruit bunch (EFB) and oil palm trunk (OPT). The EFB and OPT fines, respectively were ground to fine particle size (0.42 mm). Two types of additives were used in this study; calcite and kaolin. Calcite was of a laboratory grade in a powder form. The kaolin was of commercial grade and supplied in powder form. The major elements of the kaolin and calcite are given in Table 1. The main mineral phases with the corresponding levels are also included in the table. In this study, the selected percentage of additives used was based on the ash content of the raw material. The additives were mixed with each oil palm biomass at different ratios. OPT were supplemented with six different additives concentrations (0.1%, 0.3%, 0.5%, 1.0%, 1.5% and 2.0%). Higher dose was applied to EFB due to the higher percentage of ash content in EFB. EFB was supplemented with six different additives concentrations (0.5%, 1.0%, 1.5%, 2.0%, 2.5% and 3.0%). The additives added to the lignocellulosic biomass were at the dose range between 0.1–1.5 g/g ash. The ash-forming elements of oil palm biomass is depicted in Table 2. The additives were mixed well with the lignocellulosic biomass samples, prior to each tests. Samples with different percentage of additives were evaluated for ash melting characteristic and weight loss under four different combustion temperature (700 °C, 800 °C, 900 °C and 1000 °C).

Table 1

Chemical composition and main mineral phases of kaolin and calcite used (% w/w).

	Kaolin	Calcite
SiO_2	46.3	0.1
Al_2O_3	35.2	–
CaO	< 0.1	98.7
K_2O	0.7	–
MgO	0.1	0.1
Fe_2O_3	0.7	< 0.01
Na_2O	0.2	–
SO_3	< 0.1	–
P_2O_5	< 0.01	< 0.01
Cl	< 0.1	< 0.05
Content of the main mineral phases		
$Al_2Si_2O_5(OH)_4$	91.6	–
SiO_2	4.2	–
$CaCO_3$	–	> 98

Table 2

Ash-forming elements of oil palm biomass (Chin et al., 2015; Chin et al., 2013).

Test Parameter	Unit	EFB	OPT
Ash Content	%	5.96	1.33
Al	mg/kg	6.00	4.04
Si	mg/kg	153.05	25.32
Ca	mg/kg	798.89	903.00
Fe	mg/kg	251.02	32.32
K	mg/kg	12194.05	1998.67
Mg	mg/kg	1069.87	734.98
Na	mg/kg	117.55	239.61
P	mg/kg	408.51	209.66

2.2. Evaluation

2.2.1. Ash sintering/melting behavior at various heating temperature

The method used to determine the ash sintering/melting characteristic was adapted from Chin et al. (2015) and Tonn et al. (2012). Low-temperature ash of oil palm biomass with additional additives were prepared by heating the crucible that contained 10 g of the oil palm biomass samples with and without additives at 550 °C and kept at this temperature for 6 h.

0.2 g of the oil palm biomass ash with additive samples (low-temperature ash) were placed in crucibles and heated in a furnace with the respective heating temperature; 700 °C, 800 °C, 900 °C and 1000 °C for two hours. Both microscopic and macroscopic findings were considered in the classification. The microscopic findings were evaluated under magnification level up to 40× based on the sample appearance with a stereo microscope. As shown in Table 3 which adapted from (Chin et al., 2015; Tonn et al., 2012), the ash samples were categorized using the classification scheme with four ash sintering classes. Ash classification under 'loose' or 'slightly sintered' are to be expected to cause no or less problems, while ash that fall under 'molten' and 'strongly sintered' are expected to cause operation problems during combustion (Chin et al., 2015; Tonn et al., 2012).

The ash residues were also analyzed by a combination of Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDX) and also powder X-ray diffraction. Further information on the microstructure and microchemistry were obtained using EDX semi quantitative spot analyzes on respective samples.

2.2.2. Weight loss of ash at different combustion temperature

The weight loss of the low temperature ash of oil palm biomass with additional additives after combusted at 700 °C, 800 °C, 900 °C or 1000 °C were calculated using the following expression.

$$W_L = [(M_I - M_D) / M_I] * 100$$