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Product characteristics from the torrefaction of oil palm fiber pellets in inert and oxidative atmospheres

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HIGHLIGHTS

- Torrefaction of oil palm fiber pellets (OPFP) in inert and oxidative environments is studied.
- The enhancement factor of HHV in this study is between 1.07 and 1.24.
- OPFP torrefied at 300 °C is recommended to upgrade the biomass.
- The calorific value of condensed liquid is improved by 92–139% from dewatering.
- The recovery of condensed liquid can enhance the energy efficiency of a torrefaction system.

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ABSTRACT

The aim of this work was to study the characteristics of solid and liquid products from the torrefaction of oil palm fiber pellets (OPFP) in inert and oxidative environments. The torrefaction temperature and O_2 concentration in the carrier gas were in the ranges of 275–350 °C and 0–10 vol%, respectively, while the torrefaction duration was 30 min. The oxidative torrefaction of OPFP at 275 °C drastically intensified the HHV of the biomass when compared to the non-oxidative torrefaction. OPFP torrefied at 300 °C is recommended to upgrade the biomass, irrespective of the atmosphere. The HHV of condensed liquid was between 10.1 and 13.2 MJ kg^{-1}, and was promoted to 23.2–28.7 MJ kg^{-1} following dewatering. This accounts for 92–139% improvement in the calorific value of the liquid. This reveals that the recovery of condensed liquid with dewatering is able to enhance the energy efficiency of a torrefaction system.

1. Introduction

Solid biomass has been an important fuel for heat and power generation through burning alone or co-firing with coal (Sami et al., 2001; Saidur et al., 2011). However, its energy density or calorific value is substantially lower than that of coal; this limits its applications in industry. In addition to the energy density, other drawbacks accompanied by using biomass as a fuel include the hygroscopic nature, high oxygen and moisture contents, low density, poor grindability, and lignocellulosic heterogeneity of biomass (Chen et al., 2012a; Tran et al., 2013; Lu et al., 2013; Basu et al., 2014). In recent years, torrefaction and pelletization (also called densification) have received a great of deal of attention because these pretreatment processes are able to overcome the aforementioned drawbacks effectively (Chen and Kuo, 2010; Chen et al., 2015b).

Torrefaction is a thermal conversion process in nature. While biomass undergoes torrefaction at temperatures of 200–300 °C, the reactions of dehydration, deoxygenation, and dehydrogenation occur in the material (Chen et al., 2012b). These mechanisms transform raw biomass into hydrophobic and low-oxygen materials with higher calorific values. A large amount of hemicellulose and certain amount of cellulose in biomass are thermally degradated from torrefaction. This disruption in the lignocellulosic structure of biomass leads to its grindability and uniformity improved (Rousset et al., 2011). Pelletization inherently is a physical conversion process. In this pretreatment method, a mechanical force is employed to compact biomass residues or wastes, and uniformly sized solid pellets are produced (Chen et al., 2015b). The pelletized biomass is characterized by lower moisture content, higher bulk density, and higher volumetric energy density (Li et al., 2012). This is conducive to biomass handling, storage, and transportation (Tumuluru et al., 2011).

On account of a number of benefits gained from biomass torrefaction and pelletization, a few studies concerning the

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combination of the two pretreatment methods have been carried out. Stelte et al. (2011) focused on the pelletizing properties of spruce which was torrefied at 250, 275, and 300 °C. The value of torrefied biomass could be further improved by mechanical compression into pellets with high physical and energetic density. However, a pronounced decrease in pellet compression strength was exhibited, resulting from the spring-back effect and poor adhesion between particles. In particular, no pellets could be made from spruce torrefied at 300 °C. Li et al. (2012) torrefied sawdust in a fluidized bed reactor at temperatures of 260–300 °C for 10–90 min, followed by pelletization. Seeing that the chemically bonded water and low-melting point compounds in biomass were lost from torrefaction, energy consumptions for compacting torrefied sawdust into pellets were significantly higher than untreated sawdust at the same compression temperature, and the hardness of pellets decreased with increasing torrefaction severity. Wang et al. (2013) performed the oxidative torrefaction of sawdust to evaluate the feasibility of using combustion flue gases as the carrier gas for biomass torrefaction in association with pelletization. They found that the oxidative torrefaction of sawdust at O_2 less than 6% did not change the properties of the torrefied biomass compared to the torrefaction in N_2, leading to similar energy consumption associated with pelletization. However, more energy was consumed to make pellets from torrefied sawdust than the raw sawdust at the same die temperature and compression force.

By using a severity factor which integrated the effects of reaction time and temperature into a single variable, Na et al. (2013) torrefied oil palm mesocarp fiber and investigated the influence of the severity factor on pellet formation. They concluded that at a high severity factor, no pellets could be made from torrefied biomass, or many defects were shown in the torrefied pellet, while the pellets were produced with good formation at a low severity factor. Shang et al. (2012) pointed out that the durability of Scots pine pellet had a negative relationship with torrefaction temperature, and compression strength of a single pellet could be used as a product quality control method to predict the durability of the whole batch pellets and the energy use in grinding. Peng et al. (2013) addressed that the density and the hardness of torrefied pellets depended mainly on the densification die temperature and the weight loss of torrefied samples, and preconditioning the torrefied samples to a moisture content of around 10% could improve the quality of torrefied pellets.

The aforementioned studies were all focused on biomass torrefaction and subsequent pelletization, indicating that torrefaction disadvantaged pelletization to a certain extent. In other words, it was difficult to bind torrefied biomass particles and a binding agent might be needed to carry out effective pelletization with reasonable energy consumption. To avoid this drawback, torrefaction following pelletization may be another potential route to upgrade biomass as a solid fuel. Ren et al. (2012) torrefied sawdust pellets under microwave assisted-heating, and reported that the HHV of the biomass was intensified to 6–31% while the energy yield was between 67% and 90%. Ghiasi et al. (2014) assessed two process pathways for energy and mass balance in making torrefied pellets from softwood chips, and qualities of the resulting torrefied pellets were compared. Their results showed that wood chips dried, ground, densified, and finally torrefied was more efficient in terms of overall energy and material balance when compared to the biomass undergoing torrefaction and grinding followed by densification. The review of relevant literature suggests that very little attention has been paid to the torrefaction of biomass pellets. For this reason, the present study is intended to investigate the product characteristics from the torrefaction of oil palm fiber pellets in different environments. The obtained results are able to provide a useful insight into the upgrade of biomass through the combination of pelletization and torrefaction.

2. Experiment

2.1. Raw material and pellet

Oil palm fiber (OPF) is an abundant agricultural waste (Sumathi et al., 2008; Uemura et al., 2011), especially in Malaysia. To achieve energy recovery from agricultural wastes, OPF, which came from oil palm empty fruit bunches, obtained from Malaysia was used as the raw material in this study. The biomass was trimmed by a shredder, followed by sieved by a screen. The fiber lengths less than 30 mm were collected, and the moisture content in the needle-shaped OPF was adjusted to 20 wt.%. Thereafter, oil palm fiber pellets (OPFP) were made by a commercial pellet machine. The average length and diameter of the pellets were approximately 30 mm and 8 mm, respectively. To avoid the biodegradation of the pellets during storage, they were dried in an oven at 105 °C for 24 h to remove free water in the samples. Afterward, the pellets were stored in a desiccator at room temperature until torrefaction experiments were carried out.

2.2. Experimental setup

The experimental system consisted of four units to perform OPFP torrefaction, collect solid and liquid products, and clean flue gas. The four units were made up of a gas supply unit, a torrefaction unit, a volatile condensation and treatment unit, and a solid cooling unit. The gas supply unit comprised nitrogen, air, a gas mixer, and two mass flow controllers (Alicat Scientific). The torrefaction unit was an electrical furnace, in which a cylindrical chamber (i.d. $\times$ height = 125 $\times$ 440 mm) for holding samples was installed. The chamber was heated in the furnace so as to carry out torrefaction experiments. The torrefaction temperature was controlled by a proportional integral derivative (PID) temperature controller, and the power of the furnace was automatically adjusted by a solid state relay (SSR) power controller. The volatile condensation and treatment unit had three Dimroth condensers and a conical flask in series. The solid cooling unit contained a vessel which was enveloped by a water jacket.

2.3. Experimental procedure and operating conditions

Prior to experiments, pellets were placed in a moisture analyzer (Ohaus MB45) and dried at 105 °C. The moisture in the pellets was measured by the analyzer to ensure that no free water was retained in the pellets. In each experiment, the weight of OPFP was controlled at 20 g (±5%). The sample in the chamber was heated at a heating rate of 22 °C min^{-1} until reaching the torrefaction temperature. Thereafter, OPFP was torrefied in an inert or oxidative environment. In the inert environment, nitrogen was used as a sweep gas, whereas the gas mixture of air and nitrogen was used to sweep the sample in an oxidative environment. The oxygen concentration in the gas mixture was 5 vol% or 10 vol% where the mixture was produced in the gas mixer by controlling the flow rates of air and nitrogen. The flow rate of the carrier gas was fixed at 1000 mL min^{-1} (25 °C) in the course of torrefaction. The torrefaction temperature is normally controlled at 200–300 °C where the operations of light (200–235 °C), mild (235–275), and severe torrefaction (275–300 °C) are included (Chen et al., 2015b). In the present study, only severe torrefaction at 275 and 300 °C was considered. To extend the reaction temperature, the reaction temperatures of 325 and 350 °C were also taken into account. The torrefaction duration was fixed at 30 min. The gas stream produced from torrefaction was cooled using the three Dimroth condensers to correct the condensed liquid. The cooling water at a flow rate of 3000 mL min^{-1} (10 °C) flew through the condensers. The

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