Improvement of energy density and energy yield of oil palm biomass by torrefaction in combustion gas

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Abstract. This study investigates torrefaction of oil palm empty fruit bunch (EFB) and palm kernel shell (PKS) in a fixed-bed reactor in biomass combustion gas, which consisted of 8-9 vol% O₂ and 13-14 vol% CO₂. Torrefaction experiments were carried out at 473-573K for 30 min. The mass and energy yields, and properties of torrefied biomass were investigated. Torrefaction in the presence of combustion gas resulted in a decrease in mass yield and an increase in the energy density and carbon content. For both the biomass, the highest energy yield and density was obtained by torrefaction at 473 K and 573 K in combustion gas, respectively. This study has proved that use of combustion gas has advantages in terms of product yield as well as energy saving. Production capacity of torrefied biomass at oil mill was also estimated.

1. Introduction
Torrefaction is a promising technique to improve some inferior properties of biomass residue, such as lower energy density, shorter shelf life and poor grindability. Many fundamental studies, in which torrefaction was carried out in inert gas such as nitrogen, have been done [1-3], and have proved that torrefaction can improve the inferior properties listed above.

Even though torrefaction can improve the inferior properties, biomass solid fuel, the products from the process, is rather cheap in selling price. Therefore, intensive efforts are required to minimize the investment and utility costs. The authors have proposed a process shown at the bottom of figure 1 for this purpose [4]. The background of this issue was detailed elsewhere [4]. The top illustration represents the representative current process, which was drawn based on the process proposed elsewhere [5]. In the proposed process at the bottom of figure 1, boiler flue gas is utilized directly as torrefaction gas and energy source. By comparing with the representative existing process [5], one can see the advantages of the proposed process which include less complicated pipings and free from additional equipment and auxiliary energy source for providing thermal energy for torrefaction.

In this study, a comprehensive investigation for torrefaction of empty fruit bunch (EFB) and palm kernel shell (PKS) has been conducted to validate torrefaction in combustion gas. The mass yield, energy density, and energy yield were determined for torrefaction in combustion gas at 473, 523 and 573 K. Torrefaction in nitrogen gas was also done for comparison at all the temperatures. In our previous report
[4], only one type of biomass was used, and torrefaction in nitrogen was carried out at only one temperature.

Current

Proposed

Figure 1. Comparison of the torrefaction process proposed in this study with existing one.

2. Experimental

2.1. Material
EFB and PKS collected from a nearby palm oil mill were dried in an oven at 378 K for 24 h. EFB were chopped into smaller chips with dimensions of 2.0 cm x 0.5 cm x 1.0 cm. PKS was used without further size adjustment. The elementary and chemical analyses result of EFB and PKS used in this study are listed in Table 1.

Table 1. Properties of biomass used in this study.

| Biomass | EFB | PKS |
|---------|-----|-----|
| HHV [MJ/kg] | 15.2 | 19.6 |
| Ultimate analysis [wt%] | | |
| Carbon | 40.6 | 50.4 |
| Hydrogen | 5.1 | 6.5 |
| Nitrogen | 1.2 | 0.7 |
| Oxygen | 38.1 | 36 |
| Moisture content | 7.4 | 3.8 |
| Ash content | 7.6 | 2.7 |
| Chemical composition [wt%] | | |
| Hemicellulose | 22.1 | 18.2 |
| Cellulose | 59.7 | 33.2 |
| Lignin | 18.1 | 48.6 |

2.2. Experimental setup and procedure
The experimental setup consisted of a combustion chamber for producing combustion gas and a torrefaction reactor (figure 2). The chamber and reactor were stainless steel-made vertical tubular columns with internal diameters of 0.10 m and 0.13 m, respectively. A prescribed amount of EFB (100 g) or PKS (434 g) was torrefied in combustion gas or N₂ at 473, 523 or 573 K for 30 min. The combustion
gas generated contained 13-14 vol% of carbon dioxide and 8.9 vol% of oxygen (nitrogen balance). The details were reported elsewhere [4].

Figure 2. Experimental setup for torrefaction under combustion gas atmosphere.

2.3. Data processing
The equations employed in quantifying the mass yield \((Y_m)\), calorific value \((CV)\) ratio \((CV_{ratio})\) and energy yield \((Y_e)\) from the torrefaction result are shown below:

\[
Y_m = \frac{m_f}{m_i}
\]  
(1)

\[
CV_{ratio} = \frac{CV_f}{CV_i}
\]  
(2)

\[
Y_e = \frac{CV_f \cdot m_f}{CV_i \cdot m_i}
\]  
(3)

where \(m\) denotes the mass of biomass, \(CV_{ratio}\) \((CV\) ratio\), subscript \(i\) at initial stage, subscript \(f\) after torrefaction.

3. Results and Discussion
Figure 3 shows the mass yield, \(CV\) (calorific value) ratio and energy yield of the torrefied biomass under nitrogen and combustion gas atmosphere at 473, 523 and 573 K for EFB (left) and PKS (right). The energy density (or CV ratio) of biomass torrefied in combustion gas is higher than that in nitrogen gas at all the temperatures regardless of biomass type. The energy yield of biomass torrefied in combustion gas is higher than that in nitrogen gas at the lowest temperature of 473 K. This trend is reversed at higher temperatures of 523 and 573 K. As the authors already reported, the severity of torrefaction in the presence of oxygen or carbon dioxide is more significant than that in inert gas [6], this trend may be attributed to partial oxidation of the biomass by the oxidative atmosphere.
After all, if higher energy density is preferable, torrefaction at 573 K in combustion gas is recommended. On the other hand, if higher energy yield is preferable torrefaction at 473 K in combustion gas is recommended.

**Figure 3.** Torrefaction result of EFB (left) and PKS (right) in nitrogen (N) and combustion gas (C).

The calorific value of biomass is the most important parameter to determine the energy density and energy yield if the biomass is used as a solid fuel. The authors once reported that the carbon content of lignocellulosic biomass is the major factor to determine the calorific value for biomass torrefied in inert gas [7]. But no report has been found about this issue for torrefaction under combustion gas. To investigate this point, the calorific value is plotted against the carbon content in figure 4. The data consist of the four groups of torrefaction results: PKS in nitrogen, PKS in combustion gas, EFB in nitrogen and EFB in combustion gas. All the data are approximated by only one straight line \( y = 1.31x + 24.3 \) regardless of type of torrefaction gas, as shown in figure 4. From the present study, it has been proved that the type of torrefaction gas has little effect on the relationship between the calorific value and carbon content.

**Figure 4.** A plot of higher calorific value against carbon content.
Finally, estimation of torrefied biomass production capacity at an average-sized oil mill in Malaysia was carried out based on the mass yield data obtained from this study. ‘An average-sized oil mill’ is defined as a mill of which oil production is the average in Malaysia. Torrefied biomass production at an average-sized palm oil mill was calculated for the following four cases:

1. Torrefaction of EFB in combustion gas at 573 K for higher energy density,
2. Torrefaction of EFB in combustion gas at 473 K for higher energy yield,
3. Torrefaction of PKS in combustion gas at 573 K for higher energy density, and
4. Torrefaction of PKS in combustion gas at 473 K for higher energy yield.

The result is summarized in figure 5. The limiting factor was set as the thermal energy supplied by 10% of the total monocarp fiber generated at the mill.

**Figure 5.** Estimation of torrefied EFB (left) and PKS (right) production at an average-sized oil mill.

Torrefied PKS production ranges from 12 to 21 thousand t/y, while 3 to 5 thousand t/y for EFB as shown in figure 5. The poor productivity of torrefied EFB is due to the higher moisture content of raw feed EFB (57 wt%). This may be improved if sunlight drying is applied to pre-drying of raw EFB [8].

**4. Conclusions**

In the present study, the effect of combustion gas on torrefaction behavior of empty fruit bunch (EFB) and palm kernel shell (PKS) at a temperature range of 473-573 K was investigated. Combustion gas atmosphere resulted in lower mass yield and higher calorific value ratio in comparison with nitrogen gas atmosphere. The energy yield behaved in a little more complex way. For both the biomass, the highest energy yield was obtained by torrefaction at 473 K in combustion gas. The highest energy density was obtained at 573 K in combustion gas. The relationship between the calorific value and carbon content was well correlated by only one line regardless of torrefaction atmosphere. Finally, production capacity for torrefied EFB and PKS was estimated at an average-sized palm oil mill based on the mass and energy balance.

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