



Calorific Value and Carbon Content of EFB Torrefied under Nitrogen, Oxygen and Carbon Dioxide Atmospheres

Y. UEMURA⁺⁺, M. H. SULAIMAN, M. T. AZIZAN, K. TANOUÉ*

Center for Biofuel and Biochemical Research, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.

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Abstract: Oil palm biomass residues in Southeast Asia, which are underutilized, can be converted into solid fuel if they are torrefied. In this case, flue gas in palm oil mills may be economical gas and thermal energy sources of torrefaction. This study aims to investigate the effects of oxygen (0, 9, 15 and 21 vol%) and carbon dioxide (0, 9, 15 and 21 vol%) in torrefaction gas towards torrefaction behavior of EFB, in specific calorific value and carbon content, the representative indices for solid fuel. The torrefaction temperature and time ranged 493-573 K and 30-90 min, respectively. In general, existence of oxygen resulted in higher carbon content, and thus higher calorific value. On the other hand, existence of carbon dioxide did not exhibit such an enhancement effect except for 30 min torrefaction of at the highest temperature of 573 K.

Keywords: Torrefaction, EFB, oxygen, carbon dioxide, calorific value, carbon content.

1. INTRODUCTION

Biomass is one of the promising renewable sources, which can be used as energy as well as carbon source. The drawback of this biomass is unestablished logistic system. To nurture this logistic system, we should start with small scale use of biomass. In this case, solid fuel use of biomass is definitely preferable than use as liquid or gas fuels, which requires large scale conversion process, thus suffers from logistic problem. Direct use of biomass as a solid fuel, however, has the following drawbacks: lower calorific value, reduction of quality by biodegradation, and mechanical tenacity causing grinding trouble upon required. A medium temperature treatment of biomass under inert atmosphere, so-called torrefaction, was found to be effective to get rid of those problems above (Prins *et al.*, 2006; Arias *et al.*, 2008; Bridgeman *et al.*, 2008; Uslu *et al.*, 2008; Repellin *et al.*, 2010; Uemura *et al.*, 2011). Although all these research studies were carried out by using nitrogen gas as torrefaction gas to purely observe self-decomposition of biomass, commercial torrefaction process may be carried out somewhat different such as recirculation of torrefaction gas or flue gas from boiler (Bergman *et al.*, 2005). In the light of this viewpoint, we carried out torrefaction of oil palm residue under oxygen atmosphere (Uemura *et al.*, 2013, 2011 online). Several studies published for oxidative torrefaction after the first oxygen-torrefaction paper (Rousset *et al.*, 2012; Lu *et al.*, 2012; Wang *et al.*, 2013; Chen *et al.*, 2013;

Chen *et al.*, 2014). Several studies can be found for torrefaction in carbon dioxide (Eseltine *et al.*, 2013; Saadon *et al.*, 2014; Uemura *et al.*, 2015; Li *et al.*, 2015; Bach *et al.*, 2015; Li *et al.*, 2016). However, still torrefaction under oxygen and carbon dioxide has not been thoroughly investigated and clarified.

In the present study, the authors focused on how oxygen and carbon dioxide influence the carbon content and calorific value of torrefied biomass. The effects of oxygen and carbon dioxide concentrations from 0-21 vol% on the solid yield, carbon content and calorific value were investigated for torrefaction of empty fruit bunch (EFB) at 493, 533 and 573 K.

2. MATERIALS AND METHODS

2.1 Feedstock preparation

Empty fruit bunch (EFB) was collected from a nearby FELCRA palm oil mill in Perak, Malaysia. The biomass material was dried first under sunlight. After most of the moisture was removed by natural drying, the biomass was dried further in an electrical oven overnight at 378 K. The dried biomass was first chopped into pieces by a handsaw and then by a cutter. Those small strips were ground by a biomass grinder, and sieved to obtain a 0.25-0.50 mm fraction. The powders were stored in an airtight vessel till its use for torrefaction and characterization. The results of proximate, calorific and elementary analyses of raw material EFB are summarized in (Table 1).

⁺⁺Corresponding author: Y. UEMURA

*Dept of Mechanical Engineering, Yamaguchi University, 2-16-1 Tokiwa-dai, Ube, 755-8611 Yamaguchi, Japan.

Table 1: Proximate, calorific and elementary analyses of raw material EFB

Proximate analysis [wt.%]		Elementary analysis [wt.%]	
Moisture	6.92	Carbon	42.36
Ash	5.06	Hydrogen	6.24
Volatile matter	87.80	Nitrogen	0.73
HHV	17.0 MJ/kg	Oxygen	38.69

2.2. Torrefaction experiment and product analysis

A vertical fixed-bed type tubular reactor made of stainless steel (0.028 m ID and 0.56 m length) was used for torrefaction. The entire setup of the torrefaction reactor is illustrated in (Fig. 1). The sample of approximately 3 g was placed in the reactor, and was then flushed with torrefaction gas (100 vol% nitrogen, 9-21vol% oxygen or 9-21 vol% carbon dioxide) for 15 min. The reactor temperature was raised to a desired torrefaction temperature (493, 533 or 573 K) with a rate of 10 deg/min and torrefaction was carried out at the temperature for 30, 60 or 90 min with 30 mL/min of torrefaction gas. After cooling down the reactor, the torrefied biomass was taken from the reactor, and weighed. The solid phase conversion, X , was calculated by Eq (1).

$$X = \{1 - (\text{mass of torrefied biomass}) / (\text{mass of raw material biomass})\} \times 100 \quad (1)$$

Elemental analysis of torrefied biomass was carried out by using a CHN analyzer (Perkin Elmer 2400). High heat value HHV of torrefied biomass was measured by a bomb calorimeter (IKA C6000 Isoperibol).

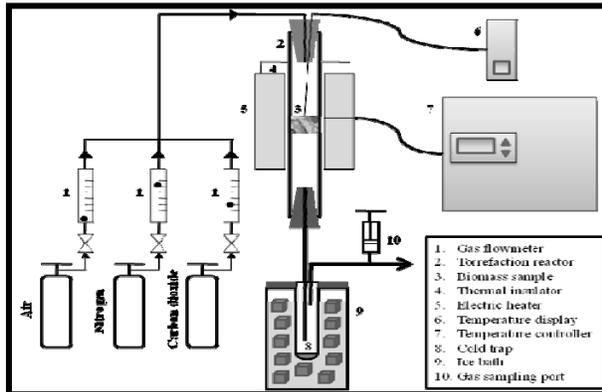


Fig. 1. Schematic diagram of the torrefaction experiment setup.

3. RESULTS AND DISCUSSION

3.1. Solid phase conversion

Fig. 2 shows the time course data of the solid phase conversion of EFB at different concentrations of oxygen at 533 K. The solid phase conversion increased monotonously with torrefaction time, but its increase became slightly less significantly at longer torrefaction time, regardless of oxygen concentration. The second prominent trend is that the higher the oxygen concentration the higher the solid phase conversion.

This enhancement effect can be attributed to partial oxidation (Uemura *et al.*, 2015). The third trend in Fig. 2 is that the enhancement effect by oxygen is saturated at higher oxygen concentrations. In general, these three characteristic trends in (Fig. 2), discussed above, were also observed at different temperatures of 493 and 573 K and different atmospheres (9, 15 and 21 vol% carbon dioxide). Net increases of the solid phase conversion $X(\text{O}_2) - X(\text{N}_2)$ and $X(\text{CO}_2) - X(\text{N}_2)$ by existence of oxygen and carbon dioxide are plotted in (Fig. 3(a) and (b)), respectively. In both the results, the net increase increased from 493 to 533 K, but its increase became insignificant from 533 to 573 K.

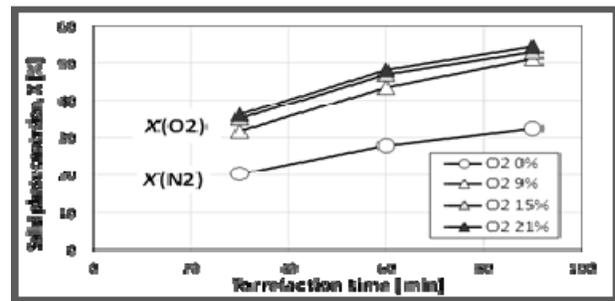
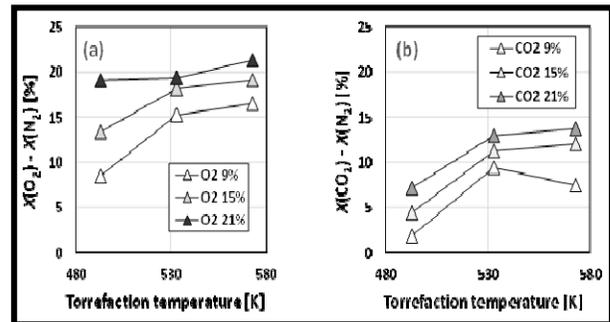


Fig. 2. Solid phase conversion of EFB at different concentrations of oxygen at 533 K.

Fig. 3. $X(\text{O}_2) - X(\text{N}_2)$ (a) and $X(\text{CO}_2) - X(\text{N}_2)$ (b) as a function of torrefaction temperature.

This asymptotic increase in $X(\text{O}_2) - X(\text{N}_2)$ and $X(\text{CO}_2) - X(\text{N}_2)$ with temperature for EFB (Fig. 3) is different from what was observed for palm kernel shell (PKS) (Uemura *et al.*, 2015). For PKS, the trend of the net increase vs. torrefaction temperature showed little increase at 493-533 K, then significant increase at 533-573 K. This may be attributed to the difference of lignin content and three-dimensional texture between EFB and PKS.

By comparing (Fig. 3(a) with Fig. 3(b)), one can notice that the enhancement effect by oxygen is obviously stronger than that by carbon dioxide. This implies that the enhancement mechanism by carbon dioxide is different from oxygen, which is partial oxidation (Uemura *et al.*, 2015).

3.2. High heat value and carbon content of torrefied EFB

Fig. 4 shows the time course data of the high heat value (HHV) of EFB torrefied at different concentrations of oxygen and carbon dioxide at 493 and 573 K. Fig. 5 shows the time course data of the carbon content of EFB torrefied at different concentrations of oxygen and carbon dioxide at 493 and 573 K.

The HHV of EFB torrefied under oxygen atmosphere at 493 K (Fig. 4(a)) showed similar values regardless of torrefaction time. Meanwhile, existence of oxygen in torrefaction gas obviously increased the HHV. At this temperature, partial oxidation may remove organic components containing more oxygen than the average oxygen content of the biomass, thus resulted in carbon content increase. In fact, higher carbon contents are observed for torrefaction in oxygen compared with torrefaction in nitrogen (Fig. 5(a)). At higher temperature of 573 K, this enhancement effect was observed only at 30 min (Fig. 4(b)). At longer reaction time periods of 60 and 90 min, the HHV under oxygen atmosphere gave lower values than nitrogen atmosphere. This decrease in HHV can be attributed to the lower carbon content as shown in (Fig. 5(b)). At higher temperatures, more vigorous partial oxidation may have removed char component in torrefied biomass, thus resulted in carbon content loss.

In general, the HHV and carbon content profiles with torrefaction time in the presence of carbon dioxide (Fig. 4(c), (d), Fig. 5(c) and (d)) are similar with those for oxygen (Fig. 4(a), (b), Fig. 5(a) and (b)). But the enhancement effect observed for oxygen at 493 K was not observed for carbon dioxide. The negative effect of oxygen at 573 K at longer residence time periods of 60 and 90 min was also not observed for carbon dioxide. These similarities and differences between oxygen and carbon dioxide imply that carbon dioxide acts in a similar way with oxygen towards torrefaction, but its extent is milder than oxygen.

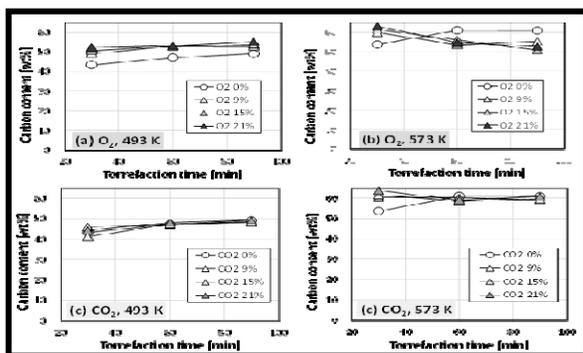


Fig. 4. High heat value of EFB torrefied at different concentrations of oxygen and carbon dioxide at 493 and 573K.

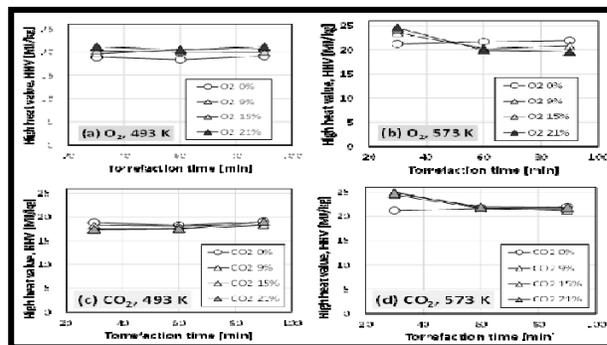


Fig. 5. Carbon content of EFB torrefied at different concentrations of oxygen and carbon dioxide at 493 and 573K.

4. CONCLUSIONS

Torrefaction of empty fruit bunch (EFB) was carried out under nitrogen, oxygen and carbon dioxide atmospheres at 493, 533 and 573 K for 30, 60 and 90 min.

The solid phase conversion was enhanced by existence of either oxygen or carbon dioxide compared to pure nitrogen condition. The extent of the carbon dioxide enhancement effect was milder than that of oxygen.

In general, existence of oxygen in torrefaction gas resulted in higher carbon content, and thus higher calorific value than that of nitrogen. On the other hand, existence of carbon dioxide did not exhibit such an enhancement effect except for 30 min torrefaction at the highest temperature of 573 K.

At the lowest temperature of 493 K, torrefaction under oxygen atmosphere resulted in higher carbon content, thus higher calorific value. This enhancement effect was observed at the highest temperature of 573 K at only 30 min torrefaction. However, longer torrefaction time than 60 min at 573 K resulted in lower carbon content, thus lower calorific value. This transition from 493 K to 573 K may be caused by difference of partial oxidation mechanism between 493 and 573 K. At lower temperature, partial oxidation may extract more hydrogen and oxygen. On the contrary, partial oxidation at higher temperature may extract more carbon. On the contrary, torrefaction under carbon dioxide exhibited neither the enhancement effect observed for oxygen torrefaction at 493 K nor the preventing effect observed for oxygen torrefaction at 573 K for carbon content and calorific value in general.

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