Effect of atmosphere on torrefaction of oil palm wastes

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Abstract: Torrefaction is a low temperature treatment for lignocellulosic biomass at lower temperatures between 473 K and 573 K under an inert atmosphere, which has been found to be effective not only for improving the quality of lignocellulosic solid fuels, such as their energy density and shelf life, but also to make them useful as a feedstock for further decomposition such as gasification and liquefaction. Although more than ten papers on this subject have been published in the last several years, in all of these studies, the atmosphere has been inert (nitrogen). When we try to utilize waste thermal sources, such as flue gas from boilers for torrefaction, the gas contains some components other than nitrogen such as oxygen, carbon dioxide and water vapor. The most serious problem is thought to be the existence of oxygen in the gas. In this study, torrefaction of Malaysian oil palm wastes was carried out in a fixed bed tubular reactor under oxygen/nitrogen flow at a temperature range of 494 to 573 K, in order to clarify the effect of oxygen on torrefaction of lignocellulose. The effects of torrefaction conditions such as atmosphere, temperature and time, on the torrefaction behavior were investigated. The lignocellulosic biomass wastes utilized were mesocarp fiber and kernel shell of oil palm, which are typical agricultural wastes in Malaysia.

Keywords: *Torrefaction, Oil palm waste, Lignocellulose, Oxygen*

1. Introduction

One of the promising renewable energy sources is biomass, which can be utilized as solid, liquid or gas fuels. Specifically, lignocellulosic biomass residues are attracting interest worldwide because they are non-edible. Due to their availability in Malaysia, oil palm wastes are considered as the best among all biomass wastes [1]. In 2008, Malaysia was the second largest producer of palm oil with 17.7 million tonnes, or 41% of the total world supply, while Indonesia was the world's largest producer of palm oil with 19.3 million tonnes of oil, or 45% of the total world supply [2]. In 2008, productive oil palm plantations in Malaysia covered 4.5 million hectares, a 4.3% increase from the figures in 2007, which stood at 4.3 million hectares [3]. The types of biomass produced by the oil palm industry include empty fruit bunches (EFB), mesocarp fiber, kernel shells, fronds and trunks. EFB, mesocarp fiber and kernel shells are either utilized or discarded at palm oil mills. Similarly, the rest, fronds and trunks are either utilized or discarded at plantations. The amount of each type of biomass is summarized in Table 1. Since the current primary energy supply in Malaysia is about 70 Mtoe (million tons of oil equivalent), the total oil palm biomass energy potential of 17 Mtoe may be able to contribute considerably to the decrease in consumption of fossil fuels (natural gas, coal and oil). In order to utilize biomass wastes efficiently, the following drawbacks about biomass compared to fossil fuels must be properly solved:
(1) Higher energy consumption during collection
(2) Heterogeneous and uneven composition
(3) Lower calorific value.
(4) Quality decay by biodegradation.

There are a few options to solve some of those problems; the major ones are pelletization, liquefaction and gasification of biomass. Pelletization includes the following processes: drying, chipping, grinding and pelletizing of lignocellulosic biomass. Though pelletization is the least expensive option, there are some problems associated with it; lower heat value and quality deterioration by moisture (pellet disintegration, moss growth and bioorganic decomposition). In recent investigations, a low temperature treatment at 473 to 573 K under an inert atmosphere was found to be effective for improving the energy density and shelf life of the biomass. The treatment is called 'torrefaction,' and has been reported for wood and grass biomass over the past few years [4-16]. Arias et al. torrefied woody biomass (eucalyptus) at 513 to 553 K, and found that the grindability of the biomass was improved [5]. Prins et al. proposed a kinetic model of torrefaction [9], and reported the details of torrefaction mass balance [10]. Some papers have focused on the fuel quality [6] and the feedstock quality for gasification [4,7] of the torrefied lignocellulosic biomass. Uslu et al. focused on a comparison of torrefaction, fast pyrolysis and pelletization from the viewpoint of international bioenergy logistics [8]. Currently, experimental torrefaction studies are mostly conducted on woody and grass biomass; wood dusts [8], beech [4, 9, 10], eucalyptus [5], willow [6, 7, 9, 10], larch [9, 10], and canary grass [6]. Few academic papers have been found for torrefaction of agricultural lignocellulosic wastes, such as wheat straw [6, 9, 10], although they are among the most promising renewable resources, especially in Southern Asia. The authors have already reported on the torrefaction behaviour of three types of oil palm residue; empty fruit bunches (EFB), mesocarp fiber and kernel shell [17].

Table 1. Oil palm biomass wastes and their potential.

Site	Waste type	Generation rate		Plantation area or FFB processed		Annual generation	Moisture	CV (LHV, dry base)	Annual energy (dry base)	
						million t-wet/y	wt%	GJ/t	PJ	Mtoe
Palm plantation	Trunk	40	t-dry/ha-replantation/y	0.08	million ha-replantation	11	71	16.4	52	1.2
	Fronds	15				4.1	71	14.4	17	0.4
	Fronds	6	t-dry/ha-plantation/y	4.488	million ha-plantation in 2008	92.9	71	14.4	388	9.2
Palm oil mill	EFB	0.2	t-wet/t-FFB	85.71	million t-FFB processed in 2009	17.1	65	15.8	95	2.3
	Fiber	0.12				10.3	42	18.3	109	2.6
	Shell	0.05				4.3	17	18.5	66	1.6
	POME	0.6				51.4	-	-	28	0.66
Total									727	17.3

At palm oil mills in Malaysia, we may be able to utilize flue gas from the boilers as a thermal energy source for torrefying unutilized residues. Currently, in most of the palm oil mills, all the mesocarp fiber and part of the kernel shell generated at the mills are utilized as fuel for the boilers. EFB and most of the shell are not utilized. Specifically, EFB is simply incinerated without any thermal recovery due to its high moisture content. If it is possible to utilize the flue gas from the boilers for torrefying EFB, (1) a considerable quantity of energy can be saved in the process; and (2), EFB could be sold as a solid fuel. This makes the oil mill more economically viable. In this case, the problem is that no data are available to demonstrate if torrefaction can be carried out properly in the presence of oxygen, because flue gas from the boilers at palm oil mills contains oxygen. According to our survey, the oxygen concentration in the flue gas is around 13%. Based on this point of view, the authors have already studied and reported the effect of oxygen on torrefaction behavior of EFB [18]. In addition, recent developments in boiler technology have improved their efficiency considerably. If such updated technology is applied, boilers at oil mills will only consume part of the fiber generated at the mills. In the very near future, kernel shell and part of the mesocarp fiber, therefore, could be the source for torrefaction to produce solid fuel.

In this paper, torrefaction of mesocarp fiber and kernel shell residue was carried out in a fixed bed tubular reactor in the presence of oxygen in the range of 3 to 15 %, in order to answer the question above. The effects of torrefaction conditions, oxygen concentration, temperature and biomass size, on the mass and energy yields were investigated.

2. Experimental

2.1. Biomass samples

Mesocarp fiber and kernel shell were collected from an oil palm plantation at Bota in Perak, Malaysia in July, 2010. After drying at 378 K for 24 h, they were ground by a mechanical grinder. The ground powders were sieved into four fractions as shown in Table 2.

Table 2. Biomass size used in this study.

Range of sieve opening [mm]	Nominal average diameter [mm]
0.25-0.50	0.375
1.0-2.0	1.5
2.0-4.0	3.0
4.0-8.0	6.0

2.2. Torrefaction

Torrefaction of the biomass samples was carried out using a horizontal tubular type reactor made of stainless steel, with a 46 mm internal diameter. The entire set-up is illustrated in Fig. 1.

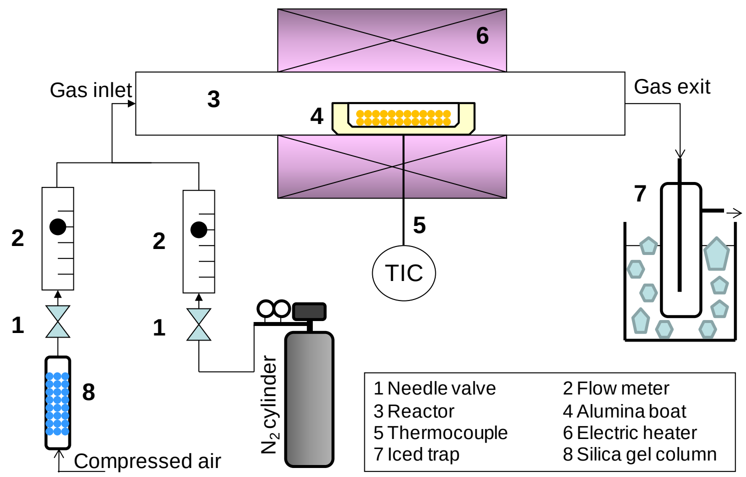


Fig. 1. Experimental apparatus used in this study.

A prescribed amount of biomass waste (1.6 g) was weighed, and put in a ceramic boat. The boat was placed at the center of the reactor. After flushing the reactor with torrefaction gas for 15 min, the temperature of the reactor was raised to different desired levels, *i.e.* 493, 523 or 573 K at a constant rate of 10 deg/min by an electric furnace surrounding the reactor. The temperature range (493 to 573 K) was chosen because selective decomposition of hemicelluloses occurs between 473 and 573 K. The reason for selecting the minimum temperature as 493 K is that we may not have a substantial torrefaction rate at less than 493 K. After 30 min of torrefaction, the heater was turned off and the reactor was left to cool down to an ambient temperature. The torrefied sample was then recovered, weighed and kept in an air-tight vessel till the characterization. Throughout the procedure described above, 0.1 L/min of torrefaction gas was flowed through the reactor. The concentration of oxygen in the gas was adjusted to 3, 9 or 15 %, in order to investigate the effect of oxygen concentration on torrefaction. During each torrefaction experiment, collection of volatile substances generated from the reactor was attempted by an iced trap as shown in Fig. 1. After all, no condensation was observed in the trap for all the runs.

2.3. Measurements

For all the eight samples used in this study, the mass and the calorific value were measured before and after torrefaction. The calorific value was measured using a bomb calorimeter, model C2000 series manufactured by IKA Werke. The calorific value from a bomb calorimeter is the high heat value (HHV), which includes the latent heat of the vapor emitted from the specimen. From the experimental results described above, the three parameters were calculated by the following three equations:

$$y_M = \frac{Mass\ of\ solid\ after\ torrefaction}{Mass\ of\ EFB\ used} \quad (1)$$

$$CV\ ratio = \frac{CV\ of\ solid\ after\ torrefaction}{CV\ of\ EFB\ used} \quad (2)$$

$$y_E = y_M \times CV\ ratio \quad (3)$$

Where y_M means the mass yield, *CV* means the calorific value, and y_E means the energy yield.

3. Results and Discussion

The biomass samples after torrefaction and their physical properties are listed in Tables 3 and 4. In this study, the calorific values of the untorrefied mesocarp fiber and the untorrefied kernel shell were 18.6 and 19.9 MJ/kg, respectively. Wahid reported 18.8 and 20.1 MJ/kg as the calorific values of mesocarp fiber and kernel shell [19]. The difference between this and other studies is surprisingly small, although the physical properties of biomass frequently depend on soil conditions and the harvesting season [20].

Table 3. Torrefaction results for fiber of 0.375mm.

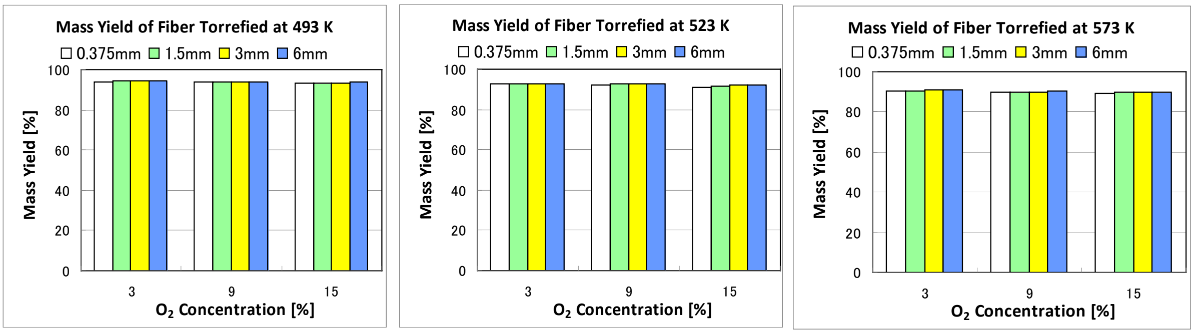
Temp [K]	O_2 conc [%]	Calorific value [MJ/kg]	CV ratio [%]	Mass yield [%]	Energy yield [%]
493	3	21.2	114.2	94.0	107.4
523	3	21.3	114.6	92.8	106.3
573	3	22.1	118.8	90.3	107.3
493	9	21.0	113.2	93.7	106.1
523	9	21.4	114.8	92.4	106.1
573	9	22.1	119.0	89.8	106.9
493	15	21.1	113.4	93.1	105.5
523	15	21.6	116.1	91.2	105.9
573	15	22.1	118.8	89.5	106.3

Table 4. Torrefaction results for shell of 0.375mm.

Temp [K]	O_2 conc [%]	Calorific value [MJ/kg]	CV ratio [%]	Mass yield [%]	Energy yield [%]
493	3	22.0	110.4	95.8	105.8
523	3	21.7	109.0	94.3	102.8
573	3	22.8	114.5	93.1	106.6
493	9	21.9	110.2	95.4	105.2
523	9	21.6	108.8	93.8	102.0
573	9	22.7	114.3	92.5	105.7
493	15	21.8	109.8	94.9	104.2
523	15	21.6	108.7	93.6	101.7
573	15	22.7	114.3	91.9	105.0

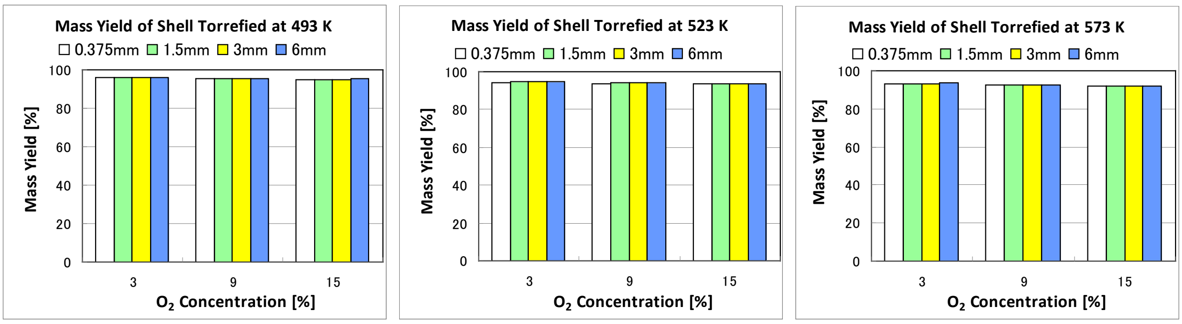
3.1. Effect of biomass size on mass yield

Figures 2 and 3 show the results of mass yield for mesocarp fiber and kernel shell, respectively. It is obvious that mass yield shows no significant dependency on particle size under the conditions of this study. Hereafter, the effects of temperature and oxygen concentration on the torrefaction results will be discussed. Also, the results are for 0.375 mm biomass unless otherwise noted in the text.



(a) (b) (c)

Fig. 2. Mass yield for mesocarp fiber.



(a) (b) (c)

Fig. 3. Mass yield for kernel shell.

3.2. Effects of temperature and oxygen concentration on mass yield

Figures 4 and 5 show the relationship between mass yield and temperature at oxygen concentrations of 3, 9 and 15 % for mesocarp fiber and kernel shell, respectively. The mass yield decreases with an increase in temperature. A similar tendency was reported in previous torrefaction studies [6, 11] as well as in our study on EFB torrefaction [18]. This tendency reflects the positive effect of temperature on the torrefaction rate. On the other hand, the mass yield slightly decreases with an increase in oxygen concentration as shown in Figs. 4 and 5. As we have reported already, for torrefaction of EFB, the mass yield decreased with an increase in oxygen concentration. EFB is found to be not as resistant to oxygen in the atmosphere as mesocarp fiber or kernel shell. When the mass yield of fiber is compared with that of shell, shell always shows a larger mass yield than fiber at any temperature.

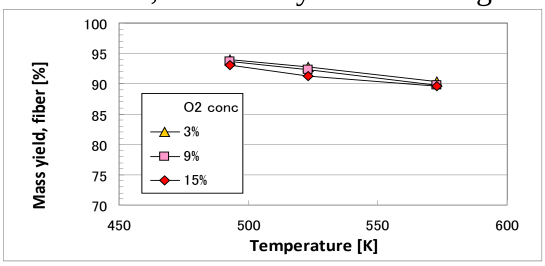


Fig. 4. Effects of temperature and O_2 conc. on mass yield for mesocarp fiber.

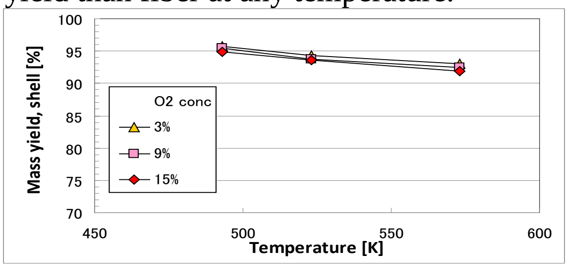


Fig. 5. Effects of temperature and O_2 conc. on mass yield for kernel shell.

This tendency may be attributed to the fact that shell contains 22.7 % hemicellulose, which is less than that of fiber, which contains 38.8 % hemicellulose [21].

3.3. Effects of temperature and oxygen concentration on calorific value

Figures 6 and 7 show the relationship between calorific value and temperature at oxygen concentrations of 3, 9 and 15 % for mesocarp fiber and kernel shell, respectively. The calorific value increases with an increase in temperature. This tendency has been reported in previous papers, in which wood and grass-type lignocellulosic biomass samples were used. It can be explained by the fact that the main gaseous products during torrefaction are water and carbon dioxide [4,10]. Surprisingly, the calorific value has little dependency on oxygen concentration in the range of 3 to 15%. This is the same tendency as what the authors already reported in a previous paper [18]. In that report, the authors proposed that EFB may undergo torrefaction and oxidation in parallel during torrefaction in the presence of oxygen, and these two reactions do not interact with each other. From the results as shown in Figs. 6 and 7, it is likely that the torrefaction mechanism of mesocarp fiber and kernel shell is similar to that of EFB.

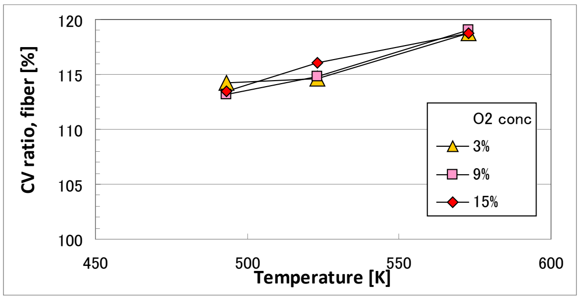


Fig. 6. Effects of temperature and O_2 conc. on CV ratio for mesocarp fiber.

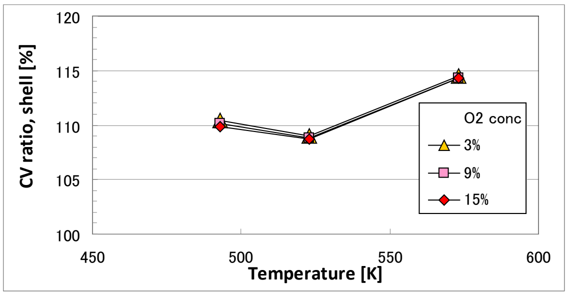


Fig. 7. Effects of temperature and O_2 conc. on CV ratio for kernel shell.

3.4. Effects of temperature and oxygen concentration on energy yield

Figures 8 and 9 show the relationship between energy yield and temperature at oxygen concentrations of 3, 9 and 15 % for mesocarp fiber and kernel shell, respectively. The energy yield is the key parameter to understand how much energy has been reserved after torrefaction. For both types of biomass, the energy yield slightly decreases with an increase in oxygen concentration. For mesocarp fiber, the energy yield has little dependency on temperature. From this result, when we focus only on the energy yield, it is recommended that mesocarp fiber be torrefied at 493 K. Sometimes, however, the calorific value itself does matter. In that case, the torrefaction temperature should be 573 K. For kernel shell, the energy yield shows a concave profile against temperature. This tendency is attributed to the fact that the energy yield is a product of the mass yield and the CV ratio; the former decreases with an increase in temperature, and the latter increases with an increase in temperature. Kernel shell shows a smaller energy yield value than that of fiber under the same conditions. From this fact,

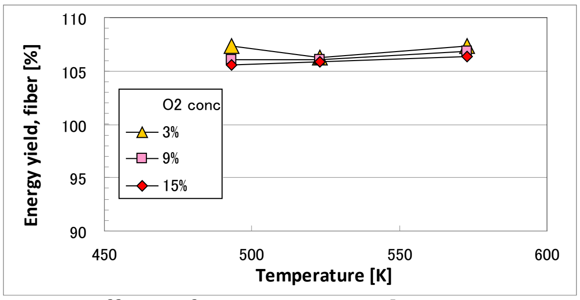


Fig. 8. Effects of temperature and O_2 conc

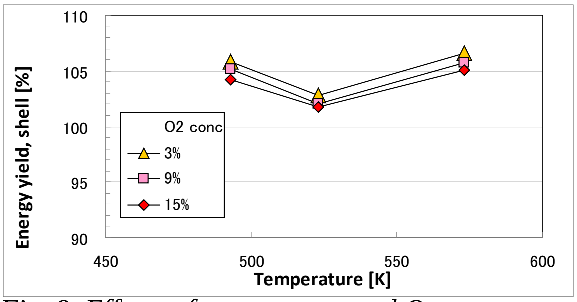


Fig. 9. Effects of temperature and O_2 conc

on energy yield for mesocarp fiber. *on energy yield for kernel shell.*
mesocarp fiber is more suitable than kernel shell as a feedstock for torrefaction.

4. Conclusion

Torrefaction of mesocarp fiber and kernel shell was carried out in the presence of oxygen in order to investigate the effects of various torrefaction conditions, *i.e.*, oxygen concentration (3, 9 and 15 %), temperature (493, 523 and 573 K) and biomass size (0.375, 1.5, 3 and 6 mm), on the mass and energy yields. The mass yield decreased considerably with an increase in temperature, and decreased slightly with an increase in oxygen concentration, but showed very little dependency on biomass size. In other words, the torrefaction reaction rate was affected only by temperature. The other two factors, oxygen concentration and biomass size, had no significant effects on the rate. The energy yield against temperature showed either a slight and steady increase profile or a concave profile. This rather complex behavior is due to the fact that energy yield is a product of the mass yield and the CV ratio; the former decreases with an increase in temperature, and the latter increases with an increase in temperature. The energy yield slightly decreased with an increase in oxygen concentration, but all the values fell between 105 and 108 % for mesocarp fiber and between 102 and 107 % for kernel shell. It is worthwhile pointing out that torrefaction in the presence of oxygen can be carried out without any significant problem, while the mass and energy yields slightly decrease with an increase in oxygen concentration from 3 to 15%. Since the flue gas from a palm oil boiler contains around 13% oxygen based on our survey described in the introduction, direct use of boiler flue gas to torrefaction will not deteriorate the quality of the torrefied biomass.

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