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Effect of Gasification Temperature on Synthesis Gas Production and Gasification Performance for Raw and Torrefied Palm Mesocarp Fibre

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Biomass gasification is widely used for converting solid biomass into synthesis gas for energy applications. Raw biomass is commonly used as feedstock for the gasification process but it usually contains high moisture content and low energy value which lowering synthesis gas production. Thus, torrefaction as a pre-treatment process is necessary in order to upgrade the properties of feedstock for producing more synthesis gas production and improving gasification performance. The objective of this work is to study the effect of gasification temperature on the synthesis gas production and gasification performance using raw and torrefied palm mesocarp fibre (PMF). The gasification process is conducted using bubbling fluidized bed using steam as gasifying agent. Based on experimental work, by increasing gasification temperature from 650 – 900 °C, the compositions of hydrogen and carbon monoxide gases were enhanced greatly while carbon dioxide and methane gases were decreased for both raw and torrefied PMF. In terms of gasification performance, synthesis gas yield for raw and torrefied PMF is increased from 0.91 to 1.23 Nm^3/kg and 1.10 to 1.35 Nm^3/kg respectively. Besides, lower heating value (LHV) of torrefied PMF is 0.04 MJ/Nm^3 higher than raw PMF at 900 °C. The result showed that the percentage of cold gas efficiency (CGE) reached maximum of 67% for raw PMF while carbon conversion (CC) at 85.6% for torrefied PMF at a gasification temperature of 900 °C. The higher CC obtained by torrefied PMF is because of the increment of carbon content from 45.2% to 53.7% as a result of torrefaction. Gasification temperature of 800 °C showed the best performance of the PMF gasification since the maximum performances of LHV is achieved and started to decrease once the gasification temperature is operated beyond 800 °C.

Keywords: Bubbling fluidized bed, gasification, palm mesocarp fibre, synthesis gas

INTRODUCTION

The global consumption of fossil fuels as energy sources has increased due to industrial development and population growth. In this case, the demand for fossil fuel has rapidly increased and lead to the depletion of fossil fuel as well as resulting in the degradation of the environment. Recent issues on the greenhouse gas

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(GHG) emission and increasing of the carbon content in the atmosphere are contributed from the combustion of fossil fuels. Hence, an alternative energy source is necessary in order to supplement energy demand as well as mitigating GHG emissions. Biomass is one of the renewable energy sources which can be converted into solid, liquid and gaseous product through thermochemical conversion processes.

In Malaysia, palm oil wastes are identified as potential biomass sources. From palm oil plantation, only 10% of the palm oil fruits produce oil-based product while the other 90% are considered as waste in the forms of palm mesocarp fibre (PMF), empty fruit bunch (EFB) and palm kernel shell (PKS) (Harun et al. 2017). In Malaysia, there are 31.94 million tonnes of oil palm wastes produced, and about 30% are PMF waste. Current practices point that PMF is used as organic fertilizer and to some extent as fuel for steam production at palm oil mills. As biomass is an organic matter which is derived from living things, a thermochemical conversion process is required to produce energy and fuels. There are several thermochemical conversion processes such as combustion, pyrolysis, liquefaction and gasification can be operated to convert biomass into energy and fuels. Among all processes, biomass gasification is an attractive thermochemical conversion process that produces useful product gas consisting of mainly H_2, CO, CO_2 and CH_4 (Bach et al. 2019).

In biomass gasification, several types of gasifiers can be used such as fixed bed, fluidized bed and entrained flow gasifiers. Among all of these technologies, a fluidized bed gasifier offers a good temperature distributor and higher cold gas efficiency (CGE) which are more desirable in studying the effect of gasification temperature on synthesis gas production and gasification performance (Lahijani & Zainal 2011). There are two types of fluidized bed gasifiers which are bubbling and circulating fluidized bed gasifiers. Both gasifiers have almost the same operating procedures except for the product extraction part where for circulating fluidized bed gasifiers, the product will partially extract from the top and recycle to the bottom of gasifier (Karl & Pröll 2018). This situation will give limitations to the size of biomass feedstock where it is not suitable for a wide range of biomass particle sizes. Thus, in this study, the bubbling fluidized bed gasifier is chosen to perform the biomass gasification.

The utilization of raw biomass for gasification process is found to be less efficient due to the higher moisture content in the raw biomass. In order to increase the efficiency of the gasification, a pretreatment method to improve the properties of biomass is introduced. This method reduces the moisture content of the biomass by performing torrefaction process at temperature in the range of 200 – 300 °C which subsequently enhancing the fixed carbon, volatile matter and ash content of torrefied biomass. However, research on gasification of the torrefied biomass is significantly lacking. Bach et al. (2019) conducted a biomass steam gasification using spruce wood branches and bituminous coal which were pretreated using the torrefaction process at different temperatures (240 °C, 270 °C and 300 °C).

From this research, the results showed that the higher the torrefaction temperature, the higher the efficiency of the gasification performances. Besides, Muslim et al. (2017) used raw and torrefied EFB as the biomass feedstock for gasification study using Aspen Plus as the simulating and modelling tool. The model was developed for the fixed bed gasifier only in order to analyze the gasification performances of EFB. It was found that the use of torrefied EFB contributes to higher yield of synthesis gas. Another researcher, Lau et al. (2018) conducted a torrefaction experiment for co-firing in coal power plants that use oil palm fronds as the biomass feedstock. The optimum temperature for torrefaction of oil palm fronds at 250 °C was obtained. Thus, torrefaction process is the potential method in upgrading the properties of biomass such as fixed carbon, energy content and enhancing the efficiency of the gasification performance (Harun et al. 2017). In this pre-treatment process, the moisture content of the biomass is reduced during the heating process at 200-300 °C for residence time between 30 – 60 min under inert condition (Samad et al. 2017). Furthermore, higher heating value (HHV) which usually used as a measure of energy content will be improved during the torrefaction method (Wahid et al. 2017).

Hence, this study focuses on gasification of raw and torrefied PMF at 300 °C as the feedstock using bubbling fluidized bed. The effect of the gasification temperature is performed on the synthesis gas production. In addition, the gasification performance based on synthesis gas yield, lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion (CC) are evaluated and discussed.

MATERIALS AND METHOD

Feedstock

Palm mesocarp fibre (PMF) is the waste collected after the crude palm oil was extracted from the oil palm fruits. In this study, PMF was chosen as the biomass feedstock and obtained from Lepar Hilir Palm Oil Mill, Kuantan, Pahang. In order to reduce the moisture content of PMF, it was oven-dried for about 4 hours at temperature of 105 °C in order to maintain the quality of the sample. Then, the sample was grinded and sieved to obtain the particle size in the range of 0.5 – 1.0 mm.

Torrefaction process

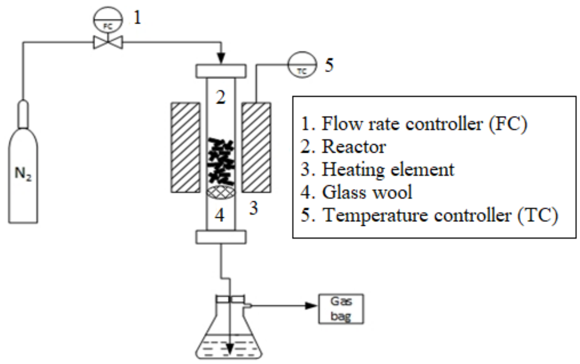

Fig. 1: Schematic diagram of the vertical tubular reactor

The torrefaction experiment is conducted at temperature of 300 °C to obtain torrefied PMF for the gasification process. Torrefaction was carried out using a vertical-stainless steel reactor with 39.7 cm long and 1.9 cm internal diameter as shown in Fig. 1. The grinded and dried sample was fed in the reactor for 5 min with 10 mL/min nitrogen to create the inert atmosphere. The electric furnace was used to heat the sample to the desired temperature for about 30 minutes. After the heating process, the sample was cooled to ambient temperature and placed in the air-tight container to maintain the moisture content (Harun et al. 2017).

Table 1. The proximate and ultimate analysis of the raw and torrefied PMF

Properties	Raw PMF	Torrefied PMF at 300 °C
Proximate Analysis		
Moisture Content	14.85	3.19
Volatile Matter	62.24	49.27
Fixed Carbon	18.23	38.9
Ash	4.68	9.64
Ultimate Analysis		
C	45.20	53.70
H	5.94	5.44
N	1.12	1.77
S	0.11	0.12
O	47.63	38.98
HHV (MJ/kg)	16.94	21.49

After the torrefaction process, the properties of torrefied PMF including proximate and ultimate analysis were analyzed as shown in Table 1. The torrefaction process enhanced the percentage of fixed carbon from 18.23 wt% to 38.9 wt% and the moisture content was decreased from 14.85 wt% to 3.19 wt%. In terms of ultimate analysis, the torrefaction process promoted the composition of carbon (C) in the biomass from 45.20 wt% to 53.70 wt%. Meanwhile, the HHV has been increased from 16.94 to 21.49 MJ/kg when the PMF undergo torrefaction process.

Gasification Experimental Setup

A stainless-steel bubbling fluidized bed gasifier with a bed diameter of 60 mm and a height of 850 mm was used in this experiment as shown in Fig. 2 and silica sand was used as the bed material. With a mass flow rate of 0.4 kg/h, the feedstock was fed into the reactor using a screw feeder. The gasifying agent used is steam with ratio of 0.6 to biomass feedstock and flushed from the bottom of the reactor. An electric furnace was used to heat the reactor to the desired temperature.

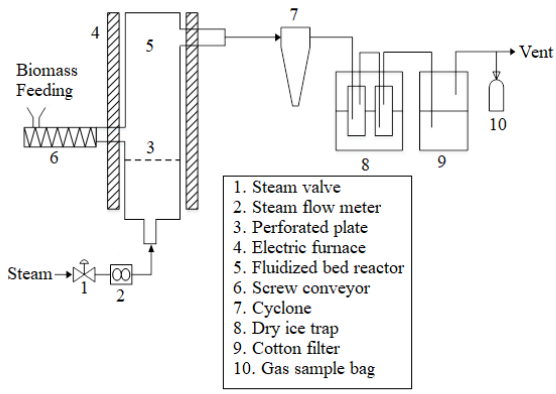

Fig. 2: Schematic diagram of fluidized bed gasifier

In order to study the effect of gasification temperature on the gas production and gasification performance, six different gasification temperatures were used from 650, 700, 750, 800, 850 and 900°C. Cyclone was used to separate the produced gas from tar and ash and went through cleaning and drying processes using a dry ice trap and cotton filter. An Agilent 6890N gas chromatograph with a thermal conductivity detector (GC–TCD) was used to analyze the produced gas. The standard gas mixture was used as calibration for GC–TCD and nitrogen gas was used as the carrier gas for the analysis.

Gasification Performance

The synthesis gas yield, lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion (CC) were calculated and determined for both raw and torrefied PMF to evaluate the gasification performance. The synthesis gas yield (Y_{syngas}) was calculated using Eq. (1).

$$Y_{syngas} = \frac{Vol_{gas}}{Mass_{feedstock}} \quad (1)$$

The volume of product gas (Vol_{gas}) was obtained from experimental work and the unit mass of PMF ($Mass_{feedstock}$) used is kg/h. After calculating the synthesis gas yield for both raw and torrefied PMF, the LHV of product gas was determined. LHV is one of the energy contents in biomass includes all the sensible energy except for the heat of condensation of water. The LHV of the product gas is expressed in Eq. (2).

$$LHV = (30x_{CO} + 25.7x_{H_2} + 85.4x_{CH_4}) \times 4.2 \quad (2)$$

where x represents the mole fraction of the gas species. Furthermore, CGE is the amount of chemical energy received by the syngas from the total chemical energy of the biomass (Mazaheri et al. 2019) and calculated using Eq. (3).

$$CGE(\%) = \frac{LHV_{gas} \times Syn_{yield}}{HHV_{feedstock}} \times 100 \quad (3)$$

where HHV is the higher heating value of the feedstock. In addition to CGE, CC is also analyzed and defined in Eq. (4).

$$CC(\%) = \left[1 - \frac{m_{pg}\left(y_{CO_2}\frac{12}{44} + y_{CO}\frac{12}{28} + y_{CH_4}\frac{12}{16}\right)}{m_{fuel}y_C}\right] \times 100 \quad (4)$$

where m_{pg} is the flow rate of the product gas, m_{fuel} is the flow rate of the biomass feedstock and y_{CO}, y_{CO2}, y_{CH4} are the compositions of the carbon monoxide, carbon dioxide and methane from product gas respectively and y_C is the composition of the carbon from ultimate analysis.

RESULT AND DISCUSSION

Effect of Gasification Temperature on Synthesis Gas Composition

The composition of hydrogen, carbon monoxide, carbon dioxide and methane were determined and presented in Fig. 3 for both raw and torrefied PMF as a function of gasification temperature.

The composition of hydrogen gas was greatly enhanced as the gasification temperature is increased for raw PMF from 14.23 mol% to 29.94 mol% and 12.36 mol% to 25.68 mol% for torrefied PMF. Meanwhile, the composition of carbon monoxide was also increased from 31.23 mol% to 45.89 mol% for raw PMF and 34.32 mol% to 47.68 mol% for torrefied PMF. However, the composition of carbon dioxide for raw and torrefied PMF were decreased from 46.23 mol% to 23.54 mol% and 44.27 mol% to 25.26 mol% respectively. Besides, methane produced from both raw and torrefied were also decreased from 8.31 mol% to 0.63 mol% and 9.06 mol% to 1.38 mol%.

These situations can be explained by considering the endothermic reactions involved in the gasification process with the rise of gasification temperature. The increase in carbon monoxide composition can be clarified by considering the endothermic water-gas (Eq. (5)) and Boudouard reaction (Eq. (6)) which is producing carbon monoxide and reached equilibrium at a higher temperature. Besides, the composition of carbon monoxide for torrefied PMF is higher than raw PMF. This is due to the increment of the C content in the feedstock from 45.2% to 53.7% as shown in Table 1 which was used in both reactions. Meanwhile, the increment of the gasification temperature promoted the composition of hydrogen for both raw and torrefied PMF which initiated from the endothermic methane steam reforming (Eqs. (7) and (8)) and dry reforming reactions (Eq. (9)) (Lahijani & Zainal 2011).

$$C + H_2O \leftrightarrow CO + H_2 \quad (5)$$
$$\Delta H^0 = +131.4 \text{ kJ/mol}$$

$$C + CO_2 \leftrightarrow 2CO \quad (6)$$
$$\Delta H^0 = +176.6 \text{ kJ/mol}$$

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad (7)$$
$$\Delta H^0 = +206 \text{ kJ/mol}$$

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2 \quad (8)$$
$$\Delta H^0 = +165 \text{ kJ/mol}$$

$$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2 \quad (9)$$
$$\Delta H^0 = +247 \text{ kJ/mol}$$

Consumption of methane in these three reactions (Eqs. (7) to (9)) contributes

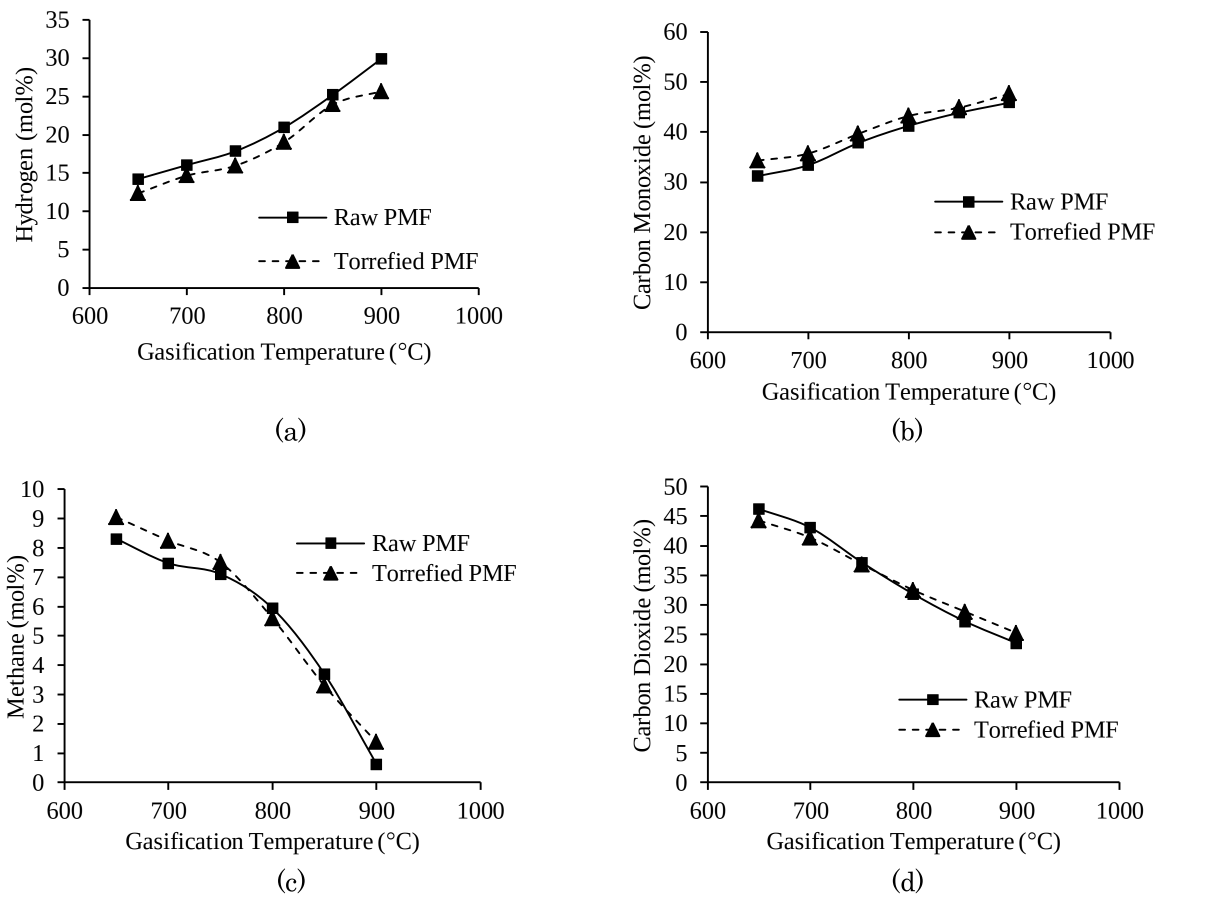

Fig. 3: The composition of (a) hydrogen, (b) carbon monoxide, (c) methane and (d) carbon dioxide for raw and torrefied PMF at different gasification temperature

to the reduction of the methane composition from 8.31 mol% to 0.63 mol% for raw PMF and 9.05 mol% to 1.38 mol% for torrefied PMF. In addition, the reduction of carbon dioxide for both raw and torrefied PMF is due to the consumption of carbon dioxide in dry reforming reaction and Boudouard reaction.

Meanwhile, the torrefied PMF produces lesser amount of hydrogen, carbon dioxide and methane compare to the raw due to the torrefaction process that reduces the volatile matter from 69.04% to 59.58% which contributing to the lower reactivity in gasification applications (Bach et al. 2019).

Based on synthesis gas composition, it shows that the torrefied PMF produces higher carbon monoxide compare to raw PMF. On the contrary, higher hydrogen gas is obtained by using raw PMF. Meanwhile, the amount of methane and carbon dioxide are relatively similar for both feedstocks which in accordance with the finding from Kwapinska et al. (2015).

Effect of Gasification Temperature on Gasification Performance

Fig. 4 shows the synthesis gas yield, LHV, CGE and CC for both raw and torrefied PMF which represents the efficiency of bubbling fluidized bed gasifier. The synthesis gas yields are increased for raw and torrefied PMF with the increasing of gasification temperature. Due to the torrefaction process, carbon content is increased which contributes to more production of synthesis gas.

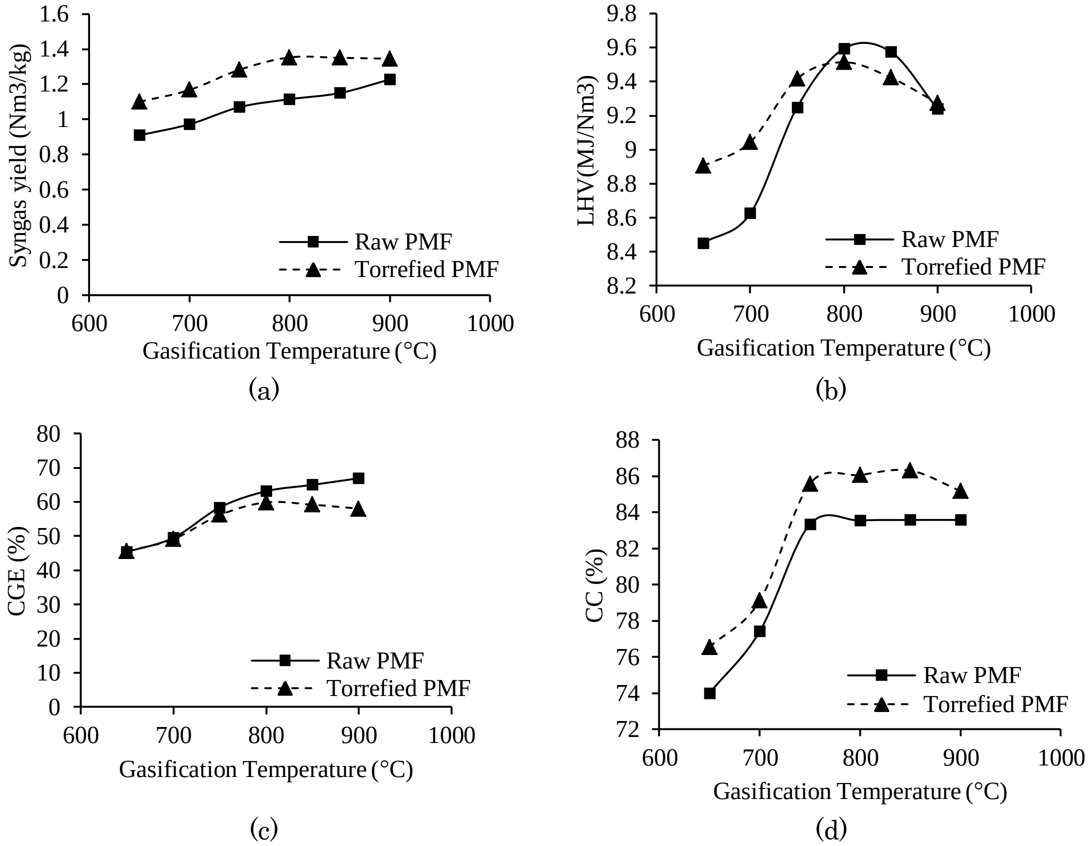

Fig. 4: The (a) synthesis gas yield, (b) lower heating value, (c) cold gas efficiency and (d) carbon conversion for raw and torrefied PMF

The LHV is increased from 8.45 to 9.59 MJ/Nm^3 and 8.90 to 9.51 MJ/Nm^3 for raw and torrefied PMF respectively from temperature 650 to 800°C due to the composition of hydrogen, carbon monoxide and methane as shown in Eq.(2). However, the LHV started to decrease at temperature 800 to 900°C because of the slower volatile reaction phase and the char phase started to begin (Li & Chen 2018). At higher temperatures, the evolutions of hydrogen and carbon monoxide gases from gasification of both feedstocks are enhanced which contributes to the increment of LHV. However raw PMF shows slightly better LHV compare to torrefied PMF. This is due to great amount of hydrogen production using raw PMF compare to torrefied PMF which directly produce slightly higher LHV as indicated in Eq. (2).

Meanwhile, the CGE is promoted from 45% to 67% for raw PMF and 45% to 58% for torrefied PMF. CGE is an indication of the chemical energy of the produced gas (Xiao et al. 2006). The increasing in CGE is due to the promotion of synthesis gas yield and LHV which is based on Eq.(3). However, the torrefied PMF has lower CGE compared to the raw PMF. The HHV of the feedstock is increased from 16.94 to 21.49 MJ/kg as results from the torrefaction process thus ultimately decrease the CGE.

Carbon conversion (CC) was calculated using Eq. (4) which is depending on the composition of carbon in biomass feedstock. Initially the CC is increased for both feedstocks but then remains steady when the gasification is operated beyond 800°C. In overall torrefied PMF shows better CC compare to raw PMF. As shown in Table 1, the C content in the PMF had improved from 45.2% to 53.7% after the torrefaction process. This is due to the higher C content in torrefied PMF, hence more C will be converted to carbon monoxide, carbon dioxide and methane which explains why CC for torrefied PMF is higher compared to raw PMF (Villetta et al. 2017). Based on this work, it was found that the gasification of torrefied PMF produces lower hydrogen content and thus may not suitable for production of hydrogen-rich synthesis gas. However, the torrefied PMF used in this work is able to produce higher synthesis gas yield and carbon conversion which highlighting the advantages of using torrefied biomass.

CONCLUSION

An experimental study on raw and torrefied palm mesocarp fibre gasification using bubbling fluidized bed gasifier were conducted by varying gasification temperature from 650 to 900°C. The PMF was torrefied at 300°C before performing the gasification process which improved the properties of the PMF in terms of proximate and ultimate analysis. In order to study the gasification performance, the synthesis gas yield, LHV, CGE and CC were calculated and analyzed based on the result of the synthesis gas production. The results showed that hydrogen and carbon monoxide gases produced were increased when the temperature is increased. Meanwhile, carbon dioxide and methane were decreased for both raw and torrefied PMF. In terms of the gasification performance, the synthesis gas yield obtained were increased for both raw and torrefied PMF. Besides, the LHV of raw and torrefied PMF also increased in the increasing of temperature. However, the LHV of torrefied PMF is slightly higher compared to raw PMF which is about 8.4 MJ/Nm^3. Furthermore, the CGE of the raw PMF showed higher than torrefied PMF. Meanwhile, the CC of the torrefied PMF is enhanced by the increasing temperature which is from 76% to 85% due to the higher carbon content compared to raw PMF. Even though the difference of the result between raw and torrefied was small, the synthesis gas produced are in high quality which has higher heating value, less moisture content and able to be utilized as direct fuel. Besides, temperature 800°C was the optimum temperature for PMF gasification as it obtained higher LHV at that temperature.

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