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Effects of Gasification Temperature and Equivalence Ratio on Gasification Performance and Tar Generation of Air Fluidized Bed Gasification Using Raw and Torrefied Empty Fruit Bunch

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This paper presents gasification performance study and tar generation at different gasification temperature and equivalence ratio using air fluidized bed gasification process. Empty fruit bunch (EFB) is selected as feedstock where two types of EFB were used which are raw EFB and EFB undergo torrefaction process as pretreatment. Experimental results show the synthesis gas yield, lower heating value (LHV), cold gas efficiency (CGE) and tar generation are steadily increased for both feedstock when gasification temperature is increased from 700 to 900°C. When ER is increased from 0.26 to 0.33 at fixed gasification temperature of 900°C, all gasification performances except LHV show an increment trend. Torrefied EFB shows superior performance in terms of producing more synthesis gas and better LHV compared to raw EFB. However, tar generated from torrefied EFB is higher than raw EFB. Based on tar component analysis, it has been found that 7 tar components are detected where all of tar components are classified as tertiary polycyclic aromatic hydrocarbons (PAHs) group for both feedstocks. Based on tar analysis, naphthalene is the most produced tar components obtained from gasification of raw and torrefied EFB.

1. Introduction

Nowadays biomass gasification provides feasible methods for converting biomass into energy related product based on thermochemical conversion principle. The application of biomass gasification is preferable because its ability to reduce the greenhouse gases (GHG) emissions and to overcome biomass waste disposal problem. Usually, biomass gasification is performed at high temperatures between 600 and 1000°C using air, steam, oxygen, carbon dioxide or combination air-steam as gasifying agents. From gasification process, the biomass is converted into product gas known as synthesis gas which consists of hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and traces of methane (Safarian et al., 2019). The produced synthesis gas after purification processing is then can be utilized in energy related application such as combined heat and power production. However, during gasification process other by-products are also generated such as particulates, alkali metals, chlorine, sulfur and tars (Rakesh and Dasappa, 2018; Horvat et al., 2016). Among these by-products, removal of tar is one of the challenges in biomass gasification process. During gasification process, synthesis gas is produced together with different tar components. These tar components are black in nature and considered as sticky material which may condenses at reduced temperature and form sticky deposits by quenching downstream (Rios et al., 2018). Thus, contributing to the blocking and fouling process equipment such as engines and turbines (Zhou et al., 2018; Horvat et al., 2016).
Due to the growing interest in alternative renewable energy sources, many studies and experimental work on biomass gasification have been performed which mostly focusing on the effects of operating condition such as gasification temperature and equivalence ratio (ER) on the synthesis gas production and gasification performance (Halim et al., 2019; Safarian et al., 2019). Other than operating condition, the effect of torrefaction on feedstock is widely investigated by researcher for optimizing biomass gasification process. For

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example, raw and torrefied spruce have been used as feedstock for steam dual fluidized bed and synthesis gas produced have been analyzed at different gasification temperature and steam to biomass ratio (Bach et al., 2019). Effect of gasification temperature on synthesis gas production and gasification performance such as yield, lower heating value (LHV), cold gas efficiency (CGE) and carbon conversion has been studied using raw and torrefied palm mesocarp fibre (Halim et al., 2019). Simulation study of two-stage gasification model using Aspen Plus has been performed for comparing raw and torrefied wood as feedstocks (Tapasvi et al., 2015). Gasification performances of raw and torrefied bamboo in a downdraft fixed bed gasifier has been performed using thermodynamic analysis (Kuo et al., 2014). Although significant progress has been made on the biomass gasification process but only limited work can be found on tar generation study from gasification process. The effect of torrefaction on spruce and ash woods as feedstocks have been investigated in oxygen-steam blown gasification (Tsalidis et al., 2017). The feedstocks were gasified at 850°C with difference ER and steam to biomass ratio where the synthesis gas species, tar species content and classes have been evaluated. It has been found out that majority of tars are belonged in Classes 3 and 4 for both feedstocks. Formation of tars from entrained-flow gasification of beech, biogenic residuals, municipal and green wastes have been studied and most of tar compounds are mainly light polycyclic aromatic hydrocarbons (Briesemeister et al. 2017). The effect of temperature, equivalence ratio and biomass composition on tar yields have been performed by Horvat et al. (2016). Two types of feedstock have been used which are raw and torrefied *Mischantus x giganteus* where their study indicates the tar yields depend significantly on biomass composition.

Therefore, the objective of this work is to study the effects of gasification temperature and ER on gasification performance and tar generation using raw and torrefied empty fruit bunch (EFB). The selection of EFB is because it is one of energy potential sources identified by National Biomass Strategy (NBS2020) in Malaysia for producing target energy of 2080 MW (National Biomass Strategy, 2013). In this work raw and torrefied EFB is used as feedstock for fluidized bed gasification process using air as gasifying agent. Based on both feedstock, tar generation as well as gasification performance in terms of synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE) are compared and evaluated. Tar component generated from gasification of raw and torrefied EFB is characterized and analyzed.

2. Materials and Methods

2.1 Sample preparation

The samples used in this study were raw Empty Fruit Bunch (EFB) and torrefied EFB. The raw EFB were obtained from Lepar Hilir Palm Oil Mill, Kuantan, Pahang. Initially, the biomass sample were dried using an oven for about 4 hours at 105°C to reduce the moisture content and to avoid biomass degradation. Then, the samples were grinded and sieved into particle size of 0.5 – 1.0 mm. Subsequently, the torrefied EFB has been obtained based on torrefaction experiment of raw EFB at temperature of 300°C with a residence time of 30 minutes as described in previous work of Rashid et al. (2017). The properties of proximate analysis, ultimate analysis, high heating value (HHV) and chemical composition for raw and torrefied EFB are shown in Table 1.

Table 1: Properties of raw and torrefied EFB (Rashid et al., 2017)

Properties	Raw EFB	Torrefied EFB
Proximate analysis (wt.%)		
Moisture content	15.77	4.63
Volatile matter	67.01	48.44
Ash	3.85	7.70
Fixed carbon	13.37	39.23
Ultimate analysis (wt.%)		
C	43.53	54.63
H	7.20	5.63
N	1.73	6.37
S	0.46	0.21
O (by difference)	47.09	36.04
High heating value (HHV) (MJ/kg)	15.49	19.60
Chemical composition (dry and ash free basis) (wt. %)		
Hemicellulose	30.82	12.33
Cellulose	41.67	37.28
Lignin	21.55	44.18
Extractives	5.96	6.21

2.2 Gasification Experimental Setup

Figure 1 shows fluidized bed gasification experimental setup and similar gasification procedure as described in Jamin et al. (2020) is used in this work. The feedstock was fed to the reactor using screw conveyor at a rate in the range of 0.25-0.4 kg/h. The gasifying agent used is air where it is fed into reactor using blower where the air flow rate was varied from 0.3 to 0.7 m^3/h. An electrical heater is used to heat the fluidized bed reactor to the desired gasification temperature. In this work, fluidized bed gasification is operated at three different temperatures (700, 800, 900°C) and three different ER (0.26, 0.3, 0.33). ER is used for studying the effects of gasifying agent. ER is defined as the ratio between amount of oxygen fed into the gasifier and stoichiometric amount of oxygen necessary for complete oxidation (Motta et al., 2018). After biomass is gasified at specified operating condition, the dry and clean gas was then collected using gas sampling bag and analysed using an Agilent 6890N gas chromatograph with mass spectroscopy (GC–MS). For tar component analysis, the temperature program in GC-MS was initiated at 30°C for 5 min before it is heating to temperature of 300°C. The standard gas mixture was used as calibration for GC–MS and nitrogen gas was used as the carrier gas for the analysis. For tar collection, the impinger inside dry ice trap is rinsed with isopropanol solvent and the tar sample in liquid form is then collected using flask. Subsequently it is heated to temperature between 80 and 90°C for 40 to 60 min using rotary evaporator in order to remove the solvent. Finally, the amount of tar is weighed for determining tar generation.

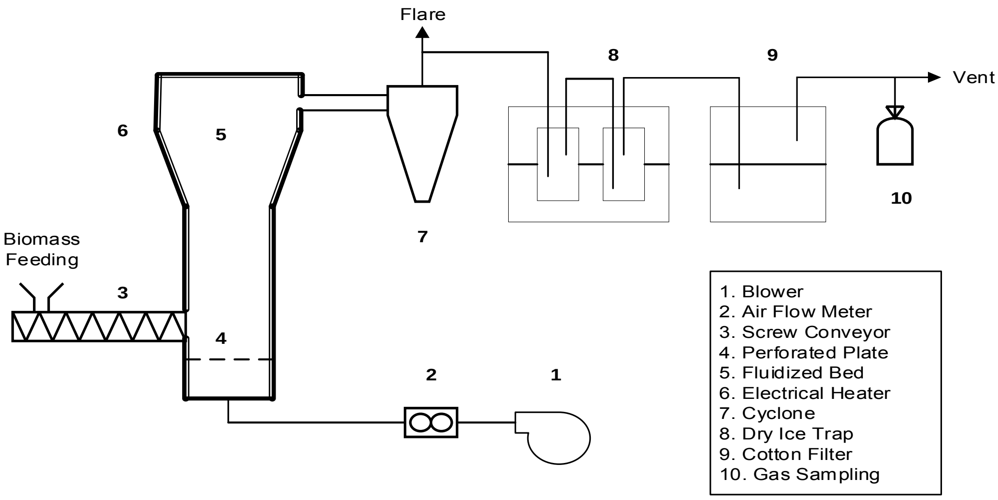

Figure 1: Schematic diagram of fluidized bed gasification (Jamin et al., 2020)

2.3 Gasification Performance

The gasification performances are measured based on synthesis gas yield, lower heating value (LHV) and cold gas efficiency (CGE). Syngas yield (Y_{gas}) as shown in Eq(1) is defined based on ratio between the volume of syngas at standard conditions (V_{gas}) and the mass flow rate of biomass feed ($\dot{m}_{bio}$) (Motta et al., 2018).

$$Y_{gas} = \frac{V_{gas}}{\dot{m}_{bio}} \quad (1)$$

LHV is the indicator for energy contents for syngas is calculated using Eq(2).

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

Where x is represents the mole fraction of the synthesis gas components. For measuring the chemical energy of product gas to the chemical energy of feedstock, the CGE is used as shown in Eq(3).

$$CGE = \frac{LHV_{gas} \times Y_{gas}}{HHV_{bio}} \times 100\% \quad (3)$$

Where HHV_{bio} is the HHV for feedstock as shown in Table 1.

3. Results and Discussions

3.1 Effect of Gasification Temperature and Equivalence Ratio on the Gasification Performance and Tar Generation

Figure 2 shows gasification performance and tar generation at different gasification temperature and fixed ER at 0.3. It can be observed that torrefied EFB produces higher synthesis gas yield and LHV compare to raw EFB. As shown in Table 1, the amount of carbon content for torrefied EFB is higher than raw EFB. Thus more carbon monoxide and hydrogen gases are produced from endothermic water-gas ($C + H_2O \leftrightarrow CO + H_2$) and Boudouard reactions ($C + CO_2 \leftrightarrow 2CO$) which explains torrefied EFB produces better synthesis gas yield and LHV. On the contrary CGE obtained from gasification of raw EFB is better than torrefied EFB since HHV for torrefied EFB is higher than raw EFB which lowering the CGE value as calculated in Eq(3). More tar generation from gasification of torrefied EFB is obtained compare to raw EFB at all investigated gasification temperature. Torrefied EFB produces more tar generation is due to the amount of lignin content in torrefied EFB is higher compare to the raw EFB as shown in Table 1. This finding is in accordance with Horvat et al. (2016) which suggests lignocellulosic composition of feedstock contributing to the tar evolution during gasification process.

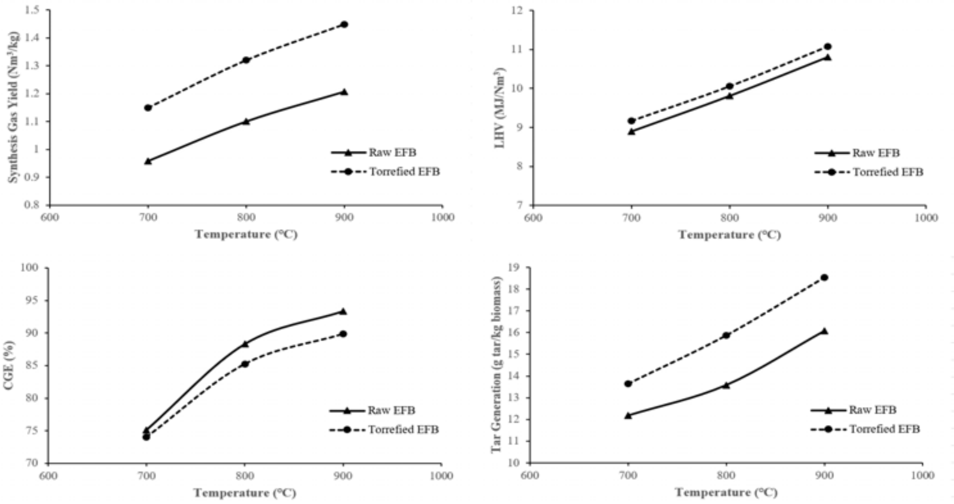

Figure 2: Effect of gasification temperature on gasification performance and tar generation

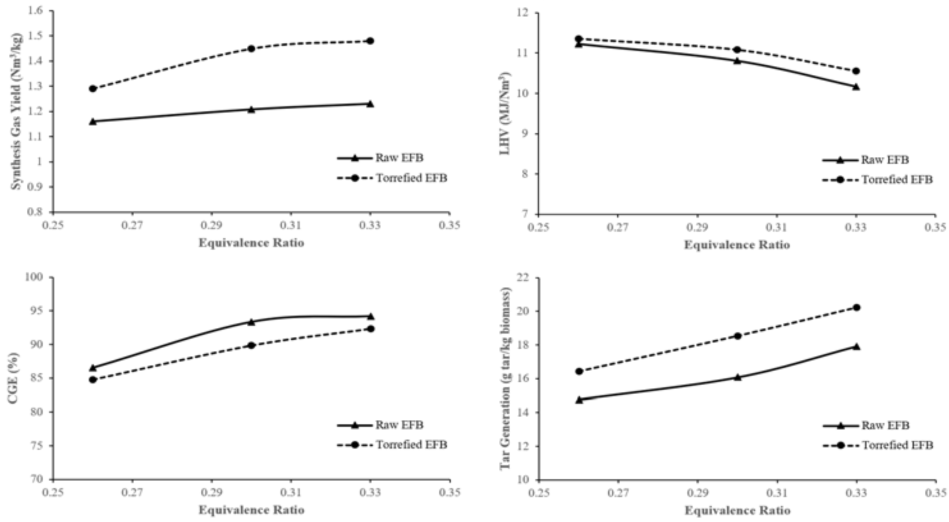

Figure 3: Effect of equivalence ratio on gasification performance and tar generation

Figure 3 shows the effect of ER on gasification performances for both raw and torrefied EFB at fixed gasification temperature of 900°C. As ER is increased, increasing trends were obtained for synthesis gas yield and CGE for both feedstocks. The synthesis gas yield is increased due to the oxidations of hydrogen, carbon monoxide and methane which produce more carbon dioxide and steam. The increment of synthesis gas yield directly contributes to steady increment of CGE. Torrefied EFB produces higher synthesis gas yield compared to raw EFB due to more carbon monoxide and carbon dioxide gases production which contributing to better LHV. However raw EFB shows better CGE compare to torrefied EFB. Due to the torrefaction process, physical and chemical structures of EFB are changed which results into higher fixed carbon and carbon content. Thus torrefied EFB becomes more difficult to convert into product gas due to the slow char gasification reactions (Ku et al., 2017). As consequence torrefied EFB requires longer conversion process compare to raw EFB which explains lower CGE is obtained for torrefied EFB. In terms of tar generation, torrefied EFB produces more tar compare to raw EFB. Initially torrefied EFB produces 16.43 g tar/kg biomass and is increased to 20.23 g tar/kg biomass when ER is increased from 0.26 to 0.33. As ER is increased, more air is supplied into the system where more hydrogen and carbon monoxide compositions are produced which contributing to the increment of synthesis gas yield. However tar reforming by oxidation may be limited during gasification process since the tar needs to be competed with more reactive gas compositions (Rios et al., 2018). In addition, torrefied EFB produces more tar compared to raw EFB due to low moisture content which reducing the amount of tar converted into synthesis gas composition due to tar steam reforming reaction (Horvat et al., 2016).

3.2 Analysis of Tar Components

The tar generated from raw and torrefied EFB gasification is measured and characterized using GC-MS in order to determine components available in tar by-product. Normally tar generated from gasification may consists of acid, aldehyde and ketone functional groups since EFB is part of ligno-cellulosic biomass. The tar components are identified based on GC-MS retention time and classification according to Milne et al. (1998). The list of detectable tar component obtained from raw and torrefied EFB gasification at temperature of 900°C and ER of 0.33 is shown in Table 2. In overall 7 components represent most of the observable peak from GC-MS spectrum and are identified as tertiary-polycyclic aromatic hydrocarbons (PAHs) tar. No primary or secondary tar is detected from raw and torrefied EFB gasification indicating that the primary and secondary tar may quickly decompose during gasification. Tar concentration measured using standard tar sampling method is shown in Figure 4. It has been found that naphthalene represents the most dominant tar concentration for both feedstocks.

Table 2: Tar component analysis

Tar Components	GC-MS Retention Time (min)	Tar Group
Naphthalene	16.75	Tertiary-PAH
Acenaphtylene	24.67	Tertiary-PAH
Fluorene	28.55	Tertiary-PAH
Phenanthrene	32.85	Tertiary-PAH
Anthracene	33.12	Tertiary-PAH
Pyrene	36.84	Tertiary-PAH
Benzofluoranthene	46.65	Tertiary-PAH

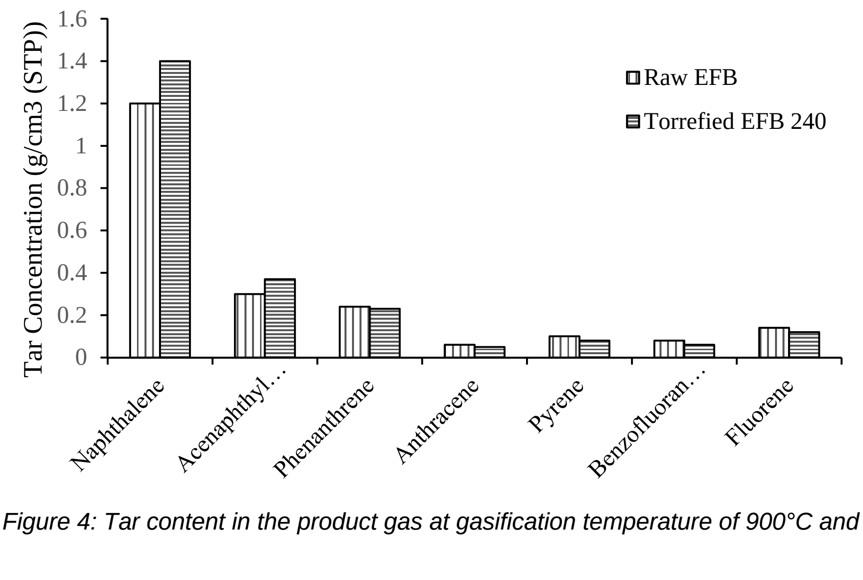

Figure 4: Tar content in the product gas at gasification temperature of 900°C and equivalence ratio of 0.3

4. Conclusions

Air fluidized bed gasification has been used for analysing gasification performance and tar generation using raw and torrefied EFB. Gasification of raw and torrefied EFB has been conducted at different gasification temperature between 700 and 900°C and different ER between 0.26 and 0.33 respectively. Based on experimental results, it has been found that torrefied EFB produces better synthesis gas yield and LHV at all investigated operating conditions. On the contrary higher CGE is obtained during gasification using raw EFB. Although high synthesis gas yield and LHV is obtained but more tar generation is produced using torrefied EFB compared to raw EFB. High tar generation is attributed mainly to the higher lignin content and low moisture content of the torrefied EFB. Based on tar components analysis, all 7 tar components are detected and classified as tertiary polyaromatic hydrocarbons group. Meanwhile, naphthalene is the most abundant species found in tar content in the product gas for both feedstocks.

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