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Influences of Gasification Temperature and Equivalence Ratio on Fluidized Bed Gasification of Raw and Torrefied Wood Wastes

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Gasification of raw and torrefied wood wastes from municipal solid waste (MSW) were investigated in fluidized bed gasifier using air as gasifying agent. The effect of gasification temperature from 600 and 1000°C and the effect of equivalence ratio (ER) from 0.21 to 0.37 on syngas composition and gasification performance were studied. Based on gasification experimental results, the suitable operating condition of fluidized bed gasification is found at gasification temperature of 1000°C and ER of 0.21. At this condition highest high heating value (HHV) of 5.78 and 5.71 MJ/Nm^3, syngas yield of 2.77 and 2.57 Nm^3/hr, cold gas efficiency (CGE) of 70.66% and 76.24%, carbon conversion (CC) of 77.17% and 77.83% were obtained for torrefied and raw wood wastes respectively. In terms of feedstocks, torrefied wood waste produces higher syngas yield and HHV compare to raw wood waste due to the presence more carbon content in the torrefied wood waste which ultimately produces more hydrogen and carbon dioxide gases. However higher CGE and CC are obtained for raw wood waste compare to torrefied wood waste indicating torrefied wood waste needs a longer conversion process compared to raw wood waste.

1. Introduction

In Malaysia, the increase in municipal solid waste (MSW) generation nowadays is due to population growth, urbanization and industries. Their impact on the environment and public health has been the biggest concern nowadays (Fazeli et al., 2016). In addition, the depletion of fossil fuels over the years has raised awareness and accelerated more research on the conversion of MSW into energy. Waste-to-energy (WtE) has been portrayed as one of the strategies in MSW management and utilization for energy generation to decrease the dependency on natural gas and fossil fuel. One of the MSW components in Malaysia is wood waste where it has been collected from municipal park, landscaping, garden and yard. Approximately around 5.41 tonne/day of wood waste has been collected and dumped to landfill (Fazeli et al., 2016).

In order to convert wood waste into energy, gasification process can be used where wood waste can be converted into useful gases using air, oxygen, steam, carbon dioxide or hydrogen as gasifying agent at high temperature (>600°C) (Motta et al., 2018; Muslim et al., 2017). The gaseous mixture produced after gasification is called syngas, which contains hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and traces of methane (CH_4). Usually gasification process can be conducted into three widely used gasifiers such as fixed bed, fluidized bed and entrained flow. Among these gasifiers, fluidized bed is the most feasible gasifier due to the good temperature distribution, high rates of heat and mass transfers, and good flexibility in feedstocks (Ku et al., 2017). Thus, many biomass gasification studies have been conducted using fluidized bed gasifier (Motta et al., 2018; Lahijani and Zainal, 2011). However most of the fluidized bed gasification works found in literature use raw biomass as feedstock where normally it contains high moisture and oxygen contents, low energy density, low bulk density and utilization limitation (Ku et al., 2017). In order to improve properties of raw feedstock, a suitable pretreatment process is necessary. Among many pretreatment approaches, torrefaction can be used to upgrade the properties of feedstock. Torrefaction is thermal degradation technique which involves the heating of feedstock to moderate temperatures in the range of 200

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and 300°C for 15 to 60 min of residence time under inert condition (Wahid et al., 2017). Through torrefaction process, the properties of feedstocks will be upgraded in terms of higher heating value, higher fixed carbon and lower moisture content. However, only limited publications can be found on gasification employing torrefied biomass as feedstock. Ku et al. (2017) developed computational fluid dynamics-discrete element method (CFD-DEM) to compare gasification performances in terms of yield and carbon conversion between raw and torrefied grassy biomass. Kuo et al. (2014) investigated the fixed bed gasification performances of raw and torrefied biomass using thermodynamic analysis. Kosov and Zaichenko (2016) employed two stages fixed bed gasification for studying the syngas production from raw and torrefied wood. However most of the works are used either fixed bed or model-based analysis and the study involves fluidized bed for torrefied product has not yet studied in terms of the suitable operating temperature and equivalence ratio (ER) for producing best gasification performance.

Therefore the objective of this work is to study the effects of gasification temperature and equivalence ratio (ER) on the production of syngas using fluidized bed gasifier. Two types of feedstocks are considered which are raw and torrefied wood wastes at 300 ºC. The effects of gasification temperature and ER on syngas composition are investigated by varying the gasification temperature between 600 and 1000°C and by manipulating ER in the range of 0.21 to 0.37. In addition, gasification performances are evaluated in terms of syngas yield, high heating value (HHV), cold gas efficiency (CGE) and carbon conversion (CC) for both raw and torrefied wood wastes.

2. Materials and methods

2.1 Wood waste preparation

The feedstocks used in this work were wood waste and torrefied wood waste. The wood waste was obtained from Sungai Ikan Landfill Terengganu in Malaysia. The wood waste was dried in the oven at temperature of 105°C for 24 hours in order to reduce the moisture content below 15%. This specification is used due to the fact that higher moisture content is not preferable for fluidized bed gasification since it reduces the bed temperature which lowering the gasification efficiency (Motta et al., 2018). After drying process, the feedstocks undergo grinding and sieving processes in order to obtain particle sizes between 0.5 and 1 mm. The samples are stored in air-tight containers until the experiments were performed. The torrefied wood waste has been obtained based on torrefaction experiment at temperature of 300°C with residence time of 30 minutes. Details of the torrefaction experiment can be found in Samad et al. (2017). The properties of proximate analysis, ultimate analysis and high heating value (HHV) for raw and torrefied wood wastes are shown in Table 1.

Table 1: Proximate analysis, ultimate analysis and HHV of raw and torrefied wood wastes

Properties	Raw Wood Waste	Torrefied Wood Waste
Proximate analysis (wt.%)		
Moisture content	10.15	2.71
Volatile matter	66.08	41.56
Ash	6.62	16.26
Fixed carbon	17.15	39.47
Ultimate analysis (wt.%)		
C	52.75	60.03
H	6.87	5.77
N	1.88	2.93
S	0.16	0.23
O (by difference)	38.34	31.04
High heating value (HHV) (MJ/kg)	19.27	28.66

2.2 Gasification process

The gasification experimental set-up used in this work is shown in Figure 1. The fluidized bed reactor was constructed from stainless steel. The height of fluidized bed reactor is 650 mm with internal diameter of 120 mm. The feedstock was fed to the reactor using screw conveyor at a rate in the range of 0.3-0.4 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. Five different gasification temperatures between 600 and 1000°C were selected for investigating the effects of gasification temperature on syngas composition and gasification performance. Equivalence ratio (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). Four different ER are chosen which are 0.21, 0.26, 0.32 and 0.37. The produced gas exited at the top of reactor and fed to cyclone for separating char and ash. The gas exited the cyclone and underwent a cleaning and drying process using dry ice trap and cotton filter. The dry and clean gas was then collected using a gas sampling bag and analyzed using Agilent 6890N gas chromatography with thermal conductivity detector (GC-TCD). Standard gas mixture was used as calibration for GC-TCD and nitrogen gas was used as the carrier gas for the analysis. In this work, the experiment was repeated three times in order to enhance data reliability and the average syngas data was presented.

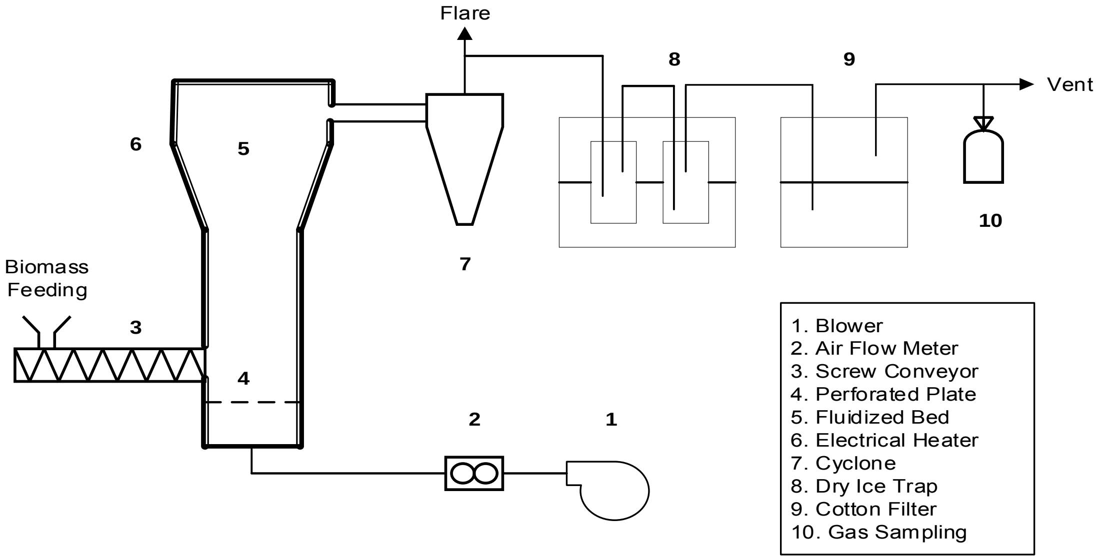

Figure 1: Schematic diagram of fluidized bed gasification

2.3 Gasification performances

The gasification performances are measured based on syngas yield, high heating value (HHV), cold gas efficiency (CGE) and carbon conversion (CC). 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).

$$Y_{gas} = \frac{V_{gas}}{\dot{m}_{bio}} \tag{1}$$

The HHV for syngas is calculated using Eq(2) (Xiao et al., 2006).

$$HHV_{gas} = (H_2\% \times 30.52 + CO\% \times 30.18 + CH_4\% \times 95) \times 4.1868 \tag{2}$$

Where $H_2\%$, $CO\%$ and $CH_4\%$ are the volumetric percentages of hydrogen, carbon monoxide and methane in the gas. For measuring the chemical energy of product gas to the chemical energy of feedstock, the CGE is used as shown in Eq(3) (Xiao et al., 2006).

$$CGE = \frac{HHV_{gas} \times Y_{gas}}{HHV_{bio}} \times 100\% \tag{3}$$

Where HHV_{bio} is the HHV for feedstock as shown in Table 1. The carbon conversion (CC) is calculated using Eq(4) (Xiao et al., 2006).

$$CC = \frac{Y_{gas}(CO\% + CH_4\% + CO_2\%) \times 12}{22.4 \times C\%} \times 100\% \tag{4}$$

Where $C\%$ is the mass percentage of carbon in the feedstock based on ultimate analysis in Table 1.

3. Results and discussions

3.1 Effect of gasification temperature

The effect of gasification temperature at fixed ER of 0.32 on syngas composition for both raw and torrefied wood wastes are shown in Figure 2. By increasing gasification temperature from 600 to 1000°C, the hydrogen gas composition is increased from 6.33 to 17.22 vol% for raw wood waste and from 6.17 to 16.43 vol% for torrefied wood waste. Meanwhile carbon monoxide gas composition for both feedstocks also show improvement from 11.86 to 14.21 vol% (raw wood waste) and from 12.26 to 15.05 vol% (torrefied wood waste) as the gasification temperature is increased. The increment of both hydrogen and carbon monoxide gases are due to the endothermic water-gas ($C + H_2O \leftrightarrow CO + H_2$) and Boudouard reactions ($C + CO_2 \leftrightarrow 2CO$) (Motta et al., 2018; Lahijani and Zainal, 2011). As the temperature is increased, both reactions become dominant which promotes more production of hydrogen and carbon monoxide gases. Meanwhile carbon dioxide composition shows an increment trends at low temperature but steadily decrease when gasification is conducted beyond 800°C for both feedstock. Initially more carbon dioxide gas is produced due to the water-gas shift reaction ($CO + H_2O \leftrightarrow CO_2 + H_2$) but the generated carbon dioxide gas is then consumed by Boudouard reaction at higher temperature (>800°C) to produce more carbon monoxide gas. Methane gas composition show steady trend at all temperatures for both feedstocks. Usually methane gas is produced due to the cracking of tar but it is subsequently consumed through methane dry reforming reaction ($CH4 + CO_2 \leftrightarrow 2CO + 2H_2$) which explain the constant level of methane gas composition at all temperatures for both feedstock. For comparison in terms of feedstock, raw wood waste produces more hydrogen gas compare to torrefied wood waste. This is due to the hydrogen content of raw wood waste (6.87%) is higher than torrefied wood waste (5.77%). Furthermore the raw wood waste has 10.25% of moisture content compare to only 2.71% of moisture content in the torrefied wood waste. This contributes to more production of hydrogen gas due to endothermic water-gas and water-gas shift reactions for raw wood waste. However torrefied wood waste shows higher production of carbon monoxide than raw wood waste due to the presence of higher carbon content for torrefied wood waste (60.03%) compare to only 52.75% carbon content in raw wood waste. The high amount of carbon content will promote endothermic water-gas and Boudouard reactions which contributing to more carbon monoxide production.

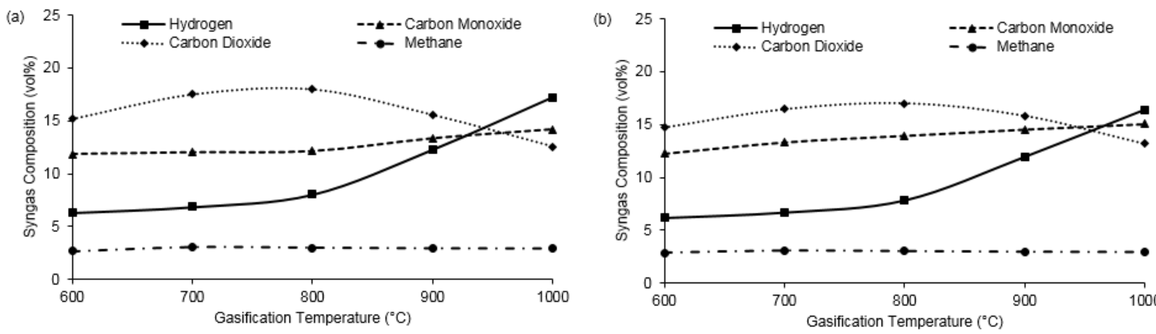

Figure 2: Effect of gasification temperature on syngas compositions for (a) raw wood waste (b) torrefied wood waste

The gasification performances using raw and torrefied wood wastes are investigated in terms of syngas yield, HHV, CGE and CC at different gasification temperature as shown in Figure 3. Increment of gasification temperature from 600 to 1000°C improves the syngas yield from 2.5 to 2.93 Nm^3/hr for raw wood waste and 2.81 to 3.14 Nm^3/hr for torrefied wood waste due to the more dominant endothermic water-gas ($C + H_2O \leftrightarrow CO + H_2$) and Boudouard reactions ($C + CO_2 \leftrightarrow 2CO$) at higher gasification temperature (Motta et al., 2018; Lahijani and Zainal, 2011). The HHV for both feedstocks also show increment trends and reach the highest HHV at 5.15 MJ/Nm^3 for raw wood waste and 5.17 MJ/Nm^3 for torrefied wood waste at gasification temperature of 1000°C. At high temperature, more carbon monoxide and hydrogen gases are produced which in turn results in an increase in HHV of both feedstocks. The increment of syngas yield and HHV are ultimately improve CGE for both feedstocks where approximately 78.47% and 71.66% of CGE were achieved at gasification temperature of 1000°C for raw and torrefied wood waste. In terms of CC, raw wood waste shows an increment from 75.38 to 88.42% which is slightly better compare to torrefied wood waste which indicates increment from 74.74 to 87.45%. This is due to the fact that the torrefied wood waste has a smaller volatile matter (41.56% vs 66.08%) and larger fixed carbon (39.47% vs 17.15%) compare to raw wood waste which contributing to low CC (Ku et al., 2017).

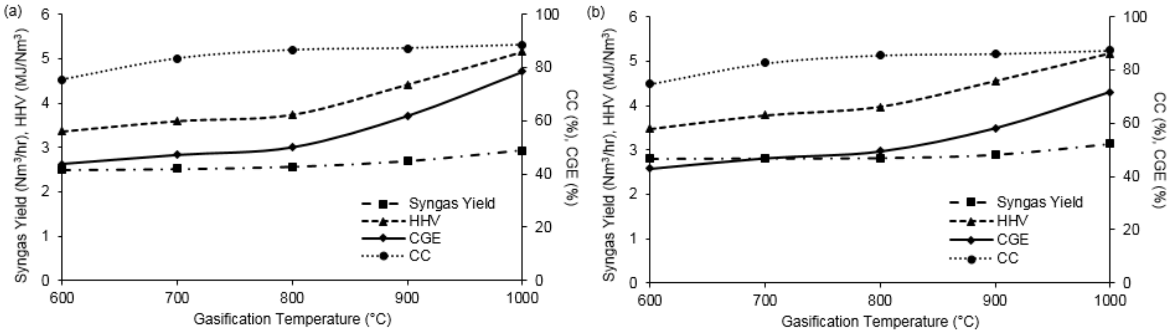

Figure 3: Effect of gasification temperature on gasification performances for (a) raw wood waste (b) torrefied wood waste

3.2 Effect of equivalence ratio (ER)

The effect of equivalence ratio (ER) on the syngas composition was conducted by varying ER in the range of 0.21 to 0.37 at fixed gasification temperature of 1000°C. Figure 4 shows the amounts of hydrogen and carbon monoxide gases produced are decreased when the ER is increased from 0.21 to 0.37. On the contrary, the increment of ER produces more carbon monoxide gas for both feedstocks. When ER is increased, more oxygen is fed to the fluidized bed gasifier which contributes to more oxidation of hydrogen ($H_2 + 0.5O_2 \leftrightarrow H_2O$) and carbon monoxide ($CO + 0.5O_2 \leftrightarrow CO_2$) gases. As a result more carbon dioxide gas is produced at the expense of hydrogen and carbon monoxide gases. Initially methane gas composition shows an increment trends when ER is increased from 0.21 to 0.26 but the amount of methane gas composition is decreasing when ER is increased beyond 0.26. This is due to the oxidation of methane ($CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$) where methane is reacted with oxygen from air flow rate to produce carbon dioxide and steam. In terms of feedstocks, torrefied wood waste produces lower hydrogen gas and higher carbon monoxide gas compare to raw wood waste. As mentioned earlier, the higher carbon content but low hydrogen content presence in the torrefied wood waste compare to the raw wood waste contributes to more carbon monoxide production and less hydrogen production for torrefied wood waste gasification.

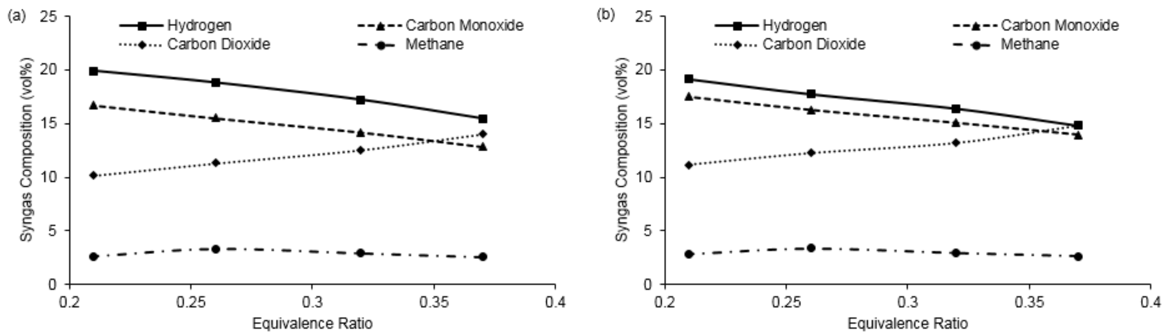

Figure 4: Effect of ER on syngas compositions for (a) raw wood waste (b) torrefied wood waste

Figure 5 shows the effect of ER on gasification performances for both raw and torrefied wood wastes. As the ER is increased, increasing trends were obtained for syngas yield, CGE and CC for both feedstocks. The syngas yield is increased due to the oxidations of hydrogen, carbon monoxide and methane which produce more carbon dioxide and steam. The increment of syngas yield directly contributes to steady increment of CGE. Maximum CC around 98% has been obtained for both feedstocks at ER of 0.37. More steam is produced due to the oxidation of hydrogen and methane which promotes the endothermic water-gas reaction ($C + H_2O \leftrightarrow CO + H_2$). However the maximum HHV is obtained at ER of 0.21 for both feedstocks. This indicates the highest amounts of hydrogen and carbon monoxide gases are produced at low ER. By increasing ER beyond 0.21, the HHV shows decrement trends due to the presence of more nitrogen gas from air flow rate. This contributes to more dilution of the producer gas by nitrogen which lowering the energy content of syngas (Lahijani and Zainal, 2011). For feedstocks comparison, torrefied wood waste produces higher syngas yield compare to raw wood waste due to more carbon monoxide and carbon dioxide gases production. This contributes to better HHV obtained for torrefied wood waste compare to raw wood waste. However raw wood waste shows better CGE and CC compare to torrefied wood waste. Due to the torrefaction process, physical and chemical structures of wood waste are changed which results into higher fixed carbon and carbon content. Thus torrefied wood waste becomes more difficult to convert into product gas due to the slow char gasification reactions (Ku et al., 2017). As consequence torrefied wood waste requires longer conversion process compare to raw wood waste which explains lower CGE and CC are obtained for torrefied wood waste.

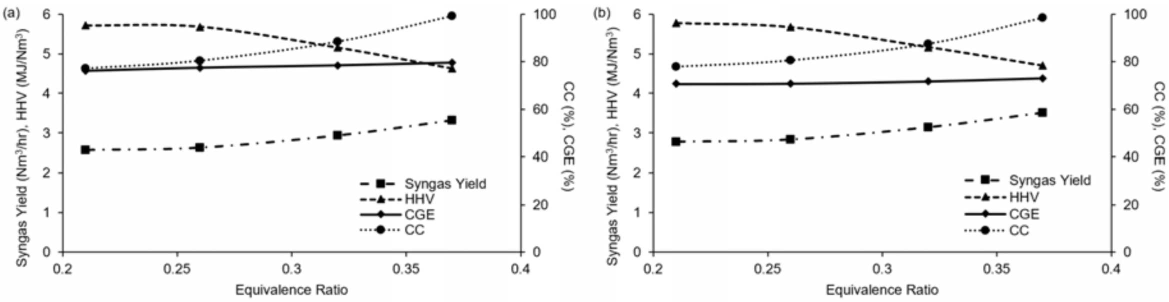

Figure 5: Effect of ER on gasification performances for (a) raw wood waste (b) torrefied wood waste

4. Conclusions

The gasification of raw and torrefied wood waste were performed at different gasification temperature and ER using air as gasifying agent. Based on the effect of gasification temperature, hydrogen and carbon monoxide gas compositions are increased for both feedstocks when the temperature is increased. However carbon dioxide gas composition shows opposite trends and methane gas composition remains steady at all temperatures for both feedstocks. As the gasification temperature is increased, the syngas yield, HHV, CGE and CC are also increased and reach highest value at gasification temperature of 1000°C. In terms of ER, carbon dioxide gas composition shows increment trend but hydrogen and carbon monoxide gases are decreased for both feedstocks when ER is increased. Similar increment trends are also observed for syngas yield, CGE and CC for both feedstocks. However the highest HHV is obtained when ER is conducted at 0.21 for both feedstocks. Thus, it was found that the suitable operating condition for both feedstocks is gasification temperature at 1000°C and ER at 0.21 for producing the best gasification performance in terms of HHV.

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