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Research Article

EQUILIBRIUM MODELING OF RAW AND TORREFIED *LEUCAENA* IN A DOWNDRAFT FIXED BED GASIFIER

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ABSTRACT:
The gasification performance of raw Leucaena, torrefied Leucaena at 200 °C (T200), and torrefied Leucaena at 275 °C (T275) in a downdraft fixed bed gasifier are performed based on thermodynamic equilibrium model using STANJAN (v.3.93L). The effects of torrefaction temperature and gasification temperature on syngas contents (H_2, CO, CH_4), syngas heating value, cold gas efficiency (CGE) and carbon conversion (CC) were studied. The results showed the torrefied biomass leads to lower syngas yield. The syngas heating value of T275 is much higher than those of raw and T200 but it has the lowest CGE among the three fuels due to its heating value. The gasification temperature does not affect the gasification performance. In this study, the optimal torrefaction temperature and gasification temperature are 200 °C and 800 °C respectively.
Keywords: *Torrefaction, Gasification, Syngas, Thermodynamic equilibrium, Leucaena*

1. INTRODUCTION

Gasification is a thermochemical process that can convert carbonaceous materials into producer gas, synthesis gas or syngas including H_2, CO, CH_4 and other gaseous hydrocarbons. It is usually occurs in temperature range of 750 °C to 1300 °C in a partial oxidation process [1]. The application of the gasification may include heat, power and chemical products [2]. Many reaction processes may occur simultaneously during the process, namely (1) drying of the biomass particles, (2) pyrolysis of the dried biomass particles, also called devolatilization, (3) Partial oxidation of the pyrolysis gases and/or char, and (4) char gasification, also called reduction. In the gasification process, a gasifying medium is required which includes air, steam, CO_2, pure O_2 or their mixtures [2].
Torrefaction is one of the thermochemical conversion process that operates in temperature range of 200-300 °C [3]. The process is performed at near atmospheric pressure in an enclosed chamber without oxygen and with relatively low heating rates (< 50°C/min) [4]. It can increase energy density [5, 6], improving grindability, reducing the cost of transport and storage, generating dehydrated feedstock, and producing fuels of uniform properties [7].
The applications of torrefied biomass in gasification have been conducted by many researchers. Couhert et al. [8] used raw and torrefied wood as a feedstock in a high temperature entrained flow reactor with 20 vol. % steam in N_2. They found that torrefied wood may generate higher H_2 and CO than raw wood at 1400 °C. Chen et al. [9] studied numerically the gasification of raw and torrefied bamboo and bituminous coal in an entrained flow gasifier using O_2 as the gasification agent. It was noted that torrefaction improved biomass properties and the properties are close to that of coal. It increased the content of combustible gases in the syngas of biomass gasification. Moreover, the cold gasification efficiency of torrefied bamboo was enhanced by 88% compared with raw bamboo under the optimum conditions.

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In the past, many studies have focused on gasifier modeling in order to have better understanding on the gasification process are important for proper design of a gasifier in large scale process. The simulations of biomass gasification comprise kinetic rate models and thermodynamic equilibrium models [10]. The kinetic rate model relates on how different experimental conditions can influence the speed of a chemical reaction and yield information [11]. In thermodynamic equilibrium models, the state is approached or eventually reached as the system interacts with its surroundings over a long time or uniform temperature.

The gasification performance of integrated CO_2 gasification using Aspen plus was investigated by Adnan et al. [12]. A reformer and a CO_2 absorber are performed to improve syngas content (H_2, CO) and decrease CO_2 content. The effect of CO_2/C at various pressure, steam to carbon (S/C) and equivalence ratio (ER) on cold gas efficiency (CGE) and gasification efficiency (GSE) are performed. Results showed that gasifying with CO_2 enhance H_2, reduce CO n syngas and have minor influence on CGE and GSE.

Adnan et al. [13] also performed a thermodynamic model using Aspen plus to examine the gasification performance of microalgae, palm frond, mangrove, and rice husk. They found the gasification performances were sensitive with the gasification temperature, the oxygen equivalence ratio, and the steam to carbon ratio. The highest ratio of H_2/CO and cold gas efficiency was found when gasified the algae with oxygen. For steam gasification, the highest cold gas efficiency was found when gasified the palm frond. Kuo et al. [10] applied thermodynamics equilibrium models to predict gasification performance of raw and torrefied bamboo in a downdraft fixed bed gasifier. The effect of modified equivalence ration (ER_m) and steam supply ratio (SSR) on the cold gas efficiency (CGE) and carbon conversion (CC) are examined. The optimum ER_m and SSR for the raw and torerfied bamboo are in the range of 0.2-0.28 and 0.9, respectively. They concluded that the torrefied bamboo at 250 °C is more fit fuel in gasification after simultaneously counting syngas yield, CGE, and CC. Gasification performance of torrefied biomass was also investigated by Xue et al. [14]. They gasified raw and torrefied Micanthus × giganteus in a bubbling fluidized bed using olivine as catalyst. They found that at ER = 0.21 and 800 °C are the optimum conditions of the torrefied biomass. Syngas contents including H_2, CO and CH_4 are 8.6%, 16.4% and 4.4% respectively, syngas higher heating value of 6.7 MJ/NM^3, and cold gas efficiency of 62.7% are estimated. According to the notable reviews, the preliminary examination on gasification for torrefied biomass have insufficient information. In this work, the gasification temperature and torrefaction temperature are investigated in terms of their gasification performance including syngas yield, cold gas efficiency and carbon conversion. Some interesting and important results were obtained and discussed, are useful of torrefied biomass in gasification process and suitable design for the corresponding gasifiers.

2. METHODOLOGY

The gasification process in this work is schematically shown in Fig.1. Biomass enters the gasifier at environmental temperature T_0. The temperature of the gasifying agent air has a temperature of T_a. The syngas products leave the gasifier at the reactor temperature T. To simplify the analysis, the following assumptions are made:

(1) The chemical formula of the biomass is assumed as $CH_aO_bN_c$ without considering the sulfur.
(2) The gasifier operates as an adiabatic reactor at atmospheric pressure P_0.
(3) Carbon is completely converted to CO, CO_2, and ash. The syngas is a mixture of H_2, CO, CH_4, CO_2, H_2O and N_2. All the gases conduct the ideal gas law.
(4) The gasifier is performed at the thermodynamic equilibrium state. The residence time of reactants is sufficiently long, so that the reactions in the gasifier are in chemical equilibrium.

Global biomass gasification (on dry basis) with gasifying agent can be written as:

$$CH_aO_bN_c + m(O_2+3.76N_2) \rightarrow n_{H2}H_2 + n_{CO}CO + n_{CH4}CH_4 + n_{CO2}CO_2 + n_{H2O}H_2O + n_{N2}N_2 \quad (1)$$

where a, b and c are atomic numbers of hydrogen, oxygen and nitrogen per one atom of carbon in the biomass respectively. $\dot{m}_{air,\ actual}$ is mole of gasifying agent which is product of a_{th} (theoretical air) and ER (Equivalence Ratio).

$$ER = \frac{(\dot{m}_{air}/\dot{m}_{biomass})_{actual}}{(\dot{m}_{air}/\dot{m}_{biomass})_{stoichiometric}} = \frac{AF_{actual}}{AF_{stoichiometric}} \quad (2)$$

The present study employed STANJAN (v 3.93 L) which calculates the equilibrium moles of syngas composition at any temperature and pressure [15]. The effect of gasification temperature is in the range of 800 °C to 1000°C has been investigated. The ER and pressure are 0.2 and 1 atm in operating condition. The biomass properties are shown in Table 1. T200 and T275 are torrefied *Leacaena* at 200 °C and 250 °C in 30 min.

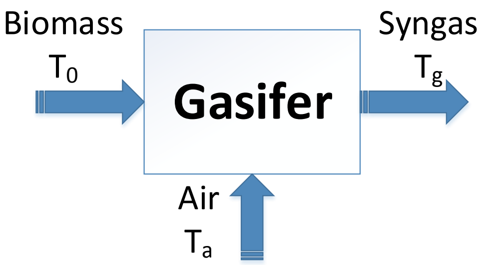


Fig. 1. Schematic of biomass gasification.

Table 1 : Proximate and ultimate analysis of raw and torrefied *Leucaena* [16]

Biomass type	Raw	T200	T275
Proximate analysis (% dry basis)			
Volatile matter	86.1	85.3	73.8
Fixed Carbon	13.1	14	24.9
Ash	0.8	0.7	1.3
Ultimate analysis (% dry ash free)			
C	50.1	51.7	57.2
H	7.4	7.1	5.5
O	41.8	40.5	36.5
N	0.7	0.7	0.8
Higher heating value (MJ/kg)	20.3	21	22.8

2.1 Gasification performance

In this work, cold gas efficiency (CGE) and carbon conversion (CC) are used to evaluate the gasification performance. Before calculating these values, the lower heating value of syngas, LHV_{syngas}, [17] needs to be known and is written as:

$$LHV_{syngas}\ (kJ/Nm^3) = (30.0y_{CO}+25.7y_{H2}+ 85.4y_{CH4}) \times 4.2 \quad (3)$$

where y is the mole fraction of gas contents in dry basis.

The CGE is an important factor to determine the performance of the gasification and shown as:

$$CGE(\%) = \frac{Y_g \times LHV_{syngas}}{HHV_{fuel}} \times 100 \quad (4)$$

where Y_g is the volume of syngas from the gasification per unit weight of fuel (Nm^3/kg fuel) and HHV_{fuel} is the higher heating value of the fuel (MJ/kg) respectively. Besides CGE, the carbon conversion (CC) of the gasification is also determined as:

$$CC(\%) = \left[1 - \frac{\dot{m}_{syngas}\left(y_{CO_2}\frac{12}{44} + y_{CO}\frac{12}{28} + y_{CH_4}\frac{12}{16}\right)}{\dot{m}_{fuel}\, y_C}\right] \times 100 \quad (5)$$

where y_{CO2}, y_{CO}, y_{CH4} and y_C are the mass fraction of CO_2, CO, CH_4 concentrations in syngas and carbon content in the biomass respectively.

2.2. Model validation

The experimental data reported in the studies of Jayah et al. [18] was used to verify the model established in this study. Rubber wood was fed into a downdraft fixed bed gasifier operated at atmospheric pressure (1 atm) along with the gasification temperature of 900 ^oC in the experiments. The air-to-fuel mass flow rate ratio (AFR) of 2.03 is considered for comparison with H_2, CO, CH_4, CO_2, and N_2 concentrations are displayed in Fig. 2. It can be seen that the model predictions are in good agreement with the results of Jayeh et al. According to the above comparison reveals that the developed thermodynamic model is reliable in this paper.

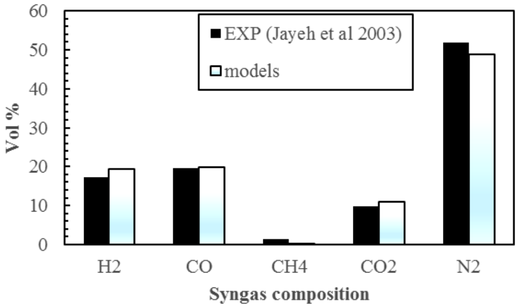
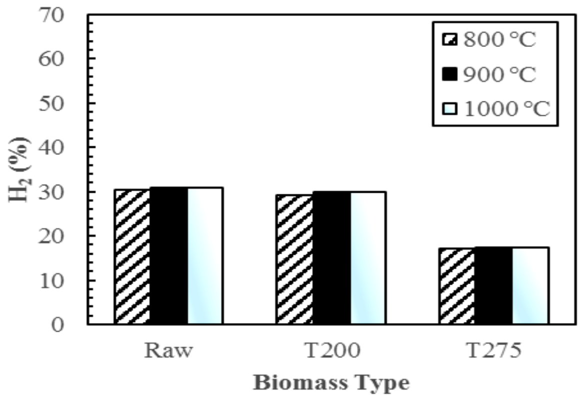


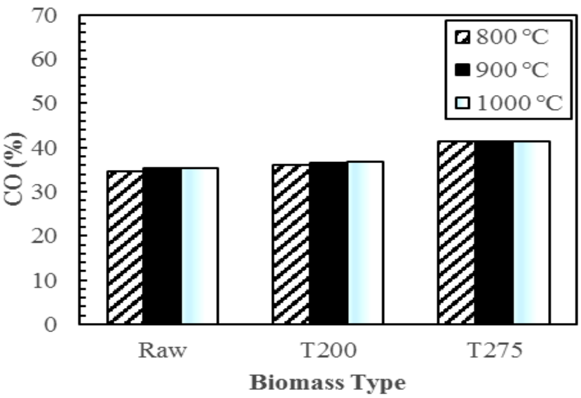
Fig. 2. Comparisons of syngas between predictions and experimental results.

3. Results and Discussion

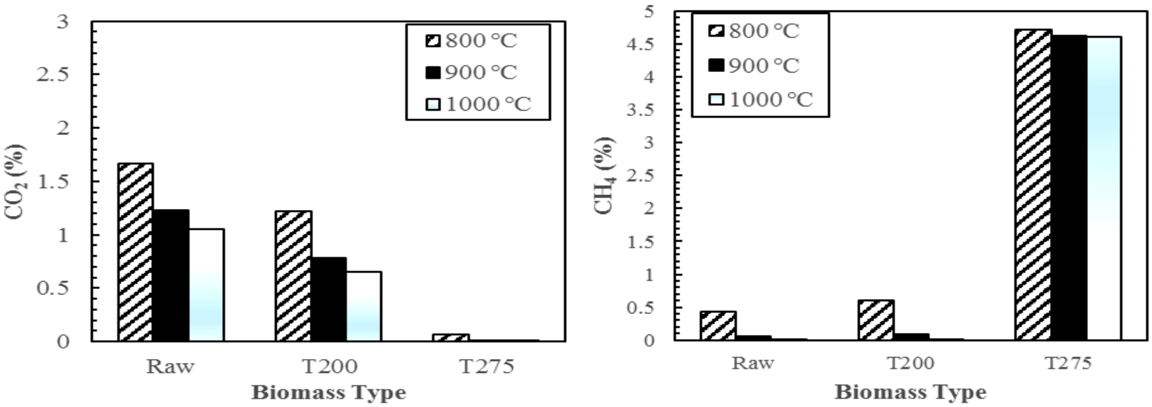
Three types of biomasses [16] are chosen as the feedstock including raw *Leucaena*, torrefied *Leucaena* at 200 ^oC (T200) and torrefied *Leucaena* at 275 ^oC (T275). The biomass gasification is analyzed in a downdraft fixed bed gasifier at ER = 0.2 and 1 atm.



(a) H_2



(b) CO



(c) CO_2 (d) CH_4

Fig. 3. (a)-(d) Syngas contents for the three fuels on gasification temperatures.

Gasification temperature is one of the most important factor affects syngas composition and gasification performance including gas yield, syngas heating value, cold gas efficiency and carbon conversion in gasification processes. Fig. 3(a)-(d) shows the syngas composition for the three biomasses on gasification temperature from 800 ^oC to 1000 ^oC. As temperature increases, the H_2 and CO increase due to endothermic reaction of water gas shift reaction and Boudouard reaction in the Eq. (6) to (10) [1, 19] respectively. The CO_2 decreases due to Boudouard reaction at temperature greater than 830 ^oC [20]. The CH_4 also decreases due to cracking and reforming reaction of the methanation reaction in Eq.(9).

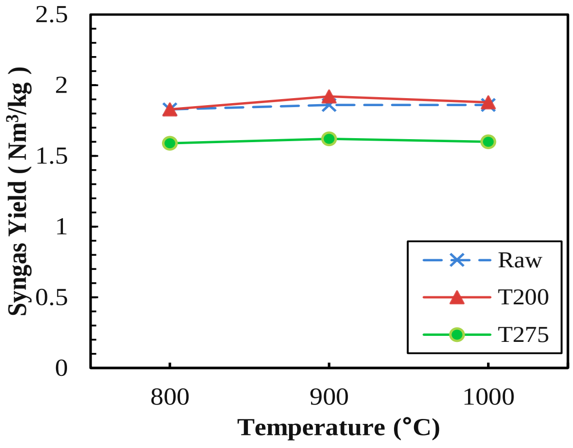
Boudouard reaction:	$C + CO_2 \leftrightarrow 2CO$,	$\Delta H = +172$ kJ/mol	(6)
Water gas primary reaction:	$C + H_2O \leftrightarrow CO + H_2$,	$\Delta H = +131$ kJ/mol	(7)
Water gas secondary reaction:	$C + 2H_2O \leftrightarrow CO + 2H_2$,	$\Delta H = +90$ kJ/mol	(8)
Methanation reaction:	$CH_4 + H_2O \leftrightarrow CO + 3H_2$,	$\Delta H = +206$ kJ/mol	(9)
Water gas shift reaction:	$CO + H_2O \leftrightarrow CO_2 + H_2$,	$\Delta H = -41$ kJ/mol	(10)

In case of the torrefaction temperature, as increased torrefaction temperature the syngas contents from the raw and T200 do not change because their properties are quite similar. For the gasification of T275, the variation of CO, CO_2 and CH_4 are sensitive to the torrefaction temperature. This may be due to more carbon content in T275 and deficient supplied oxygen at ER = 0.2 [10]. It can be concluded that torrefied biomass as the feedstock improves the CO concentrations as it reduces the H_2 concentration in the syngas.

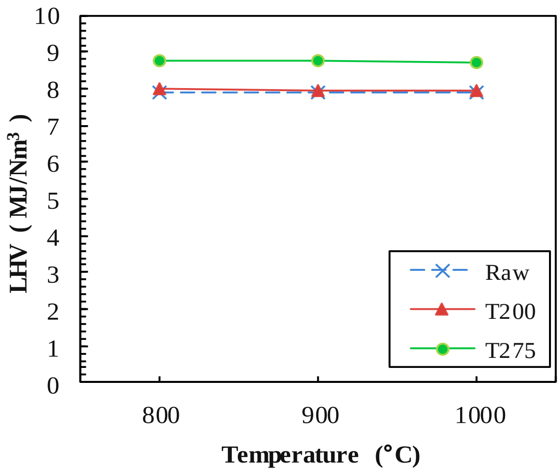
Fig.4. shows effect of torrefaction temperature and gasification temperature on the gasification performance. When rising the temperature from 800 ^oC to 1000 ^oC, the performance including syngas yield, syngas heating value, CGE and CC slightly change. It implies that the gasification temperature does not affect the performance of the three fuels.

The effect of torrefaction temperature on the syngas yield shows on Fig.4 (a). The syngas yield from gasification of T200 is slightly higher than that of the raw by approximately 10% at gasification temperature of 900 ^oC. This may cause from their properties are alike. In case of T275, its gasification leads to the lowest of syngas yield compared with other biomasses because of its lowest value H/C and O/C with insufficient oxygen at ER = 0.2.

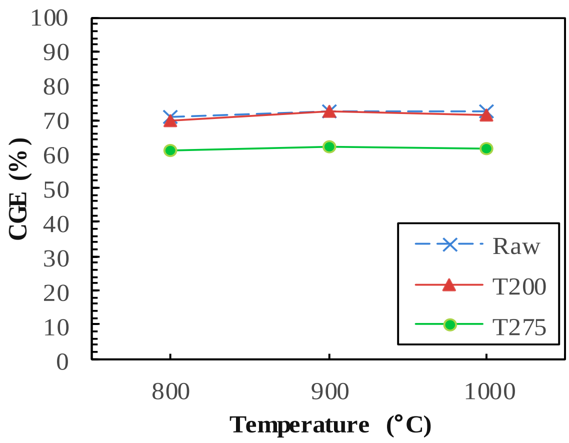
The effect of torrefaction temperature on the LHV of syngas yield shows on Fig.4 (b). The syngas LHV depends on H_2, CO and CH_4 concentrations in syngas which can be determine by Eq. (3). The gasification of raw and T200 result in similar value of syngas LHV because their H_2, CO and CH_4 concentrations close to each other which can be noticed in Fig.3 (a), (b) and (d) respectively. When *Leucaena* is torrefied at 275 ^oC, its LHV syngas value is amplified by approximately 12% due to its higher syngas concentrations.



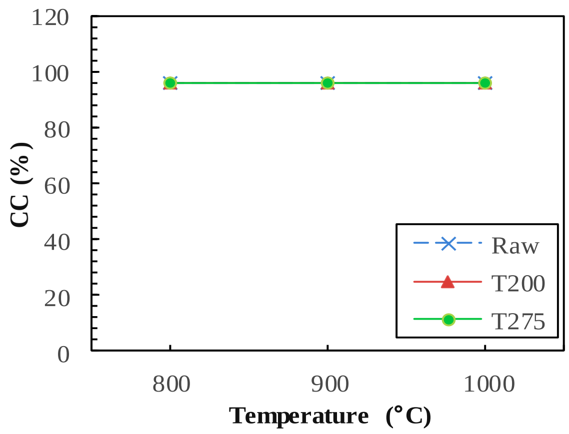
(a) Syngas yield



(b) Syngas LHV



(c) CGE



(d) CC

Fig. 4.(a)-(d) Gasification performance of the three fuels at ER = 0.2.

In examining the performance of biomass gasification, CGE and CC are determined. CGE is an essential factor to evaluate the performance of biomass gasification is determined by Eq.(4). It depends on syngas yield, syngas LHV and biomass HHV. When the three factors are counted together, as a results in Fig.4 (c). It can be noted that increase in the HHV of T275 causes its CGE is lower than the other two fuels, even though the syngas yield goes up.

The CC is also the key factor to evaluate the performance of biomass gasification is determined by Eq.(5). According to Fig. 3 (a), (b) and (d), the higher in CO and CO_2 concentration in the syngas and the lower in CH_4 concentration meaning that most of the carbon in feedstock is mainly transformed to the CO and CO_2. The syngas concentrations, mass flow rate of syngas, mass flow rate of the fuels and carbon content in the feedstock are factors that require to consider. When these factors are counted together cause the CC of the three fuels are the same values.

4. Conclusion

A thermodynamic analysis on of raw and torrefied *Leucaena* in a downdraft gasifier have been performed by thermodynamics equilibrium method using STANJAN (v.3.93L). The torrefaction temperature and gasification temperature affect the syngas contents, syngas yields, syngas LHV, CGE and CC. The higher the torrefaction temperature, the lower the syngas yield. The higher heating value of T275 results in the lowest of syngas yield and CGE.

The gasification temperature in the range of 800 ^oC to 1000 ^oC does not affect the gasification performance. In terms of syngas yields, CGE and CC, this study show that torrefaction at 200 ^oC (for 30 minutes) with gasification temperature at 800 ^oC is more feasible than the other two fuels for biomass gasification. However, torrefaction need equipment including heating, cooling, and tar collecting system and operating costs.

5. Acknowledgements

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