Thermodynamics analysis of raw and torrefied biomass 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 that the torrefied biomass leads to lower syngas yield. The syngas heating value of T275 is much higher than those of raw and T200. The T275 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: Biomass gasification; Thermodynamic equilibrium model; Torrefaction; Syngas

1. Introduction

Gasification is a thermochemical process that can convert the biomass in a partial oxidation process at raised temperature into syngas, such as H_2, CO, CH_4, and CO_2 for thermal, power and chemicals applications [1]. The gasification mediums contain air, pure O_2, steam, CO_2 or their mixtures [2]. Air is widely used for gasifying agent due to its low cost and availability. However, it holds high content of nitrogen and causes low syngas heating value of 4-7 MJ/Nm^3. While pure O_2 can raise the syngas heating value to 12-28 MJ/Nm^3, the operating cost is high due to the cost of O_2 production. Steam may increase the H_2 content in syngas and improve the heating value to 10-18 MJ/Nm^3, but external heat is needed and that may also cause high operating cost [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 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.

In the past, many studies have focused on gasifier modeling in order to have better understanding on the gasification process. The simulations of biomass gasification comprises 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. However, the preliminary examination on gasification for torrefied biomass in gasification have insufficient information. In this work, the gasification temperature and torrefaction temperature are considered to study their gasification performance including syngas yield, cold gas efficiency and carbon conversion.

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. That is, the residence time of reactants is sufficiently long so that the reactions in the gasifier are in chemical equilibrium.

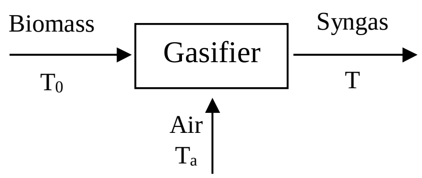


Fig. 1 Schematic of biomass gasification

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. m is mole of gasifying agent which is product of a_{th} (theoretical air) and ER (Equivalence Ratio).

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

The present study employed STANJAN(v 3.93 L) which calculates the equilibrium moles of syngas composition at any temperature and pressure [12]. The effect of gasification temperature is in 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 minutes.

Table. 1 Proximate and ultimate analysis of raw and torrefied *Leucaena* [13]

Biomass	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 [14] 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 cold gas efficiency (CGE) is an important factor to determine the performance of the gasification and shown as:

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

where Y_{sg} 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 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_i is the mass fraction of syngas species i.

2.2. Model validation

The experimental data reported in the studies of Jayah et al. [15] 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 °C 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.

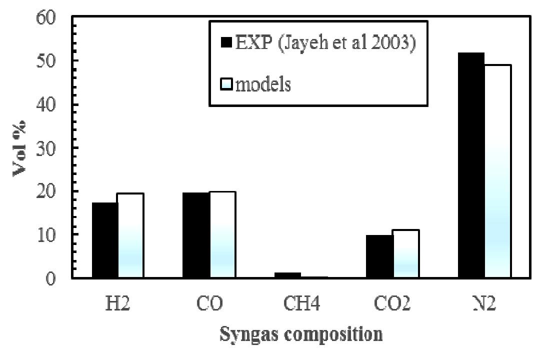
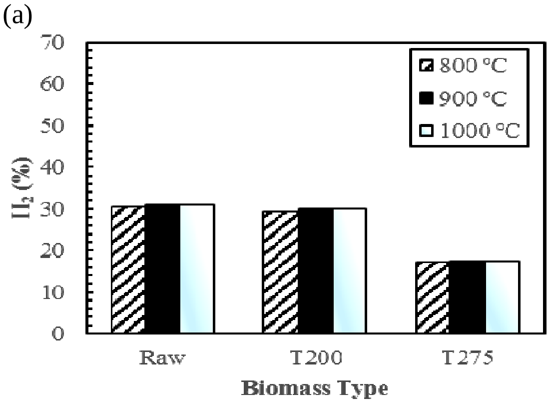


Fig. 2 Comparisons of syngas between predictions and experimental results

3. Results and discussion

Three types of biomasses [13] are chosen as the feedstock including raw *Leucaena*, torrefied *Leucaena* at 200 °C (T200) and torrefied *Leucaena* at 275 °C (T275). The biomass gasification is analyzed in a downdraft fixed bed gasifier at ER = 0.2 and 1 atm.

(a)



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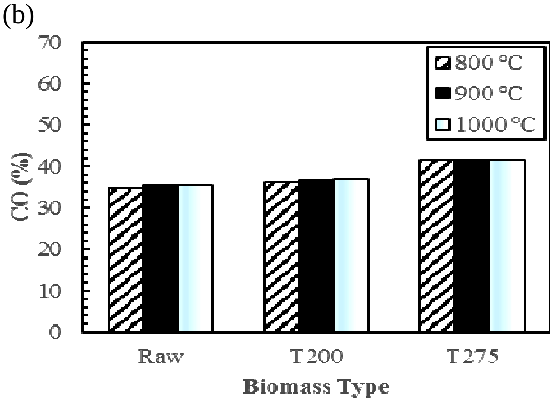

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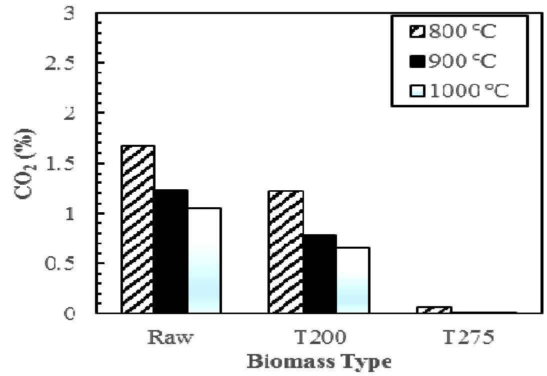

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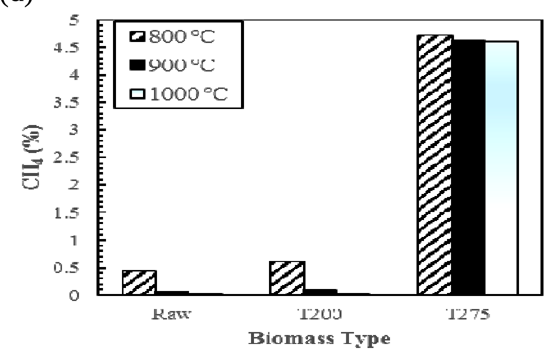


Fig. 3(a)-(d) Syngas contents for three fuels on gasification temperatures.

Gasification temperature is one of the most important factors affects syngas composition and gasification performance including gas yield, syngas heating value, cold gas efficiency and carbon conversion in gasification processes. Fig. 3 shows the syngas composition for the three biomasses on gasification temperature from 800 °C to 1000 °C. As temperature increases, the H_2 and CO increase due to endothermic reaction in the Eq. (6) to (9) [1, 16]. The CO_2 decreases due to Boudouard reaction at temperature greater than 830 °C [17]. The CH_4 also decreases due to cracking and reforming reaction of the methanation reaction in Eq.(9).

Boudouard reaction:

$$C + CO_2 \leftrightarrow 2CO,\ \Delta H = +172\ \text{kJ/mol} \quad (6)$$

Water gas primary reaction:

$$C + H_2O \leftrightarrow CO + H_2, \Delta H = +131\ \text{kJ/mol} \quad (7)$$

Water gas secondary reaction:

$$C + 2H_2O \leftrightarrow CO + 2H_2,\ \Delta H = +90\ \text{kJ/mol} \quad (8)$$

Methanation reaction:

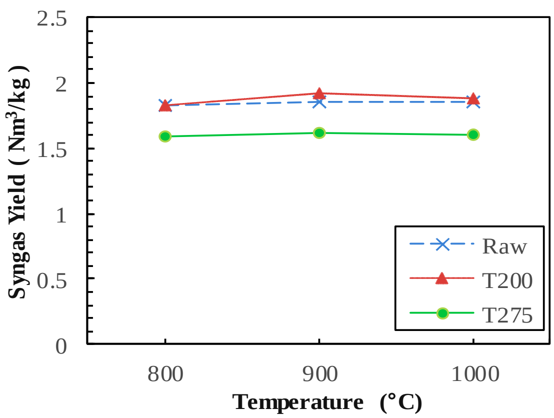
$$CH_4 + H_2O \leftrightarrow CO + 3H_2,\ \Delta H = +206\ \text{kJ/mol} \quad (9)$$

Water gas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2,\ \Delta H = -41\ \text{kJ/mol} \quad (10)$$

In case of the torrefaction temperature, as increased torrefaction temperature the syngas contents from the raw and T200 do not change and are about the same 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 lower H/C and O/C in T275.

(a)



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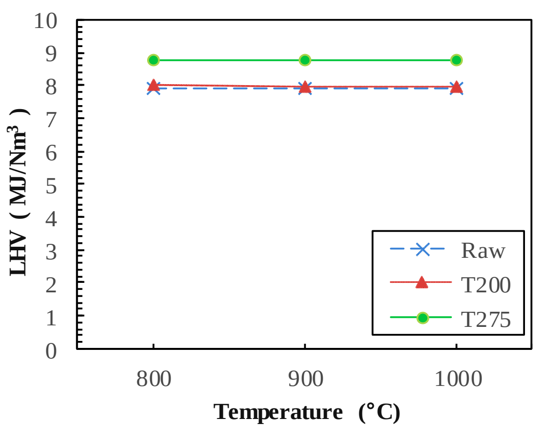

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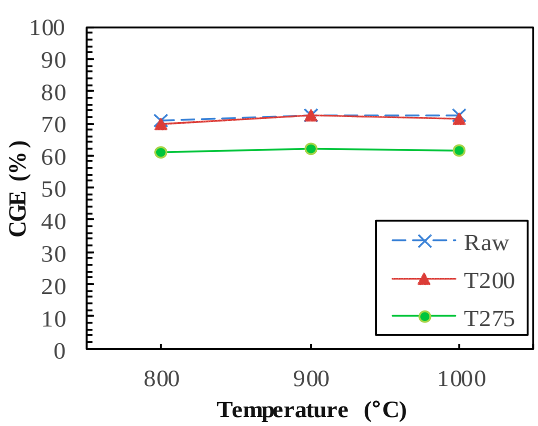

(d)

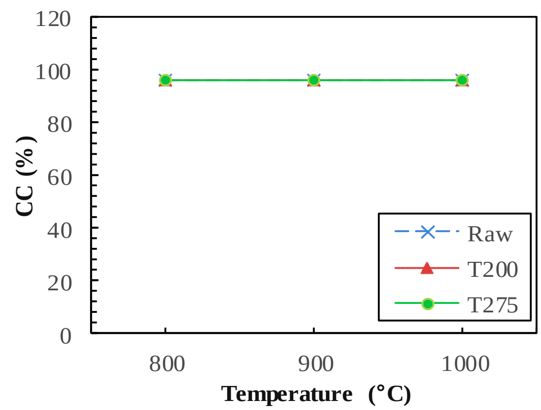

Fig. 4. Gasification performance of (a) syngas yield, (b) syngas LHV, (c) CGE and (d) CC of three fuels (ER = 0.2).

Fig.4 shows effect of torrefaction temperature and gasification temperature on the gasification performance. When rising the temperature from 800 °C to 1000 °C, 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.

From Fig.4 (a) shows the syngas yield with counting N_2 does not improve the syngas yield. The more carbon in T275 and insufficient oxygen is supplied at ER = 0.2 leads to lower in its syngas yield.

In Fig.4 (b), the more syngas (H_2, CO and CH_4) from Fig. 3(a), (b), (d) is generated when torrefied *Leucaena* is used as feedstock causes the total energy of syngas from the gasification of torrefied biomass goes up especially for T275.

Fig.4 (c) shows that the increase in the HHV of T275 results in its lower in CGE than the other two fuels as indicated in Eq.(4).

The CC of the three fuels are close to each other. More syngas is produced from the torrefied biomasses, but the HHV of the torrefied biomasses are quite high. When the two factors are counted together, as a result, the CC is about the same value as shown in Fig. 4(d).

4. Conclusions

A thermodynamic investigation 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 affects the syngas contents, syngas yields, syngas heating value (LHV) of syngas, cold gas efficiency (CGE) and carbon conversion (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. When considering syngas yields, CGE and CC, this study shows that T275 and the gasification temperature at 800 ^oC are more feasible than the other two fuels for biomass gasification. However, torrefaction need equipment including heater, cooling, and tar collecting system and operating cost.

7. References

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