Gasification performances of raw and torrefied biomass in a downdraft fixed bed gasifier using thermodynamic analysis

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HIGHLIGHTS

- Gasification performances of raw and torrefied biomass are thermodynamically analyzed.
- A downdraft fixed bed gasifier is tested using Aspen Plus.
- The modified equivalence ratio and steam supply ratio are considered.
- The cold gas efficiency and carbon conversion are examined.
- The optimum operating conditions for the gasification are found.

ABSTRACT

The gasification performances of three biomass materials, including raw bamboo, torrefied bamboo at 250 °C (TB250), and torrefied bamboo at 300 °C (TB300), in a downdraft fixed bed gasifier are evaluated through thermodynamic analysis. Two parameters of modified equivalence ratio (ER\textsubscript{m}) and steam supply ratio (SSR) are considered to account for their impacts on biomass gasification. The cold gas efficiency (CGE) and carbon conversion (CC) are adopted as the indicators to examine the gasification performances. The analyses suggest that bamboo undergoing torrefaction is conducive to increasing syngas yield. The higher the torrefaction temperature, the higher the syngas yield, except for TB300 at lower values of ER\textsubscript{m}. Because the higher heating value of TB300 is much higher than those of raw bamboo and TB250, the former has the lowest CGE among the three fuels. The values of CC of raw bamboo and TB250 are always larger than 90% within the investigated ranges of ER\textsubscript{m} and SSR, but more CO\textsubscript{2} is produced when ER\textsubscript{m} increases, thereby reducing CGE. The maximum values of syngas yield and CGE of raw bamboo, TB250, and TB300 are located at (ER\textsubscript{m}, SSR) = (0.2, 0.9), (0.22, 0.9), and (0.28, 0.9), respectively. The predictions suggest that TB250 is a more feasible fuel for gasification after simultaneously considering syngas yield, CGE, and CC.

1. Introduction

Gasification is a thermo-chemical conversion technology which transforms solid fuel into gas product through partial oxidation [1]. The main components in the product gas are hydrogen and carbon monoxide and they are called synthesis gas (syngas) [2,3]. The generated syngas can be directly consumed as gaseous fuel; it can be further processed to produce electricity and heat. In addition, syngas is a key intermediary in the chemical industry. For example, some liquid transportation fuels, such as methanol, dimethyl ether (DME), and methyl tert-butyl ether (MTBE), can be synthesized from syngas [4–6]. Generally speaking, the quality of syngas varies with the adopted oxidizing agents, such as air, steam, steam–oxygen, air–steam, and oxygen-enriched air [7]. Among these oxidizing agents, air is the most widely employed one [8].

The advantages of air-blown biomass gasification include availability and simplicity, and it has been investigated by numerous researchers using various types of biomass. For instance, Lv et al. [9] studied pine wood block gasification in a downdraft fixed bed gasifier at the equivalence ratios (ERs) of 0.24–0.28; they found that the hydrogen yield and lower heating value (LHV) of syngas were in the ranges of 21.18–29.70 g (kg-biomass)\textsuperscript{0.8} and 4.76–5.44 MJ Nm\textsuperscript{3}. González et al. [10] tested olive orujo gasification in a laboratory reactor at atmospheric pressure and temperatures of 750–900 °C. They reported that H\textsubscript{2} and CO formation favored high-temperature environments and the maximum H\textsubscript{2} and CO molar fractions occurred at temperatures of 750 and 900 °C, respectively. Gai and Dong [11] demonstrated non-woody
biomass gasification in a downdraft gasifier at atmospheric pressure. They pointed out that the operating conditions had a significant effect on the gasification efficiency and the gas compositions in the product gas; they also outlined that the optimum value of ER was between 0.28 and 0.32. Nitrogen is contained in the product gas from air-blown gasification; the LHV of the product gas is higher [7], as a result of water gas shift reaction. However, biomass steam gasification requires external heat because of the exothermic nature of the reaction, in contrast to the endothermic nature of biomass gasification using steam as an oxidizer. A higher steam-to-biomass ratio of 10–15 is typically used for steam gasification of biomass, whereas a ratio of 10–15 is typically used for biomass gasification using steam as an oxidizer.

In recent years, torrefied biomass has been widely explored for its feasibility to replace coal [20]. Torrefaction is a mild pyrolysis process carried out at temperatures of 200–300 °C in the absence of oxygen [21,22]. Torrefied biomass is characterized by lower moisture (or hydrophobicity), higher energy density, and improved ignitability, reactivity, and grindability when compared to its parent biomass [23–25]. Because most of the moisture as well as part of the volatiles and hemicellulose in biomass are removed from the feedstock during the torrefaction process, its characteristics are closer to those of coal, so torrefaction was a promising method for co-gasification. Coulhert et al. [28] evaluated the impact of torrefaction on syngas production from wood gasification in an entrained flow reactor. Seeing that torre-
faction decreased the O/C ratio of the biomass, the quantity of produced syngas increased with the severity of torrefaction.

From the studies of Prins et al. [26], Deng et al. [27], and Couhert et al. [28], it is known that torrefied biomass is a feasible feedstock for biomass gasification or co-gasification. However, just preliminary evaluation of the impact of torrefaction on gasification is provided and there still remains insufficient information in figuring out the gasification performances of torrefied biomass at various operating conditions. The fixed bed gasifiers can be catalogued into three types of reactors; they are updraft, cross-draft, and downdraft fixed bed gasifiers [7]. The updraft fixed bed gasifier is characterized by low exit gas temperature but high tar and ash contents. In the cross-draft fixed bed gasifier, the residence time of produced gas in the high temperature zone is small and this results in the significant amount of tar in the outgoing gas. With regard to the downdraft fixed bed gasifier, the gas temperature at the exit is high, while tar and ash contents are low. It follows that the gasification behavior in a downdraft gasifier is closer to the thermodynamic equilibrium. For this reason, the purpose of this study is to explore biomass gasification in a downdraft fixed bed gasifier via a thermodynamic equilibrium model. The gasification performances of raw and torrefied biomass will be compared with each other. The parameters of modified equivalence ratio (ERm) and steam supply ratio (SSR) are considered to account for their influences on gasification performances, such as syngas yield, cold gas efficiency, and carbon conversion. The optimum operation of biomass gasification will also be outlined.

2. Methodology

2.1. Assumptions

The following assumptions are employed to simplify the simulations of biomass gasification.

(1) Biomass gasification processes are isothermal and in steady state.

(2) The gasifier is operated at the thermodynamic equilibrium state; that is, the residence time of reactants is sufficiently long so that the reactions in the reactor are in chemical equilibrium.

(3) The feedstock is at normal conditions (i.e. 25 °C and 1 atm).

(4) The product gas is a mixture of H2O, N2, H2, CO, CO2, and CH4, and all the gases follow the ideal gas law.

(5) The sulfur content in the feedstocks and the formation of air pollutants, such as COS, H2S, CS2, NH3, and HCN, are neglected.

(6) Char contains solid carbon (C) and ash alone, and tar formation is disregarded.

2.2. Gasification model

The gasification model in this study is based on Gibbs free energy minimization method [16,29]. The total Gibbs free energy \( G^t \) is a function of temperature, pressure, and number of moles of species \( i(n_i) \), so it is given by

\[
G^t = g(n_1, n_2, n_3, \ldots, n_i) \tag{1}
\]

In a system at thermodynamic equilibrium, the total Gibbs free energy is defined as

\[
G^t = \sum_{i=1}^{N} n_i \mu_i \tag{2}
\]

In the preceding equation, \( \mu_i \) is the chemical potential of species \( i \) and it is presented by

\[
\mu_i = C_i^f + RT \ln \left( \frac{\hat{f}_i}{P_0^f} \right) \tag{3}
\]

where \( \hat{f}_i \), \( C_i^f \), and \( P_0^f \) are the fugacity of species \( i \) in the gas mixture, the standard Gibbs free energy, and the standard fugacity of species \( i \), respectively. For a fluid following the ideal gas law at the standard state (i.e. 1 atm), \( P_0^f = P \). Eq. (3) is thus presented in terms of pressure as

\[
\mu_i = C_i^f + RT \ln \left( \frac{\hat{f}_i}{P} \right) \tag{4}
\]

\( C_i^f \) is equal to zero for each chemical element at standard state, hence \( C_i^f = \Delta C_i^f \) for each component where \( \Delta C_i^f \) is the standard Gibbs free energy of formation of species \( i \) at 1 atm. For the gas phase reactions, \( f_i = y_i \phi \). Accordingly, Eq. (4) becomes

\[
\mu_i = \Delta C_i^f + RT \ln \left( \frac{y_i \phi}{P} \right) \tag{5}
\]

If all gases are assumed as the ideal gases at one atmospheric pressure, substituting Eq. (5) into Eq. (2) gives

\[
G^t = \sum_{i=1}^{N} n_i \Delta C_i^f + \sum_{i=1}^{RT} RT \ln(y_i) \tag{6}
\]

To find the values of \( n_i \) which minimize the objective function \( G^t \), they are subject to the constraints of material mass balance. The minimization of the Gibbs free energy can be solved by introducing the Lagrange’s undetermined multipliers as [30]:

\[
\sum_{i=1}^{N} n_i a_{ik} = A_k(k = 1, 2, \ldots, \omega) \tag{7}
\]

where \( a_{ik} \) and \( A_k \) are the numbers of atoms of \( k \) element in each molecule of species \( i \) and the total number of atoms of \( k \) element in the system, respectively, and \( \omega \) is the total number of elements comprising the system. Then the Lagrange multipliers \( \lambda_k \) is introduced by multiplying it into each equation of material mass balance as

\[
\lambda_k \left( \sum_{i=1}^{N} n_i a_{ik} - A_k \right) = 0 \quad (k = 1, 2, \ldots, \omega) \tag{8}
\]

The summation of the equations over \( k \) gives

\[
\sum_k \lambda_k \left( \sum_{i=1}^{N} n_i a_{ik} - A_k \right) = 0 \tag{9}
\]

A Lagrange function \( L \) is formed when this summation is added into \( G^t \) and it is expressed as

\[
L = G^t + \sum_k \lambda_k \left( \sum_{i=1}^{N} n_i a_{ik} - A_k \right) \tag{10}
\]

The minimization of \( L \) takes place when its partial derivatives are all equal to zero. Therefore, the system reaches the equilibrium state when the partial derivatives of Eq. (10) are equal to zero, that is

\[
\left( \frac{\partial L}{\partial n_i} \right)_{T,P,n_j} = 0 \quad (i = 1, 2, \ldots, N, \ and \ i \neq j) \tag{11}
\]

2.3. Mass and energy balances

Four elements of carbon, hydrogen, oxygen, and nitrogen are the major components in biomass; hence the feedstocks are expressed by CH\(_{x}\)O\(_{y}\)N\(_{z}\) where the subscripts \( x, y, \) and \( z \) are determined
from the elemental analysis of biomass. Based on the mass balance, the global gasification reaction is written as

$$\text{CH}_3\text{O}_3\text{N}_2 + a(\text{O}_2 + 3.76 \text{ N}_2) + b\text{H}_2\text{O} \rightarrow c\text{ CO}_2 + d\text{ CO} + e\text{ CH}_4 + f\text{ N}_2 + g\text{H}_2$$

(12)

where \(a\) is the amount of air per mol of biomass and \(b\) is the amount of supplied steam; \(c, d, e, f, \) and \(g\) are the numbers of moles of \text{CO}_2, \text{ CO}, \text{CH}_4, \text{N}_2, \) and \text{H}_2, respectively.

The energy balance between the reactants and the products is calculated based on the following equations

$$\sum_{\text{in}} H_i + Q_{\text{in}} = \sum_{\text{out}} H_j$$

(13)

$$\sum_{\text{in}} H_i + Q_{\text{in}} = H_{\text{biomass}} + H_{\text{air}} + H_{\text{steam}}$$

(14)

$$\sum_{\text{out}} H_j = H_{\text{product gas}} + H_{\text{ash}} + H_{\text{steam}}$$

(15)

where \(\sum_{\text{in}} H_i\) and \(\sum_{\text{out}} H_j\) are the enthalpy rates of input and output material streams, respectively. All inputs on the left-hand side of Eq. (13) are at 25 °C and outputs on the right-hand side are at the gasification temperature. \(H_{\text{biomass}}, H_{\text{steam}}, H_{\text{product gas}}, \) and \(H_{\text{ash}}\) are the rates of heat of formation of biomass, steam, gaseous products, and ash, respectively, and \(Q_{\text{in}}\) is the rate of heat of reaction.

The impacts of two operating parameters of modified equivalence ratio (\(\text{ER}_m\)) and steam supply ratio (\(\text{SSR}\)) on biomass gasification are taken into account [7,12]. Different from the study of Gordillo et al. [12], the modified equivalence ratio (\(\text{ER}_m\)) is defined as the ratio of the total actual oxygen mass supplied by both air and steam to the stoichiometric oxygen. \(\text{SSR}\) accounts for the oxygen supply ratio from steam and from both air and steam. The parameters of \(\text{ER}_m\) and \(\text{SSR}\) are expressed as

$$\text{ER}_m = \frac{m_{\text{oxygen in air}} + m_{\text{oxygen in steam}}}{m_{\text{oxygen in stoichiometry}}}$$

(16)

$$\text{SSR} = \frac{m_{\text{oxygen in steam}}}{m_{\text{oxygen in air}} + m_{\text{oxygen in steam}}}$$

(17)

For a given \(\text{ER}_m\), a higher \(\text{SSR}\) means a higher steam supply to replace air supply for oxidizing agent.

### 2.4. Stream and thermodynamic properties

The present study employed Aspen Plus V7.3 to evaluate biomass gasification. The information of property models and parameters are listed in Table 1. The stream classes were used to define the structure of simulation streams. The components of biomass and ash are not available in the standard Aspen Plus component database. Hence, the MCINCPSD stream class, which contains three substreams comprising MIXED, CIPSD, and NCPSD, was used in this simulation. Aspen Plus can apply various equations of state to study phase behavior of pure compounds and multi-component mixtures over wide ranges of temperature and pressure. In this study, Peng–Robinson equation of state was utilized to estimate the physical properties. The HCOALGEN model included a number of empirical correlations for heat of combustion, heat of formation, and heat capacity, hence the enthalpies of nonconventional components, say, biomass and ash, were calculated by the model. The density of biomass was evaluated by DCOALIGT model [19].

#### 2.5. System description

Typically, the gasification processes are partitioned into the following reaction zones [7,10,11].

**Drying zone**

$$\text{H}_2\text{O}(l) \rightarrow \text{H}_2\text{O}(g), \quad q \Delta H^0 = +40.7 \text{ kJ mol}^{-1}$$

(18)

**Devolatilization zone**

$$\text{CH}_3\text{O}_3\text{N}_2 \rightarrow \text{char} + \text{volatiles}$$

(19)

**Oxidation zone**

$$\text{C} + 0.5\text{O}_2 \rightarrow \text{CO}, \quad \Delta H^0 = -268 \text{ kJ mol}^{-1}$$

(20)

$$\text{C} + \text{O}_2 \rightarrow \text{CO}_2, \quad \Delta H^0 = -406 \text{ kJ mol}^{-1}$$

(21)

**Reduction zone** (Water gas reaction)

$$\text{C} + \text{H}_2\text{O} \rightarrow \text{ CO} + \text{H}_2, \quad \Delta H^0 = +131.4 \text{ kJ mol}^{-1}$$

(22)

**Boudouard reaction**

$$\text{C} + \text{CO}_2 \rightarrow 2\text{ CO}, \quad \Delta H^0 = +172.6 \text{ kJ mol}^{-1}$$

(23)

**Shift reaction**

$$\text{CO} + \text{H}_2\text{O} \rightarrow \text{ CO}_2 + \text{H}_2, \quad \Delta H^0 = -42 \text{ kJ mol}^{-1}$$

(24)

**Methanation reaction**

$$\text{C} + 2\text{H}_2 \rightarrow \text{ CH}_4, \quad \Delta H^0 = -75 \text{ kJ mol}^{-1}$$

(25)

For the purpose of analysis, the reaction zones are represented by a number of blocks. Fig. 1 shows the flow chart of biomass gasification simulation using Aspen Plus and Table 2 gives the brief descriptions of the unit operations of the blocks. The stream BIOMASS was specified as a nonconventional stream and it was defined in terms of proximate and elemental analyses. When BIOMASS was fed into the system, the first step was the heating and drying of biomass. The blocks DRYER and DRYFLASH were used to model the drying process, and the moisture in the feedstock was removed from EXHAUST stream, as shown in Fig. 1. After drying, the devolatilization stage was performed in the block DECOMP in which the RYield reactor was used. In DECOMP, the feedstock was transformed from a non-conventional solid into volatiles and char. The volatiles consisted of carbon, hydrogen, oxygen, and nitrogen, and the char was converted into ash and carbon, based on the ultimate analysis [17–19]. The yield of volatiles was equal to the volatile content in the fuel according to the proximate analysis. Moreover, the actual yield distributions in DECOMP were calculated by a calculator block which was controlled by FORTRAN statement in accordance with the component characteristics of the feedstock. The combustion and gasification of biomass were simulated by a block called GASIFIER in which the chemical equilibrium was determined by minimizing the Gibbs free energy. The product stream was then cooled to room temperature by COOLER. Water was heated in the block HEATER to become steam named STEAM.
the streams AIR and STEAM were blended in MIXER and the mixture was utilized as the oxidizing agent. Eventually, the product gas was divided into two streams SYNGAS and ASH in the block SSPLIT.

2.6. Model validation

In the present simulations, the RGibbs reactor (Table 2) was utilized to predict the equilibrium composition of the produced gas, and the predictions were based on the Gibbs energy minimization method. To ensure the developed model in the present study is purely an equilibrium model, the obtained values of CO conversion from water gas shift reaction at various steam/CO ratios and reaction temperatures are compared with the thermodynamic analyses of Chen et al. [31]. In Fig. 2, the predictions from the RGibbs reactor in Aspen Plus are in good agreement with the results of Chen et al. [31]. This verifies that the adopted model in this study is purely an equilibrium model. The thermodynamic model of gasification is also validated by comparing the current predictions to the experimental results of Jayah et al. [32]. In their experiments, rubber wood was fed into a downdraft fixed bed gasifier operated at atmospheric pressure (1 atm) along with the gasification temperature of 900 °C. Three different air-to-fuel mass flow rate ratios (AFRs) of 2.03, 2.20, and 2.37 are considered for comparison and the comparisons of H₂, CO, CO₂, and CH₄ concentrations are displayed in Fig. 3. The maximum relative errors of H₂, CO, and CO₂ concentrations between the thermodynamic analyses and experimental measurements are 8.37%, 7.89%, and 7.14%, respectively, revealing that the predicted results of the three gases at various AFRs agree with the experimental measurements (Fig. 3a–c). The experimental values of CH₄ concentration are in the range of 1.1–1.4%, whereas the predictions are close to zero (Fig. 3d). Similar results were also observed in the study of Jarunghammachote and Dutta [33] and Baratieri et al. [34]. The measured CH₄ concentration cannot be explained based on a purely thermodynamic equilibrium because of incomplete conversion of pyrolysis products [34]. Because CH₄ is not the main species in the product gas, the above comparison reveals that the developed thermodynamic model is reliable in the present work.

3. Results and discussion

In this study, three kinds of biomass [35] are selected as the feedstocks to be investigated; they are bamboo, torrefied bamboo at 250 °C (TB250), and torrefied bamboo at 300 °C (TB300). The bamboo was individually torrefied at 250 and 300 °C for one hour. The properties of the feedstocks, such as the proximate analysis, elemental analysis, and higher heating values (HHV) are listed in Table 3. The biomass gasification is fulfilled in a downdraft fixed bed gasifier at 900 °C and 1 atm. Details of the operating conditions are given in Table 1.

3.1. Effect of ERₘ

The supply of oxidizing agent, namely, ERₘ, plays an important role in the performance of biomass gasification. A low ERₘ will lead to biomass reactions approaching pyrolysis, whereas a high ER causes biomass combustion. After testing, the appropriate ERₘ for biomass gasification is in the range of 0.2–0.4; hence the aforementioned range of ERₘ serves as the basis of the present study. Table 4 displays the dry-basis concentrations of H₂, CO, and CO₂ from biomass gasification at the condition of SSR = 0 (i.e. no steam is supplied as the oxidizer). The H₂ concentration decreases with increasing ERₘ regardless of which biomass is used as the feedstock. Similar to H₂ formation, the CO concentration also decreases with increasing ERₘ but an opposite trend in CO₂ concentration is exhibited. This can be explained by more oxygen supplied for biomass reactions which have a trend toward fuel combustion when ERₘ rises. The gasification of raw bamboo produces the highest H₂ concentration among the three fuels, whereas TB300 gives the
lowest H2 concentration. It has been reported that the moisture content in feedstock affected the gas compositions of product gas [32] and a higher moisture content in the feedstock led to a higher H2 concentration in the product gas [16]. By virtue of higher moisture content in raw bamboo (Table 3), its gasification results in the higher H2 concentration compared to the gasification of the others. Conversely, the gasification of raw bamboo gives the lowest CO concentration among the three materials, stemming from its lowest carbon content. Torrefaction is able to reduce the atomic H/C and O/C ratios of biomass to a certain extent [20,21]. For the gasification of TB300, the variation of CO and CO2 concentrations is insensitive to ER_m when it increases from 0.2 to 0.26. This may be due to relatively more carbon being contained in TB300 (Table 3). However, the flow rates of CO and CO2 at the exit of the gasifier increases with increasing ER_m. Within the aforementioned range of ER_m, the lower H2 concentration from the gasification of TB300 than from raw bamboo and TB250 is possibly attributed to the lower moisture content in the former.

### Table 3
Proximate and elemental analyses of three feedstocks used in simulations [35].

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Raw bamboo</th>
<th>TB250</th>
<th>TB300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximate analysis (wt%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture</td>
<td>5.76</td>
<td>3.32</td>
<td>2.97</td>
</tr>
<tr>
<td>Volatile matter (VM)</td>
<td>78.76</td>
<td>70.20</td>
<td>48.05</td>
</tr>
<tr>
<td>Fixed carbon (FC)</td>
<td>14.4</td>
<td>25.05</td>
<td>47.03</td>
</tr>
<tr>
<td>Ash</td>
<td>1.08</td>
<td>1.43</td>
<td>1.95</td>
</tr>
<tr>
<td>Elemental analysis (wt%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>48.64</td>
<td>56.58</td>
<td>69.56</td>
</tr>
<tr>
<td>H</td>
<td>5.64</td>
<td>5.55</td>
<td>4.77</td>
</tr>
<tr>
<td>N</td>
<td>0.52</td>
<td>0.52</td>
<td>0.12</td>
</tr>
<tr>
<td>O</td>
<td>44.09</td>
<td>35.9</td>
<td>23.6</td>
</tr>
<tr>
<td>S</td>
<td>0.03</td>
<td>0.02</td>
<td>0</td>
</tr>
<tr>
<td>Higher heating value (MJ kg⁻¹)</td>
<td>18.94</td>
<td>20.99</td>
<td>27.23</td>
</tr>
</tbody>
</table>

Fig. 2. Comparisons of CO conversion from water gas shift reaction at various steam/CO ratios and reaction temperature.

Fig. 3. Comparisons of (a) H2, (b) CO, (c) CO2, and (d) CH4 concentrations between thermodynamic predictions and experimental measurements.
In examining the distributions of syngas yield, Fig. 4a depicts that the syngas yield is lifted when bamboo is torrefied. The syngas yield from the gasification of TB250 is higher than that of raw bamboo by approximately 15–17%; the gasification of TB300 further increases the syngas yield by factors of 30–37% when ER_m is no less than 0.26. Seeing that more carbon is in TB300 and insufficient oxygen is supplied at ER_m = 0.20, its syngas yield is even lower than that of TB250. This results in that the maximum syngas yield develops at ER_m = 0.28. The lower heating value (LHV) of product gas is expressed as [13]

\[
\text{LHV}_{\text{product gas}} (\text{kJ Nm}^{-3}) = (30.0x_{\text{CO}} + 25.7x_{\text{H}_2} + 85.4\times_{\text{CH}_4}) \times 4.2
\]

where \(x\) stands for the mole fraction of gas species in the product gas (dry basis). As a whole, the LHV of the product gas shown in Fig. 4b depends strongly on ER_m and it is in the range of 4.49 and 7.81 MJ Nm^{-3}. On the other hand, the influence of feedstock on LHV is slight. Using torrefied bamboo as the feedstock lowers the \(\text{H}_2\) concentration in the product gas (Table 4), whereas it promotes the CO concentration. The former intensifies the LHV of the product gas but the latter abates it. This is the reason that the three curves shown in Fig. 4b are close to each other. In summary, more syngas is produced when torrefied bamboo is used as the feedstock, but the energy content of the product gas per unit volume changes slightly. When the two factors are considered together, as a result, the total energy of the product gas from the gasification of torrefied biomass goes up.

3.2. Cold gas efficiency and carbon conversion

The cold gas efficiency (CGE) is a crucial index to account for the performance of biomass gasification and it is defined as [11]

\[
\text{CGE} (%) = \frac{G_P \times \text{LHV}_{\text{product gas}}}{\text{HHV}_{\text{fuel}}} \times 100
\]

where \(G_P\) is the volume of product gas from the gasification of per unit weight of fuel (Nm^3 kg-fuel^-1) and \(\text{HHV}_{\text{fuel}}\) is the higher heating value of fuel (MJ kg-fuel^-1), respectively. Fig. 5a suggests that increasing \(\text{ER}_m\) lessens the value of CGE, stemming from the reduction of syngas yield (Fig. 4a). For the three fuels, the value of CGE is below 50% as long as \(\text{ER}_m\) is larger than 0.28. It follows that \(\text{ER}_m\) should be controlled below 0.3 from the thermodynamic point of view. When raw bamboo is torrefied at 250 and 300 °C, their HHV values are amplified by factors of 10.8% and 43.8%, respectively (Table 3). The increase in the HHV of TB300 results in its CGE being lower than the other two fuels as indicated in Eq. (27), even though the syngas yield is lifted.

### Table 4
Gas concentrations in the product gases from the gasification of raw bamboo, TB250, and TB300 (vol%, dry basis).

<table>
<thead>
<tr>
<th>ER_m</th>
<th>H2</th>
<th>CO</th>
<th>CO2</th>
<th>H2</th>
<th>CO</th>
<th>CO2</th>
<th>H2</th>
<th>CO</th>
<th>CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>29.23</td>
<td>35.75</td>
<td>3.30</td>
<td>27.22</td>
<td>38.22</td>
<td>0.46</td>
<td>23.34</td>
<td>35.79</td>
<td>0.41</td>
</tr>
<tr>
<td>0.22</td>
<td>27.75</td>
<td>34.13</td>
<td>4.04</td>
<td>25.91</td>
<td>36.83</td>
<td>1.09</td>
<td>22.00</td>
<td>35.69</td>
<td>0.41</td>
</tr>
<tr>
<td>0.24</td>
<td>26.34</td>
<td>32.58</td>
<td>4.75</td>
<td>24.53</td>
<td>35.06</td>
<td>1.96</td>
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<td>13.59</td>
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</tr>
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<td>22.06</td>
<td>9.61</td>
<td>15.42</td>
<td>23.18</td>
<td>7.83</td>
<td>12.71</td>
<td>24.68</td>
<td>6.11</td>
</tr>
</tbody>
</table>

In addition to CGE, the carbon conversion (CC) of the gasification system is also analyzed and it is defined as

\[
\text{CC} (%) = \left(1 - \frac{m_{\text{product gas}} (y_{\text{CO}} \frac{28}{12} + y_{\text{CO}} \frac{12}{28} + y_{\text{CH}_4} \frac{12}{16})}{m_{\text{fuel}} y_c}\right) \times 100
\]

where \(y_i\) is the mass fraction of species \(i\) in the product gas. The concentration of \(\text{CH}_4\) in the product gas is fairly low, implying that most of the carbon in feedstock is converted into CO and CO2. For raw bamboo and TB250, over 92% of carbon in the feedstocks is consumed, as shown in Fig. 5b. The CC of raw bamboo is slightly higher than that of TB250. In regard to TB300, it is not surprising that its CC is lower than those of the others, as a consequence of lower CGE, especially at \(\text{ER}_m < 0.28\) (Fig. 5a). When \(\text{ER}_m\) is larger than or equal to 0.28, the CC of TB300 is around 90.6%. Though more carbon is converted at higher values of \(\text{ER}_m\), more CO2 and less CO are produced (Table 4). The value of CGE decreases rather than increases with increasing \(\text{ER}_m\).
From the above observations, the optimum operating conditions and the gasification results of the three fuels at SSR = 0 are summarized in Table 5. For the raw bamboo and TB250, they should be operated at ER\textsubscript{m} = 0.2. A comparison between the two fuels, Table 4 indicates that the syngas yield is increased by a factor of 15.29% if the bamboo is torrefied at 250°C for 1 h. However, the increment in the LHV and CGE of the product gas is relatively slight. The CC of TB250 is even lower than that of raw bamboo. For TB300, the optimum operation is located at ER\textsubscript{m} = 0.272 and its syngas yield is higher than that of raw bamboo by 24.2%. However, the values of LHV, CGE, and CC of TB300 are lower than those

### Table 5

<table>
<thead>
<tr>
<th>Material</th>
<th>Raw</th>
<th>TB250</th>
<th>Increasing factor(^a) (%)</th>
<th>TB300</th>
<th>Increasing factor(^a) (%)</th>
</tr>
</thead>
<tbody>
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<td>Optimum ER\textsubscript{m}</td>
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<td>0.20</td>
<td>–</td>
<td>0.27</td>
<td>–</td>
</tr>
<tr>
<td>Syngas yield (Nm(^3)/kg)</td>
<td>1.57</td>
<td>1.81</td>
<td>15.29</td>
<td>1.95</td>
<td>24.20</td>
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<tr>
<td>LHV (MJ/Nm(^3))</td>
<td>7.68</td>
<td>7.81</td>
<td>1.69</td>
<td>6.57</td>
<td>–14.45</td>
</tr>
<tr>
<td>CGE (%)</td>
<td>63.79</td>
<td>67.26</td>
<td>5.44</td>
<td>47.08</td>
<td>–26.20</td>
</tr>
<tr>
<td>CC (%)</td>
<td>95.37</td>
<td>92.93</td>
<td>–2.56</td>
<td>90.63</td>
<td>–4.97</td>
</tr>
</tbody>
</table>

\(^a\) Increasing factor = \frac{Torrefied bamboo - Raw bamboo}{Raw bamboo} \times 100.
of raw bamboo and TB250. Accordingly, from the practical point of view, TB250 is a better feedstock for fuel gasification and syngas production.

3.3. Effect of steam

Subsequently, attention is paid to the effect of steam on the gasification results. The three-dimensional profiles of syngas yield, LHV, CGE, and CC are plotted in Figs. 6–9, respectively, where SSR ranges from 0 to 0.9. At present, 11 different values of ER_{m} (i.e. 0.2, 0.22, 0.24, 0.26, 0.28, 0.30, 0.32, 0.34, 0.36, 0.38, and 0.40) and 10 different values of SSR (i.e. 0, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, and 0.9) are taken into account. It is impossible to list all the operating conditions in a table. Therefore, only the air and
steam flow rates at the combinations of ER_m = 0.2, 0.3, and 0.4 and SSR = 0, 0.5, and 0.9 are listed in Table 6. Fig. 6 depicts that increasing SSR facilitates the syngas yield, no matter which fuel is fed. This is a consequence of more hydrogen produced from both the water gas and shift reactions, as expressed in Eqs. (22) and (24). With the addition of steam (i.e. SSR > 0), the distributions of syngas yield of the three feedstocks are similar to those at SSR = 0, but the influence of ER_m on the variation of syngas yield diminishes. An optimum ER_m can always be found at a given SSR under the situation of TB300 as the feedstock (Fig. 6c). For example, when SSR is equal to 0.9, the maximum syngas yield is 2.70 Nm^3 kg fuel/C_0 which occurs at ER_m = 0.3. As far as the LHV of product gas is concerned, Fig. 7 indicates that the LHV has a drastic trend to grow when ER_m goes down and SSR goes up. The maximum values of LHV from the gasification of raw bamboo, TB250, and TB300 are located at the same place of ER_m = 0.2 and SSR = 0.9 where their values are 10.85 (Fig. 7a), 11.21 (Fig. 7b), and 11.10 MJ Nm^{-3} (Fig. 7c), respectively.

An examination of the CGE of the three fuels, Fig. 8 reveals that the distributions of CGE are consistent with those of syngas formation (Fig. 6), reflecting that the increase in CGE is due to the increase of syngas yield. When more steam is blown into the gasification system to replace air, more hydrogen will be produced from the water gas reaction and the shift reaction. This is responsible for the improvement of syngas formation. The maximum values of syngas yield and CGE of raw bamboo, TB250, and TB300 are located at (ER_m, SSR) = (0.2, 0.9), (0.22, 0.9), and (0.28, 0.9), respectively. With the condition of fixed gasification temperature (i.e. 900 °C), it is noteworthy that CGE will exceed 100% at certain operating conditions. For instance, the maximum CGE of TB250 is 119.52% which develops at ER_m = 0.22 and SSR = 0.9. Similar results have been observed in the study of Renganathan et al. [36]. It was reported that the carbon would react with CO_2 to form CO in syngas. This contributed the LHV of the syngas and caused the value of CGE being greater than 100%. In the experimental study of Nipattumakul et al. [37], they also pointed out that the value of CGE exceeding 100% from the steam gasification of wastewater sludge was a result of substantial production of syngas.

Upon inspection of the CC distribution of raw bamboo, Fig. 9a reveals that the distribution almost keeps a constant (CC = 95.4%), even though the concentrations of CO and CO_2 vary with altering ER_m and SSR (Table 4 and Fig. 6). Similar results were also observed in the study of Campoy et al. [38]. The CC of TB250 is influenced by ER_m a bit when it is less than 0.22, whereas the variation of SSR almost plays no part in CC. The maximum and

### Table 6

A list of air and steam flow rates at various operating conditions.

<table>
<thead>
<tr>
<th>Fuels</th>
<th>ER_m</th>
<th>SSR</th>
<th>Air (kg h^{-1})</th>
<th>Steam (kg h^{-1})</th>
</tr>
</thead>
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<td>27.83</td>
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<tr>
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<td>0.5</td>
<td>14.89</td>
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<tr>
<td></td>
<td>0.9</td>
<td>2.78</td>
<td>6.53</td>
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<td>TB250</td>
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<td>6.85</td>
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</tr>
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<td>3.63</td>
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<td></td>
<td>0.9</td>
<td>2.98</td>
<td>6.69</td>
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</tr>
<tr>
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<td>41.74</td>
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<td>4.17</td>
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<td></td>
<td>0.9</td>
<td>4.47</td>
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<td>5.96</td>
<td>13.98</td>
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---

**Fig. 9.** Three-dimensional distributions of carbon conversion from the gasification of (a) raw bamboo, (b) torrefied bamboo at 250 °C and (c) torrefied bamboo at 300 °C.
minimum values of CC from the gasification of TB250 are 94.0 and 92.3%, respectively. For TB300, its CC is also insensitive to SSR, but ER\text{m} has a significant effect on CC in that the value changes from 74.3% to 90.6% when ER\text{m} rises from 0.2 to 0.28. Once ER\text{m} is larger than 0.28, the CC of TB300 remains invariant. Accordingly, it is concluded that the value of CC is mainly determined by CO and CO\textsubscript{2} concentrations. However, its relationship to syngas yield and CGE is slight.

4. Conclusion

A thermodynamic investigation on the gasification performances of raw bamboo, torrefied bamboo 250 °C (TB250), and torrefied bamboo at 300 °C (TB300) in a downdraft fixed bed gasifier has been carried out using Aspen Plus. From the viewpoint of syngas formation, the higher the torrefaction temperature, the better the syngas yield. However, the higher heating value of TB300 is much higher than those of raw bamboo and TB250; this results in the lowest CGE of TB300 among the three fuels. For raw bamboo and TB250, decreasing modified equivalence ratio (ER\text{m}) and increasing steam supply ratio (SSR), corresponding to increasing CO and H\textsubscript{2}, are able to intensify syngas formation. As a result, the CGE is enhanced and it may exceed 100% at certain operating conditions. There exists an optimum ER\text{m} for syngas production and CGE when TB300 is gasified at a given SSR, as a consequence of much higher carbon contained in the fuel. The highest carbon content in TB300 also leads to the lowest CC among the three fuels. When simultaneously considering syngas yield, CGE, and CC, the present study indicates that TB250 is more feasible than the other two fuels for biomass gasification. However, the process of biomass torrefaction implies that extra equipment and operating costs, such as energy for biomass torrefaction, torrefied biomass cooling, and tars production, are required. On the other hand, only two torrefied biomass materials (i.e. TB250 and TB300) are considered due to limited experimental data. The topics of simultaneously considering capital and operating costs for biomass torrefaction and gasification as well as the optimum torrefaction temperature deserve further investigation in the future.

Acknowledgment

The authors gratefully acknowledge the financial support of the National Science Council, Taiwan, ROC, on this study.

References