



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.

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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_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_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_m and SSR, but more CO_2 is produced when ER_m increases, thereby reducing CGE. 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. The predictions suggest that TB250 is a more feasible fuel for gasification after simultaneously considering syngas yield, CGE, and CC.

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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)⁻¹ and 4.76–5.44 MJ Nm⁻³. González et al. [10] tested olive orujillo gasification in a laboratory reactor at atmospheric pressure and temperatures of 750–900 °C. They reported that H₂ and CO formation favored high-temperature environments and the maximum H₂ and CO molar fractions occurred at temperatures of 750 and 900 °C, respectively. Gai and Dong [11] demonstrated non-woody

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Nomenclature

A	total number of atomic masses in the system	P	pressure (atm)
AFR	air-to-fuel mass flow rate ratio	R	universal gas constant ($=8.314 \text{ J mol}^{-1} \text{ K}^{-1}$)
SSR	steam supply ratio	T	temperature ($^{\circ}\text{C}$)
a	amount of air per mole of fuel (mol mol fuel^{-1})	x	mole fraction
a_{ik}	coefficient in element species matrix representing species i containing element k	y	mass fraction
b	amount of steam per mole of fuel (mol mol fuel^{-1})	<i>Greek letters</i>	
CC	carbon conversion (%)	μ	chemical potential
CGE	cold gasification efficiency (%)	ϕ	fugacity coefficient
c	amount of carbon dioxide per mole of fuel (mol mol fuel^{-1})	λ_k	Lagrange multipliers
d	amount of carbon monoxide per mole of fuel (mol mol fuel^{-1})	ω	total number of elements comprising the system
ER_m	modified equivalence ratio	<i>Superscript</i>	
e	amount of methane per mole of fuel (mol mol fuel^{-1})	$^{\circ}$	standard reference state
f	amount of nitrogen per mole of fuel (mol mol fuel^{-1})	<i>Subscripts</i>	
f_i	the fugacity of pure species i	air	air
f_i	the fugacity of species i in solution	ash	ash
G_p	the volume of product gas from the gasification of per unit weight of fuel ($\text{Nm}^3 \text{ kg fuel}^{-1}$)	biomass	biomass
G^t	total Gibbs free energy of system (J)	i	species i
G_i°	a property of pure species i in its standard state (J)	j	species j
ΔG_f°	standard Gibbs-energy change of reaction (J mol^{-1})	k	chemical element index
g	amount of hydrogen per mole of biomass (mol mol fuel^{-1})	out	output
\dot{H}	the enthalpies of material streams (kJ h^{-1})	rxn	reaction
HHV	higher heating value fuel (MJ kg fuel^{-1})	product gas	product gas of the gasification
L	Lagrange function	steam	steam
$LHV_{\text{product gas}}$	lower heating value of product gas (kJ Nm^{-3})	x	number of hydrogen atoms per carbon atom in biomass molecule
\dot{m}	mass flow rate (kg h^{-1})	y	number of oxygen atoms per carbon atom in biomass molecule
N	total number of species in the reaction mixture	z	number of nitrogen atoms per carbon atom in biomass molecule
n	number of moles		
\dot{Q}_{rxn}	heat of reaction (kJ h^{-1})		

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 thus lower and usually in the range of 4–7 MJ Nm^{-3} . In contrast, the LHV of the product gas from gasification using steam as an oxidizer is between 10 and 15 MJ Nm^{-3} and the hydrogen yield is higher [7], as a result of water gas shift reaction. However, biomass steam gasification requires external heat because of the endothermic steam reforming reactions involved [1,12]. By virtue of the aforementioned advantages and disadvantages from air or steam blown process, some studies addressed biomass gasification using the mixture of air and steam as the oxidizing agent [12,13].

In reviewing past literature, in addition to experimental studies, attempts in simulating biomass gasification have been carried out to evaluate the gasification performance affected by various operating conditions. The simulations of biomass gasification can be divided into kinetic rate models and thermodynamic equilibrium models. The equilibrium models are useful tools for recognizing biomass gasification behavior [14]. Li et al. [15] used a non-stoichiometric equilibrium model based on the method of Gibbs free energy minimization to predict the performance of coal gasification. Jarungthammachote and Dutta [16] used the thermodynamic equilibrium model to evaluate the gas compositions in the product gas from the gasification of municipal solid waste in a downdraft gasifier. Nikoo and Mahinpey [17], Doherty et al. [18], and Ramzan et al. [19] adopted the Aspen Plus simulator to predict

the compositions and cold gas efficiency (CGE) of the product gas from biomass gasification in a fixed bed, a fluidized bed, and a circulating fluidized bed gasifiers, respectively, where the equilibrium models were adopted as well.

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 $^{\circ}\text{C}$ 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 torrefaction, this pretreatment process produces more uniform feedstocks of consistent quality and makes the control of burning biomass or the use as a feedstock easier. By virtue of these advantages, torrefied biomass is considered as a more valuable fuel than raw biomass.

Most of the studies of biomass gasification were performed using raw biomass as feedstocks and relatively little research has been carried out using torrefied biomass as the fuel in gasification. Prins et al. [26] gave a preliminary assessment of air-blown gasification of torrefied wood and found that the thermodynamic loss was likely to be reduced from torrefied biomass torrefaction. Deng et al. [27] torrefied rice straw and rape stalk for their co-gasification with coal. They mentioned that the properties of the torrefied agricultural residues were closer to those of coal, so torrefaction was a promising method for co-gasification. Couhert et al. [28] evaluated the impact of torrefaction on syngas production from wood gasification in an entrained flow reactor. Seeing that torre-

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