CHEMICAL ENGINEERING TRANSACTIONS
VOL. 70, 2018
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Timothy G. Walmsley, Petar S. Varbanov, Rongxin Su, Jiří J. Klemeš

ISBN 978-88-95608-67-9; **ISSN** 2283-9216
DOI: 10.3303/CET1870283

Biomass Steam Gasification of Sugarcane Leftover for Green Diesel Production

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Biomass gasification is one of attractive processes for syngas production. In this research, sugarcane leftover is selected to use as feedstock. The produced gas has a purpose to use for green liquid fuels production through Fischer-Tropsch process. Consequently, this search aims to develop the model of syngas production from sugarcane leftover by using AspenPlus™ simulation software. In order to obtain syngas that suitable for producing liquid fuel, the content of some contaminants, i.e., CO_2 and H_2S must be concerned and thus, this process should be integrated with gas cleaning. The simulation was performed by using steam as gasifying agent. The effect of operating conditions in gasifier was also examined to find optimal conditions that provide the highest cold gas efficiency. The results showed that syngas content increases significantly with an increase in temperature and it reaches a stable at temperature higher than 750 °C. The optimal steam to biomass molar ratio is 0.6. Moreover, the absorption process by monoethanolamine (MEA) was studied to reduce H_2S in syngas (below 0.1 mg/Nm^3). Under this requirement, it was found that the optimal operating condition of adsorber is pressure of 40 bar and tray number of 10 by using MEA molar flow rate of 325 kmol/h.

1. Introduction

Presently, biomass is an interesting renewable energy source that can directly replace the depleting fossil fuels for fuel production, leading to a decrease in climate change and pollutant emission (Gadsboll et al., 2017). The advantage of using biomass is to not have CO_2 emissions into the environment owing to the cogeneration neutralization reaction. This means that the CO_2 quantities occurred via the biomass conversion is approximately same as the amount of CO_2 consumed during the plant growth (Katare and Madurwar, 2017). Many researchers have been focused on the conversion of various biomasses into fuel. Sugarcane is one of the most interesting agricultural plants with the highest bioconversion efficiency. Many parts of sugarcane can use as raw materials for industrial processes. For example, the sweet liquid (juice) inside sugarcane stalks containing sucrose is used to produce sugar and ethanol. With the sugar and ethanol productions are growing, residues from sugarcane, i.e., bagasse, leaves and tops are more generated. Bagasse can be used as alternative sources for paper production (Rainey et al., 2006), power generation, and energy production (Khatiwada et al., 2012) whereas the leaves and tops of sugarcane stalks (referred to sugarcane leftovers) are generally combusted in the field, not used for energy production. Therefore, this work is concentrated on the using sugarcane leftovers as raw material for the fuel production to add value of the agricultural waste,
Many researchers have been concentrated to develop methods to use more biomass as fuel. Biomass can be converted to synthesis gas (syngas) by gasification process considered as a key technology for biofuels production and then syngas can be continuously converted to liquid fuels or chemicals such as green diesel and methanol. This process is called biomass to liquid (BTL). Syngas production from this process is a high temperature endothermic process that also is suitable for heat and power generation (Miao et al., 2014). According to these benefit, the gasification process through thermo-chemical reactions is presently considered

Please cite this article as: Chatrattanawet N., Kanjanasorn W., Authayanun S., Saebea D., Patcharavorachot Y., 2018, Biomass steam gasification of sugarcane leftover for green diesel production , Chemical Engineering Transactions, 70, 1693-1698 DOI:10.3303/CET1870283

as a promising choice in industrial applications. Among gasifiers used in the gasification process, circulated fluidized bed (CFB) gasification technology is considered to convert biomass to syngas due to its high reaction rates and high thermal efficiency (Chutichai et al., 2015). There are several kinds of gasifying agents including steam, air, and air-steam. The use of steam as agent is the common alternative for biomass gasification process to produce the syngas rich in hydrogen (Detchusananard et al., 2017). However, the steam biomass gasification has unavoidably problem with undesirable H_2S and tar occurred during the process. Thus, the obtained syngas should be purified by removing contaminants, i.e. H_2S and CO_2 before supplying to other process. For eliminating impurities, the product gas leaving the gasifier is fed into a gas cleaning unit. An absorption process using monoethanolamine (MEA) as solvent is an interesting technology for implementing to remove CO_2 and H_2S from power plants (Abu-Zahra et al., 2007).

The aim of present work is to concentrate on the steam biomass gasification process to produce clean syngas for the green diesel production under highest cold gas efficiency. Sugarcane leftovers are used as biomass input for syngas production. The process design flow sheet for circulating fluidized bed gasifier is developed in the Aspen Plus. Then, the effect of gasifier operating conditions such as gasifying temperature and steam to biomass (S/B ratio) on product gas compositions, cold gas efficiency (CGE), and total energy consumption is studies to define the optimal operating condition for syngas production. Moreover, the effect of absorber parameters on the H_2S and CO_2 removal is considered.

2. Description of gasification process

In order to study the gasification process, there are many researches using process simulation software as Aspen Plus software that is the most commonly used to simulate process (Muslim et al., 2017). The flowsheet of steam biomass gasification of sugarcane leftovers is designed in Aspen Plus simulator, as shown in Figure 1 to analyze syngas composition and its efficiency. Firstly, sugarcane leftovers used as a non-conventional biomass are heated by B-HEATER unit and then they (HT-FEED) are fed into a conversion reactor (DECOMP) that can convert to conventional components, i.e. carbon, hydrogen, oxygen, nitrogen, sulphur, and ash (ELEMENTS). The components in ELEMENTS stream are calculated via considering proximate and ultimate analyzes. Water also heated by S-HEATER and the outlet stream from DECOMP unit are fed to circulating fluidize bed gasifier (GASIFIER) to simulate the biomass gasification using RGIBB reactor. Finally, the gases obtained from GASIFIER unit are sent to C-SEP unit to separate ash from syngas. Figure 2 shows the diagram of gas cleaning unit. The gases (SYNGAS) produced from steam gasification process should be sent to gas cleaning unit in order to remove all contaminants before using as a fuel for liquid fuels production. The chemical absorption process is considered to eliminate contaminants such as H_2S and CO_2. MEA is used as absorption solvent for CO_2 and H_2S captures in ABSORBER unit. Cleaned syngas in FT-FEED stream will be used as reactant for the production of liquid fuels through Fisher-Tropsch process.

3. Methodology

In this work, the thermodynamic calculation is performed by using AspenPlus^{TM}. The sugarcane leftovers are selected as the feedstock for steam biomass gasification process and its properties such as proximate analysis and ultimate analysis are presented in Table 1. The initial operating conditions for biomass and steam in gasification process include the inlet molar flow rate of 100 kmol/h, temperature of 25 °C, and pressure of 1 bar. Decomposition reactor and circulating fluidized bed gasifier are the same condition at 800 °C and 1 bar. For gas cleaning unit, the solvent used for absorber included 20 % MEA and 80 % H_2O is fed with the molar flow rate of 500 kmol/h, temperature of 25 °C, and pressure of 1.4 bar. The absorption column is operated at 5 trays and 1 bar.

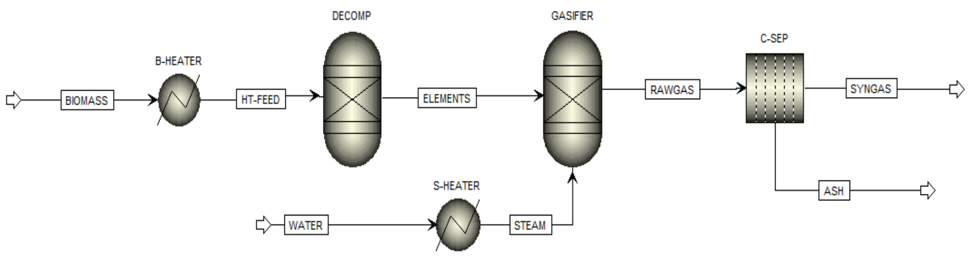


Figure 1: A schematic diagram of steam biomass gasification of sugarcane leftovers

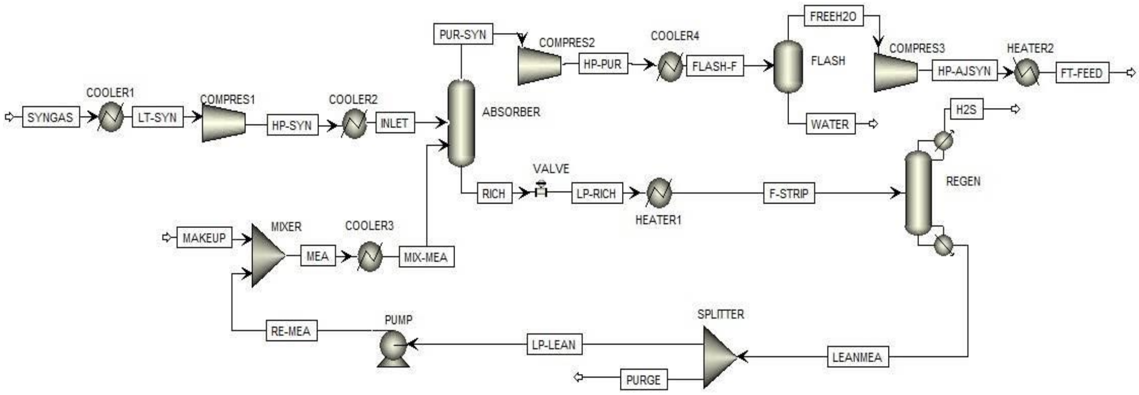


Figure 2: A simulation flowchart of the gas cleaning unit

Table 1: Proximate and ultimate analysis of sugarcane leftovers

Proximate analysis (wt.%)		Ultimate analysis (wt.% dry basis)	
Moisture	9.20	C	46.152
Fixed carbon	16.90	H	5.632
Volatile matter	67.80	O	41.485
Ash	6.10	N	0.443
		S	0.188

A standard gasification process comprises the steps as following: drying, pyrolysis, cracking, and reduction to form syngas, char, tar, and heavy hydrocarbons. In the GASIFIER unit, the chemical equilibrium calculation is based on the Gibbs free energy minimization using Soave-Redlich-Kwong as equation of state and the main reactions for biomass gasification with steam as gasifying agent are shown by Eqs(1)-(5) for combustion reactions and Eqs(6)-(12) for reduction reactions.

$$C + 1/2O_2 \rightarrow CO \quad (1)$$

$$C + O_2 \rightarrow CO_2 \quad (2)$$

$$CO + 1/2O_2 \rightarrow CO_2 \quad (3)$$

$$H_2 + 1/2O_2 \rightarrow H_2O \quad (4)$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (5)$$

$$C + CO_2 \rightarrow 2CO \quad (6)$$

$$C + H_2O \rightarrow CO + H_2 \quad (7)$$

$$C + 2H_2 \rightarrow CH_4 \quad (8)$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (9)$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad (10)$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \quad (11)$$

$$CH_4 + CO_2 \rightarrow 2CO + 2H_2 \quad (12)$$

The cold gas efficiency, CGE is defined as expressed in Eq(13). ELECNRTL is used as equation of state for absorption process.

$$\%\mathrm{CGE} = \frac{\left(n_{\mathrm{H_2}} \times \mathrm{LHV}_{\mathrm{H_2}}\right) + \left(n_{\mathrm{CO}} \times \mathrm{LHV}_{\mathrm{CO}}\right)}{\left(n_{\mathrm{Biomass}} \times \mathrm{LHV}_{\mathrm{Biomass}}\right)} \times 100 \qquad (13)$$

4. Results and discussion

Biomass gasification of sugarcane leftovers using steam as gasifying agent is studied for the syngas production. This part presents the validation result for ensuring the proposed model, the syngas production section for finding the optimal operating condition, and the gas cleaning unit for syngas purification.

4.1 Comparison with experimental results

Since the experiment data of sugarcane leftovers gasification has not been reported in the literatures, the simulation result was validated with data extracted from Kaewpanha et al. (2014). In their experiment, Japanese cedar and steam were used as feedstock in biomass gasification. The gasifier was operated at 700 °C with steam to biomass (S/B) ratio of 1. The proximate analysis and ultimate analysis of Japanese cedar are presented in Table 2. The comparison of the model predictions and the experimental data is shown in Table 3. The result can indicate that the simulation results are rather close to the experiment data, leading to ensuring to implement this model prediction for this study. Although the feedstock proposed in this work is different from the literature, if the simulation value is close to the experiment result under same feedstock and operating condition and thus, it can guarantee the accuracy of proposed model. This is reasonable to use the proposed model for studying the gasification from sugarcane leftovers.

4.2 The production of synthesis gas

The effect of gasifier temperature and S/B ratio are investigated to select the suitable operating conditions under the maximum cold gas efficient. Figure 3(a) shows the effect of the gasifying temperature (500-1,000 °C) on the product gas components, syngas molar flow rate, and cold gas efficiency by setting the S/B ratio at 1. An increase in the gasifier temperature causes a significant increase in the amount of H_2 and CO because of boudouard reaction, heterogeneous water–gas reaction, and steam and dry reforming reactions of methane, as expressed in Eqs. (6), (7), and (10)-(12). Thus, the concentrations of CO_2, CH_4, and H_2O decrease. At higher temperature (> 700 °C), it can be seen that the concentration of H_2O slightly increases and that of H_2 decreases due to reverse water gas shift, Eq.(9). The effect of temperature on the cold gas efficiency is also investigated, as shown in Figure 3(b). The cold gas efficiency will significantly increase when the temperature is operated below 750 °C. Then it slightly increases. Moreover, the cold gas efficiency shows the same trend with the syngas composition. Therefore, the suitable gasifier temperature is selected at 750 °C, leading to the maximum cold gas efficiency of 115.

The variations of the product gas composition, syngas molar flow rate, and cold gas efficiency due to changing in the S/B ratio (0.04-2) are shown in Figure 4. The gasifier temperature is set at 750 °C. The results show that the concentrations of H_2 and CO are a little increase due to heterogeneous water–gas reaction (Eq(7)) and methane steam reforming reaction Eq(10). Then, they will significantly decrease at S/B ratio operated higher 0.2 and 0.4 for CO and H_2, respectively. This is because the water gas shift reaction (Eq(9)) has more influence than heterogeneous water–gas reaction. Like the gasifier temperature effect, the syngas molar flow rate and cold gas efficiency show the same trend. Hence, the proper S/B ratio is selected at 0.6.

Table 2: Proximate and ultimate analysis of Japanese Cedar (Kaewpanha et al., 2014)

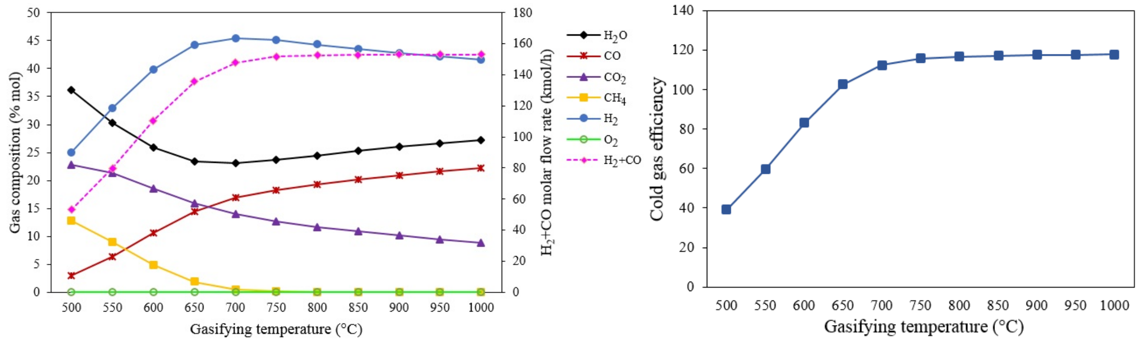
Proximate analysis (wt.% dry basis)			
Moisture	5.0	Volatile matter	52.8
Fixed carbon	33.7	Ash	13.5

Ultimate analysis (wt.% dry basis)			
C	39.2	N	1.9
H	5.0	S	1.5
O	52.4		

Then, the total energy consumption is studied as a wider range of S/B ratio (0.04-3) while the gasifier temperature is kept as constant at 750 °C. The steam generator, gasifier, and product gas cooler are included in the calculation of the total energy consumption. The result as shown in Figure 5 indicates that the total energy consumption increases when the S/B ratio increases due to the highly endothermic reaction, i.e., water gas, and steam and dry reforming reaction of methane. Although this process requires the external heat source, it has opportunity to perform energy integration with other units. Furthermore, if the thermal self-sufficient operation is concerned, air or steam-air should be used as gasifying agents instead of only-steam.

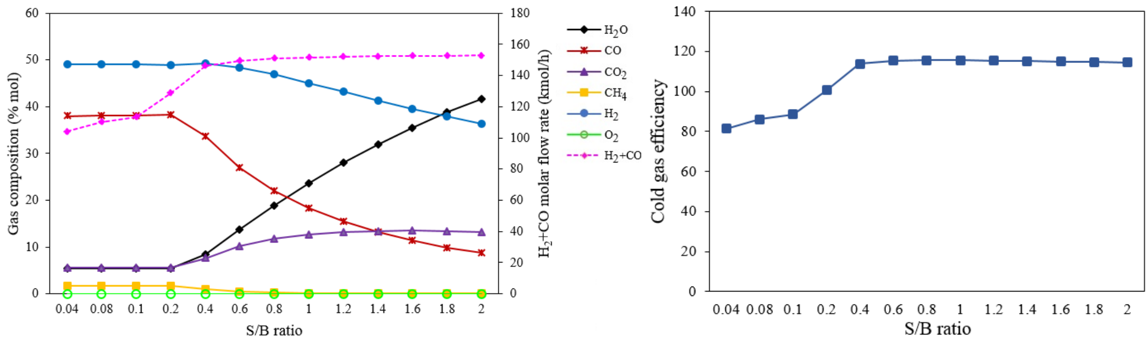
Table 3: Comparison between simulation result and experimental data from (Kaewpanha et al., 2014)

Gas composition (% volume)	Experimental data	Simulation data
H_2	44.4	45.9
CO	18.5	21.3
CO_2	29.6	27.6



(a) (b)

Figure 3: Effect of gasifying temperature on (a) gas composition (solid line) and H_2+CO molar flow rate (dash line) and (b) cold gas efficiency



(a) (b)

Figure 4: Effect of S/B ratio on (a) gas composition (solid line) and H_2+CO molar flow rate (dash line) and (b) cold gas efficiency

4.3 Gas cleaning unit

The product gas obtained from biomass gasification process still consists of impurities such as H_2S and CO_2. Syngas used for Fisher-Tropsch must have H_2S content less than 0.1 mg/nm^3. Thus, the adsorption unit is studied by varying the pressure (5-50 bar) and tray (2-10) of adsorber, and molar flow rate of MEA (100-1,000 kmol/h). The simulation result shows that an increase in column pressure and tray and molar flow rate of MEA causes better the absorption of H_2S and CO_2. The suitable operating condition for absorption process is defined at MEA molar flow rate of 325 kmol/h, column pressure of 40 bar, and column tray of 10. Although the adsorption unit can remove H_2S and CO_2, it may provide high cost. In order to ensure that the use of adsorption unit as purification process is suitable for gasification, the economic analysis should be considered.

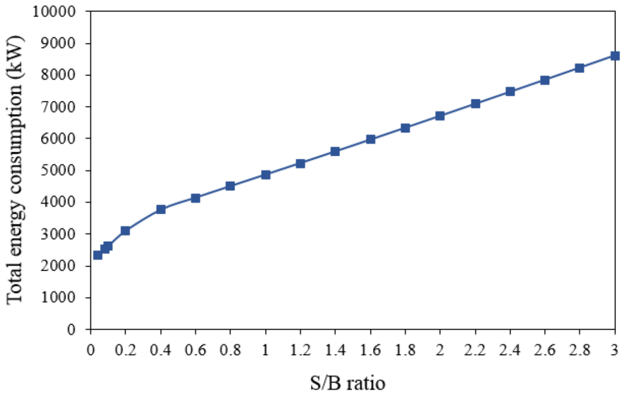


Figure 5: Effect of S/B ratio on total energy consumption

5. Conclusions

The biomass gasification of sugarcane leftovers was analyzed by using steam as gasifying agent. The syngas generated from this process will be used to produce the green liquid fuels via Fisher-Tropsch process. The effects of gasifying temperature and S/B ratio on product gas composition, cold gas efficiency, and total energy consumption were studied to determine the optimal operating condition for biomass gasification process. The simulation results showed that the operating condition for steam biomass gasification under the maximum cold gas efficiency was the gasifier temperature of 750 °C and S/B ratio of 0.6. Then, the effect of operating conditions of adsorber was examined. In order to reduce the H_2S content below 0.1 mg/Nm^3, the adsorber with 10 trays should be operated at 40 bar by using MEA molar flow rate of 325 kmol/h.

Acknowledgments

The authors gratefully acknowledge the supports from King Mongkut's Institute of Technology Ladkrabang (KREF146101).

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