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Research Article

Modeling and Simulation of Biomass Gasification with Aspen Plus for Different Types of Local Biomass from Riau Province

Pemodelan dan Simulasi Gasifikasi Biomassa dengan Aspen Plus untuk Berbagai Jenis Biomassa Lokal di Provinsi Riau

Asshiyami Zikra[1)], Ricky Okta Yohannes[1)], Faiprianda Assyari Rahmatullah[1)], Hari Rionaldo[1)], Zulfansyah[1*)]

[1)]*Universitas Riau, Department of Chemical Engineering, Bina Widya Campus KM 12.5, Simpang Baru, Tampan District, Pekanbaru City, Riau, 2829, Indonesia*

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*Corresponding Author.
Email: zulfansyah@lecturer.unri.ac.id

Abstract

Gasification is a promising technology for electrical energy generation systems in palm oil mills. The syngas components, namely CH_4, H_2, and CO, produced from gasification can be used as fuel to produce steam, which will be applied in turbine generators to produce electricity. Therefore, this study aimed to simulate and validate a flowsheet model of gasification process for oil palm mill waste using Aspen Plus to achieve an optimal syngas composition, and conduct sensitivity analysis by varying gasification temperature, equivalent ratio, as well as correlating biomass moisture content to syngas composition. Biomass moisture content, equivalent ratio, and gasification temperature are important parameters that affect the chemical composition and heating value of syngas analyzed using the sensitivity analysis method. The results showed that the syngas composition was sensitive to the parameters of temperature, moisture content, and equivalent ratio. The operating conditions of gasification process to obtain a high heating value of syngas include 650˚C gasification temperature, 0% moisture content, and 0.2 equivalent ratios.

Keywords: aspen plus; gasification; modelling; palm solid waste; simulation

Abstract
Gasifikasi merupakan teknologi menjanjikan untuk digunakan sebagai sistem pembangkitan energi listrik di pabrik kelapa sawit. Komponen syngas, yaitu CH_4, H_2, dan CO, yang dihasilkan dari proses gasifikasi dapat digunakan sebagai bahan bakar untuk menghasilkan uap, dan kemudian diaplikasikan pada turbin generator untuk menghasilkan listrik. Oleh karena itu, penelitian ini bertujuan untuk mensimulasikan dan memvalidasi model flowsheet dari proses gasifikasi limbah pabrik kelapa sawit menggunakan Aspen Plus guna memperoleh komposisi syngas optimal, serta melakukan analisis sensitivitas dengan memvariasikan temperatur gasifikasi, rasio ekuivalen, dan mengaitkan kadar air biomassa terhadap komposisi syngas. Kadar air biomassa, rasio ekuivalen, dan temperatur gasifikasi merupakan parameter kunci yang secara signifikan memengaruhi komposisi kimia serta nilai kalor syngas, sebagaimana dianalisis melalui metode analisis sensitivitas. Hasil penelitian menunjukkan bahwa komposisi syngas sangat sensitif terhadap parameter temperatur, kadar air, dan rasio ekuivalen. Kondisi operasi dari proses gasifikasi untuk memperoleh nilai kalor syngas yang tinggi meliputi temperatur gasifikasi sebesar 650˚C, kadar air 0%, dan rasio ekuivalen 0,2.
Kata kunci: *aspen plus; gasifikasi; limbah padat kelapa sawit; pemodelan; simulasi*

1. Introduction

Riau has the largest oil palm plantation area in Indonesia, with 2.87 million hectares in 2022, accounting for 18.70% of the country total oil palm plantation area [1]. Meanwhile, palm oil milling industry, responsible for crude palm oil (CPO) production, is a major contributor to solid waste generation. This solid waste produced includes palm shells, fibers, and empty fruit bunches (EFBs), which constitute approximately 40–41% each tonne of processed palm oil. Solid waste from palm oil mills, namely shells, fibers, and empty bunches, has considerable potential when used as fuel due to the high calorific values, reaching 23.604,71 kJ/kg, 14.511,961 kJ/kg, and 17.854,807 kJ/kg, respectively [2]. Conventionally, a mixture of palm fibers and shells is used as boiler fuel to generate steam for driving power plant turbines [3]. Meng et al. [4] has done an experiment using a biomass from plant and resulted a heating value as high as 11.676,61 kJ/Nm^3.

Gasification has been proposed as an alternative technology for converting biomass into renewable energy [5]. Biomass gasification comprises the thermochemical conversion of solid biomass fuels into combustible gas. The process produces syngas that consists of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), a small amount of high chain hydrocarbons (ethene and ethane), water (H_2O), nitrogen (N_2), and various small particulates such as charcoal, ash, tar, and alkali. Biomass gasification process is modeled using four stages, namely drying, pyrolysis, gasification (oxidation and reduction), and gas cleaning.

Recent studies have shown the feasibility of palm oil biomass gasification for renewable energy applications. Sivabalan et al. [6] reported the high efficiency, feedstock flexibility, and reduced emissions associated with biomass gasification. Mohammed et al. [7] investigated the thermal decomposition behavior and kinetics of oil palm empty fruit bunch (EFB) gasification, reporting that the high volatile matter content of EFBs enhanced reactivity and facilitates syngas production. Similarly, Aktawan et al. [8] showed that increasing biomass feedstock input significantly improved syngas yield, reinforcing the potential of oil palm shells and EFBs as viable feedstocks for gasification-based bioenergy systems.

The oxidation and reduction reactions that occur in gasification process are shown in equations (1) - (9) [9]. Equation (1) is a carbon oxidation. Equation (2) is a partial oxidation of carbon. Equation (3) is carbon monoxide oxidation. Equation (4) is hydrogen oxidation. Equation (5) is Boudouard reaction. Equation (6) is reforming of char. Equation (7) is water gas shift reaction. Equation (8) is hydrogasification. Equation (9) is steam-methane reforming.

$$\text{Char} + O_2 \rightarrow CO_2\ (\Delta H = -394\ \text{kJ/mol}) \quad \textbf{(1)}$$
$$C + 0.5O_2 \rightarrow CO\ (\Delta H = -110\ \text{kJ/mol}) \quad \textbf{(2)}$$
$$CO + 0.5O_2 \rightarrow CO_2\ (\Delta H = -283\ \text{kJ/mol}) \quad \textbf{(3)}$$
$$H_2 + 0.5O_2 \rightarrow H_2O\ (\Delta H = -242\ \text{kJ/mol}) \quad \textbf{(4)}$$
$$C + CO_2 \leftrightarrow 2CO\ (\Delta H = 172\ \text{kJ/mol}) \quad \textbf{(5)}$$
$$C + H_2O \leftrightarrow CO + H_2\ (\Delta H = 131\ \text{kJ/mol}) \quad \textbf{(6)}$$
$$CO + H_2O \leftrightarrow CO_2 + H_2\ (\Delta H = -42\ \text{kJ/mol}) \quad \textbf{(7)}$$
$$C + 2H_2 \leftrightarrow CH_4\ (\Delta H = -75\ \text{kJ/mol}) \quad \textbf{(8)}$$
$$CH_4 + H_2O \leftrightarrow CO + 3H_2\ (\Delta H = 206\ \text{kJ/mol}) \quad \textbf{(9)}$$

Given the high cost and risk of gasification experiment process, model is needed to consider factors associated with the process to achieve the actual results. The use of simulation and gasification model can be an initial scale reference for studying and understanding more deeply gasification process to achieve the optimal biomass composition and produce syngas with a maximum HHV (Higher Heating Value). The higher the HHV, the better syngas quality produced.

Gasification simulation using Aspen Plus has proven to be a powerful tool for optimizing biomass conversion processes, particularly for oil palm biomass. Several studies have shown the importance of detailed kinetic modeling, secondary reactions, and process parameter optimization in improving syngas quality and overall gasification efficiency. Mohammed et al. [7] investigated gasification of oil palm empty fruit bunches (EFB) using simulation, concluding that high volatile matter content enhanced gasification efficiency, making EFB a promising feedstock. Additionally, Samiran et al. [10] reviewed advancements in biomass gasification modeling and reported that Aspen Plus simulation are essential for optimizing gasifier designs and process conditions, allowing for systematic studies on feedstock variability, equivalent ratio, and catalyst selection. Therefore, this study aimed to: (1) create a flowsheet model of gasification process for oil palm mill waste using Aspen Plus, (2) simulate and validate the process model to achieve the desired syngas composition, and (3) conduct sensitivity analyses by varying gasification temperature, equivalent ratio, and correlating biomass water content to syngas composition. The results from gasification model will provide insights into biomass characteristics affecting syngas production.

2. Research Methods

2.1 Feedstock

Biomass used as feed in gasification process consists of shells, fibers, empty palm bunches, and a mixture of palm shells with a ratio of 4:1, commonly used as boiler fuel feed in palm oil mill plants. The composition of biomass was taken based on Proximate and Ultimate analysis because the components were not available in the Aspen Plus database. The Proximate and Ultimate analysis data of palm kernel shells, fibers, and empty bunches were taken from the experiment conducted by Surahmanto et al. [11] as shown in Table 1. Biomass component is defined as a non-conventional solid with the name BIOMASS. A by-product, formed from gasification process, is defined as ASH in the component with the non-conventional solid type.

Table 1. Proximate and Ultimate analysis of the feedstock

Parameter	Shell	Fiber	Empty bunch
Proximate Analysis			
- Moisture (%wt)	7.63	7.736	8.503
- Fixed Carbon (%wt)	27.976	23.521	22.004
- Ash (%wt)	1.038	6.075	7.062
- Higher Heating Value (%wt)	4781.011	4359.673	3757.582
Ultimate Analysis			
- Ash (%wt)	1.038	6.075	7.062
- Carbon (%wt)	49.01	42.93	40.63
- Hydrogen (%wt)	6.18	6.09	6.11
- Nitrogen (%wt)	0.27	1.15	1.23
- Sulphur (%wt)	0.04	0.14	0.14
- Oxygen (%wt)	43.462	43.615	44.828

2.2 Physical Property Method

The enthalpy and density were modeled with HCOALGEN and DCOALIGT for biomass and ash. Peng-Robinson with Boston-Mathias modification (PR-BM) was used as a property package because it can estimate the physical properties of conventional components. Property package PR-BM was suggested for gas, petrochemical, and refinery process applications [12]. The stream class was defined as MIXCINC, because there are two components, namely conventional and non-conventional, with solid particles in the process.

2.3 Model Assumptions

Biomass gasification simulation in Aspen Plus took into account several considerations for the downdraft gasifier configuration model, which refers to [13]. These considerations included:

1. The process operated under steady state and isothermal conditions.
2. Operation took place at atmospheric pressure with all pressure and heat losses neglected.
3. Char was 100% carbon.
4. Air consisted of 79% N_2 and 21% O_2 in moles.
5. Nitrogen was an inert compound, and does not react.
6. Sulfur bound to the feed was only converted to hydrogen sulfide (H_2S).
7. Tar formation was significantly reduced in the process.

2.4 Model Validation

Model validation was carried out to determine the accuracy of the designed simulation. The composition obtained from simulation was compared to the experimental results. Simulation was validated using experimental data from Striugas et al. [14].

The sum-squared deviation method was used to estimate the accuracy of simulation results. The sum squared deviation method can provide information on the accuracy of model used in predicting a value. In addition, it can be used to compare several different model to determine the most accurate. The sum-squared deviation method is shown in equations (10) - (12) [13]. Equation (10) is ranked set sampling. Equation (11) is median ranked set sampling. Equation (12) is mean error equation. y_{ie} is experimental syngas composition, y_{ip} is simulated syngas composition, and N is the number of components in syngas.

$$RSS = \sum_{i=1}^{N}\left(\frac{y_{ie}-y_{ip}}{y_{ie}}\right)^2 \quad \text{.......(10)}$$

$$MRSS = \frac{RSS}{N} \quad \text{.......(11)}$$

$$Mean\ Error = \sqrt{MRSS} \quad \text{.......(12)}$$

2.5 Sensitivity Analysis

Sensitivity analysis is often used to determine the effect of changes in variables or parameters that occur on the optimal solution obtained. In biomass gasification simulation using Aspen Plus, a sensitivity analysis was conducted to investigate the effect of temperature, equivalent ratio, and moisture content on syngas composition and HHV. Biomass moisture content, equivalent ratio, and gasification temperature are the most important parameters affecting syngas chemical composition and heating value.

In this study, equivalent ratio and HHV were defined respectively in equation (13) and (14). Actual AFR is the ratio of air and fuel that occurs in the combustion process, and stoichiometric AFR is the ideal ratio of air and fuel needed to achieve complete combustion [15]. X is the volume percentage of each gas component [16].

$$\text{Equivalent Ratio} = \frac{\text{AFR actual}}{\text{AFR stoichiometry}} \quad \text{......(13)}$$

$$\text{HHV} = X_{H_2}.33867.113 + X_{CH_4}.13237.094 + X_{CO}.2201.482 \quad \text{..................(14)}$$

3. Results and Discussion

The processes were designed using unit operation blocks that are integrated into a flowsheet model design. Simulation of gasification process was carried out using Aspen Plus to evaluate the performance of the gasifier with variations in feedstock. The overall biomass gasification simulation model is shown in Figure 1.

The model developed using Aspen Plus was validated with experimental data published by Striugas et al. [14]. Comparison of simulation with the experimental results in reference [14] is shown in Figure 2.

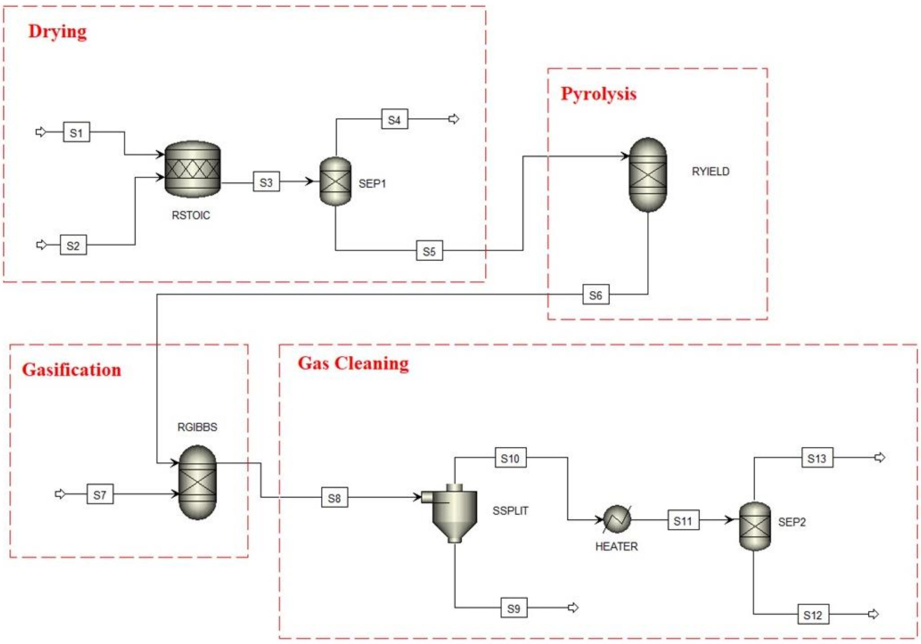

Figure 1. Biomass gasification flowsheet model

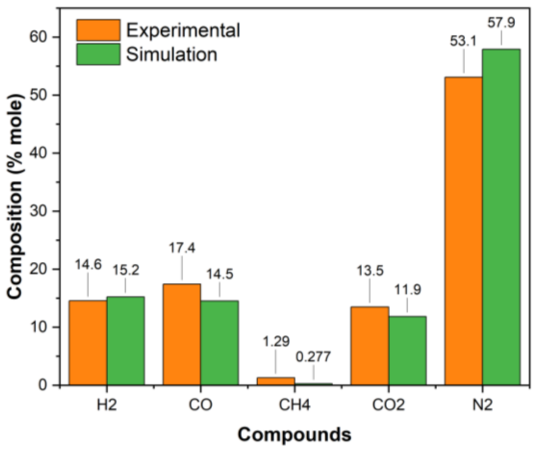

Figure 2. Model validation

Model simulation produced syngas composition with accuracy close to experimental results, namely 15.25% H_2, 14.55% CO, 11.86% CO_2, 57.90% N_2, and 0.28% CH_4. The average error obtained (mean error) was 0.365. These results prove that the predicted simulation is close to the actual experimental results because the mean error is close to zero.

One of the compositions, CH_4, has a lower result in simulation than in the experiment. The underestimation is due to differences between the actual gasification system and simulation with chemical equilibrium model [17]. More CH_4 was produced in gasification experiments than predicted by model simulation. The underestimation is because tar and heavy hydrocarbons are not included in model simulation, even though both are present in the syngas produced by the actual gasification unit [13].

3.1 Sensitivity Analysis on Gasification Temperature

Temperatures for gasification ranged from 400 to 1000˚C. Figure 3 – Figure 6 show the effect of gasification temperatures on syngas compositions. The sensitivity analysis results on temperature variables showed a decrease in the composition of CH_4 and CO_2, while CO increased with elevated temperature.

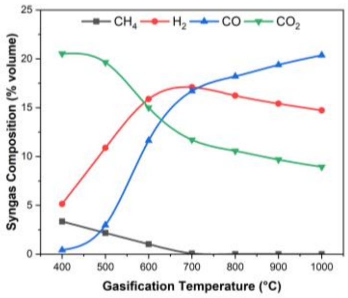

Figure 3. Effect of gasification temperature on syngas composition of palm kernel shell feed

Factors affecting the syngas composition are caused by reactions that occur in gasification process, namely the Boudouard reaction, as well as char, and the steam-methane reforming, which are endothermic reactions. Higher temperatures shift the chemical equilibrium toward the reactant side in the case of exothermic reactions and toward the product side in endothermic reactions according to Le Chatelier's principle [18]. The endothermic reaction forms more products, namely H_2, and CO, while more reactants are consumed. In addition, the steam-methane reforming causes more CO and less CH_4 to be produced.

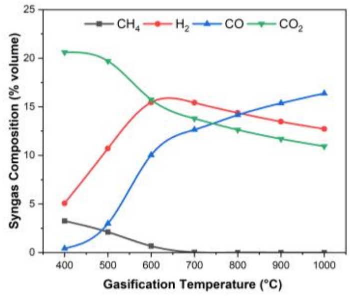

Figure 4. Effect of gasification temperature on syngas composition of palm fiber feed

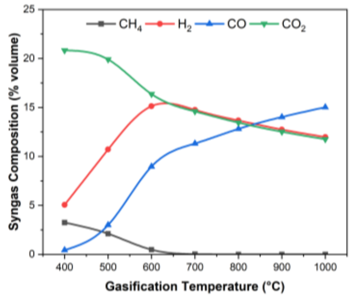

Figure 5. Effect of gasification temperature on syngas composition of palm empty bunch feed

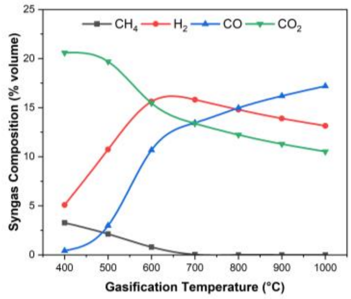

Figure 6. Effect of gasification temperature on syngas composition of fiber-shell mix feed

The fluctuations in H_2 composition are caused by the combined effects of reactions occurring in gasification reduction zone. At lower temperatures, the water gas shift reaction produces H_2 faster, but the reaction is inhibited with increasing temperature. The hydrogasification reaction consumes less H_2 at higher temperatures because it is an exothermic reaction. Other H_2-generating reactions are char and steam-methane reforming, which are endothermic reactions. Both reactions have the effect of increasing the H_2 composition below 650˚C but may be limited after this point due to the lack of reactants such as CH_4 and H_2O. Therefore, the combined effects of water gas shift reaction, reforming of char, hydrogasification, and steam-methane reforming cause fluctuations in H_2 composition.

H_2 has the potential to be a clean energy carrier because it is carbon-free, showing great potential as an alternative for future energy use. Moreover, H_2 has a high heating value in HHV which as shown in equation (14) [16]. This component is one of gasification products produced more abundantly.

The highest H_2 composition was obtained in the feed using palm kernel shells with a composition to volume of 17.12%, while the lowest was produced by empty bunch feed at 15.23% to volume. Differences in chemical composition and feed structure can affect gasification reactions and syngas formation. Palm kernel shell feed has a high carbon composition, hence, the conversion of carbon to H_2 will occur more in the reforming of char. The lowest carbon content was found in palm empty bunch feed, causing the H_2 composition to be lower than in other feeds.

3.2 Sensitivity Analysis on Feed Moisture Content

The moisture content of poultry litter pellets varied from 0-30%. Figure 7 – Figure 10 show the effect of gasification temperatures on syngas compositions. The sensitivity analysis results showed that the composition of CH_4, CO, and H_2 decreased while CO_2 increased with higher moisture content. The difference in syngas composition obtained is due to the higher heat requirement to vaporize H_2O in raw materials with higher moisture content. Therefore, the reaction temperature drops when the moisture content is increased. Changes in reaction temperature affect the chemical reactions that occur, such as steam-methane reforming, water gas shift reaction, and reforming of char. Low reaction temperatures will shift the chemical equilibrium toward the reactants in endothermic reactions and toward the products in exothermic reactions. The water gas shift reaction causes a decrease in CO composition while H_2 and CO_2 increase. However, the combined steam-methane reforming, water gas shift, and reforming of char reaction cause a decrease in H_2 composition.

The highest H_2 composition was obtained by palm kernel shell feed at 18.55%, while the lowest was produced by empty bunch feed at 14.27%. This is due to differences in chemical composition and feed structure that can affect gasification reaction and syngas formation. Empty bunch feed has a high moisture content, while the shell has a low content. The difference in moisture content of each feed will affect H_2 formation reactions such as the reforming of char, water gas shift, and steam-methane reforming.

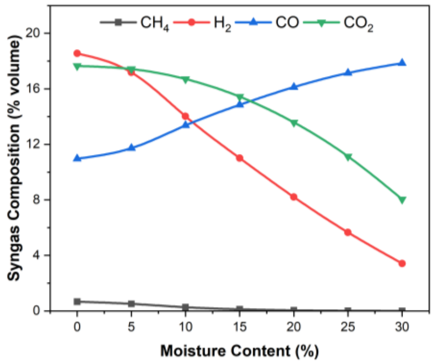

Figure 7. Effect of moisture content on syngas composition of palm kernel shell feed

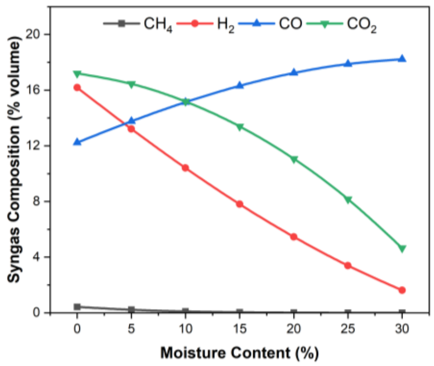

Figure 8. Effect of moisture content on syngas composition of palm fiber feed

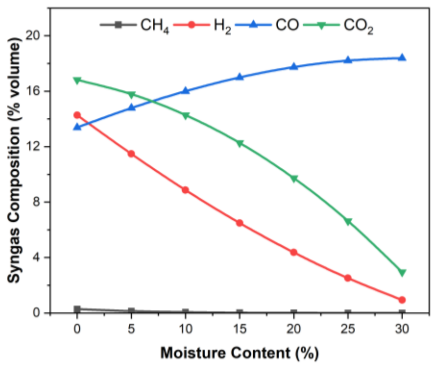

Figure 9. Effect of moisture content on syngas composition of palm empty bunch feed

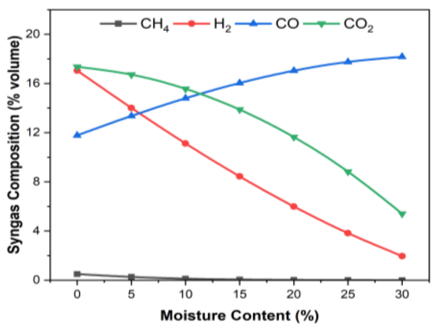

Figure 10. Effect of moisture content on syngas composition of fiber-shell mix feed

3.3 Sensitivity Analysis on Equivalent Ratio

Air is introduced into the RGibbs block as gasification agent, specifically in downdraft gasifiers under atmospheric pressure [19]. The equivalent ratio was varied in this investigation from (0.2 – 1) by varying the airflow amount while holding the temperature steady at 650˚C. The lowest equivalent ratio was set to 0.2 because when the ratio is below 0.2, there will be an insufficient gasifying agent to convert the carbon, resulting in incomplete reaction. When the ratio is above 1, it leads to the combustion reaction that will produce more CO_2, lowering the heating value [4]. Figure 11 – Figure 14 show the effect of the equivalent ratio on syngas compositions.

The sensitivity analysis results showed a decrease in the composition of CH_4, CO, and H_2 while CO_2 increased with a higher equivalent ratio. When the equivalent ratio is increased, the amount of O_2 supplied to the gasifier follows the same trend, leading to higher carbon conversion. However, the addition of oxygen to oxidize the feed reduces the composition of CO and H_2 due to complete combustion. The effect of the equivalent ratio is also influenced by several reactions, namely the Boudouard which is endothermic, leading to higher CO production with elevated temperature. In addition, the CO composition experiences a slight decrease caused by the amount of inert N_2, which increases with higher air demand.

The CH_4 content in the syngas composition from modeling results was considered zero, although experimentally some percentage of CH_4 component was found in the syngas. The CO_2 composition increased, with maximum composition results at an equivalent ratio of 0.8. This is because an increase in air rate leads to excess oxygen, which will cause the conversion of CO to CO_2, thereby increasing the carbon monoxide partial pressure. An effective gasification process produces more H_2 and CO than CO_2, hence, the equivalent ratio value should be kept very low.

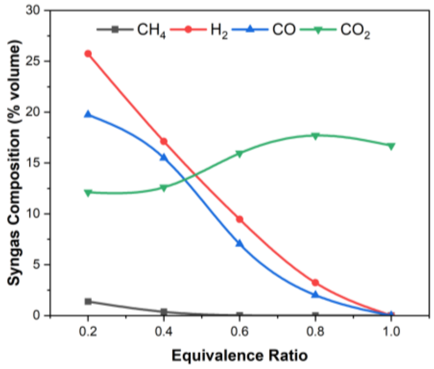

Figure 11. Effect of equivalent ratio on syngas composition of palm kernel shell feed

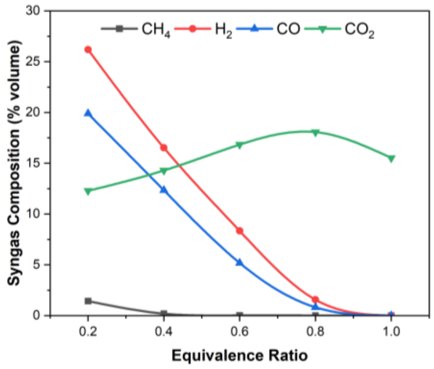

Figure 12. Effect of equivalent ratio on syngas composition of palm fiber feed

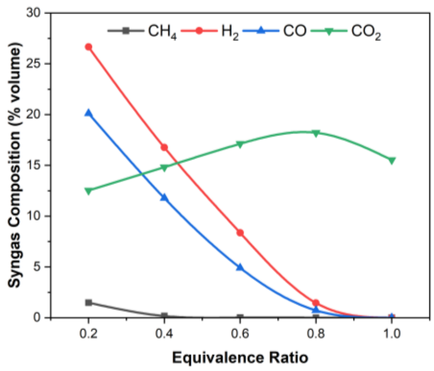

Figure 13. Effect of Equivalent Ratio on Syngas Composition of Palm Empty Bunch Feed

The highest H_2 composition was obtained by palm empty bunches at 26.66%, while the lowest was produced by palm kernel shell feed at 25.74%. This is due to differences in chemical composition and feed structure that can affect gasification reaction and syngas formation. Empty bunch feed has a high oxygen composition, while palm kernel shell has a low oxygen content. The difference in oxygen content of each feed will affect the oxidation reaction and ultimately the formation of H_2.

3.4 Heating Value

The type of feed used affects the heating value because it has a different composition of carbon, hydrogen, and oxygen. The composition can affect the amount of heating value produced. Temperature, moisture content, and equivalent ratio are parameters that affect the composition of syngas, and indirectly the heating value. The effect of temperature, equivalent ratio, and moisture content parameters on the HHV of different feed types are shown in Figure 15 – Figure 17.

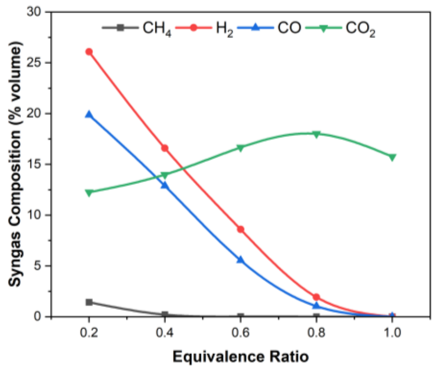

Figure 14. Effect of equivalent ratio on syngas composition of palm empty bunch feed

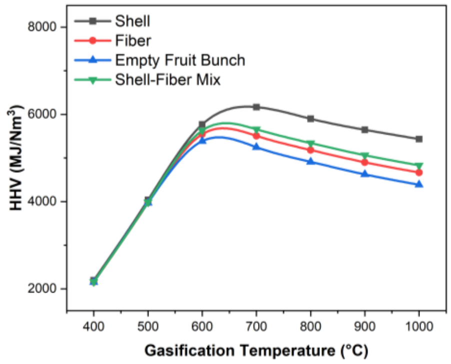

Figure 15. Effect of gasification temperature on HHV of syngas at different feeds

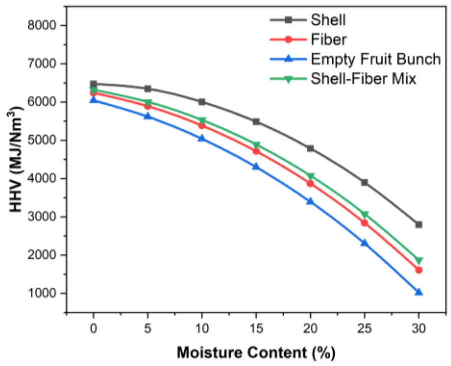

Figure 16. Effect of moisture content on HHV of syngas at different feeds

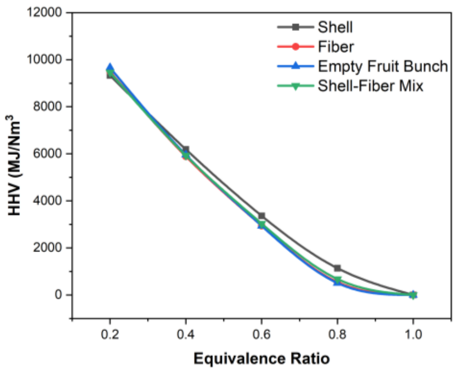

Figure 17. Effect of equivalent ratio on HHV of syngas at different feeds

The highest heating value was produced at 650˚C for each feed variation. After passing 650˚C, the HHV of the syngas decreased, due to the lower concentrations of CO, CH_4, and H_2 as shown in Figure 17. H_2 is one of the syngas compositions that affect the HHV of syngas. The HHV of 33867.1 cal/g is higher than that of other syngas components, namely CO and CH_4. When the temperature was raised to 650˚C, the concentration of H_2 increased, resulting in a higher HHV of syngas.

Palm kernel shell feed produced the highest HHV value of 6188 cal/g, presumably due to the higher carbon content compared to empty bunches [11]. This high carbon content can increase the heating value of the fuel. Figure 15 shows that the HHV of palm kernel shells increased after gasification, while the value before gasification was only 4781.011 cal/g. The HHV of other feeds, namely fibers, empty bunches, and a mixture of fiber shells, also increased after gasification. This is because, after gasification, more H_2 and CO composition is produced, which will increase the HHV of syngas.

The moisture content in the fuel generally decreases the HHV. This is consistent with the result in Figure 16 where the HHV of syngas decreases as the moisture content increases. The increased water content will affect the decrease in gasification temperature in the reduction zone. This causes the reforming of char, which is an endothermic reaction, to shift towards the reactants, leading to an increase in the composition of H_2O while CO and H_2 decrease.

The decrease in the composition of CO and H_2 is one of the main factors causing a decrease in the HHV of syngas. The highest HHV syngas was obtained by palm kernel shell feed (6474.288 cal/g) at 0% moisture content, which increased after gasification, while before gasification, the value was only 4781.011 cal/g. High water content greatly affects the quality of the feed by requiring large heat for evaporation, decreasing combustion rate, and reducing the flame [20]. Therefore, the moisture content should be kept very low.

The equivalent ratio parameter is inversely proportional to the HHV. Gasification process requires sufficient air supply, depending on the feed mass. As the equivalent ratio increases, more air is supplied to the gasifier, resulting in more oxygen to be oxidized as well as nitrogen. In general, nitrogen is an inert gas that acts as a heat carrier and lowers gasification temperature [20].

Increasing the equivalent ratio will shift the endothermic reaction to the reactants, resulting in fewer products, namely CO and H_2, being formed. The formation of CO_2, which is a product of an exothermic reaction, significantly affects the heating value produced. This is because CO_2 cannot burn or produce heat energy. The highest HHV syngas was obtained by the empty palm bunch material of 9333.816 cal/g, which increased after being gasified. Meanwhile, before being gasified, the value was only 3757.582 cal/g.

4. Conclusion

In conclusion, the flowsheet-based model can model palm solid waste gasification process, consisting of drying, pyrolysis, gasification, and syngas cleaning stages, using blocks in Aspen Plus. The validation results showed that the simulated syngas composition data were closed to the experimental syngas composition data from the literatures, with a mean error of 0.365. Based on the sensitivity analysis, the syngas composition was sensitive to parameters of gasification temperature, biomass moisture content, and equivalent ratio. Elevated gasification temperature led to an increase in CO composition and a decrease in CH_4 and CO_2 while H_2 reached maximum composition at 650˚C. An increase in biomass moisture content led to a rise in CO_2 composition and a decrease in H_2, CO, as well as CH_4. Higher equivalent ratio led to increased CO_2 composition and decreased H_2, CO, and CH_4. The results showed that the operating conditions to obtain a high heating value of syngas include 650˚C gasification temperature, 0% biomass moisture content, and 0.2 equivalent ratio.

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