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RESEARCH ARTICLE

INVESTIGATION OF MICROALGAE GASIFICATION UNDER STEAM ATMOSPHERE IN DOWNDRAFT GASIFIER BY USING ASPEN PLUS®

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ABSTRACT

Energy production faces environmental and economic problems due to growing population and fossil fuel uncertainty. These concerns have led researchers to find a widely available and renewable alternative such as biomass instead of fossil fuels. Microalgae is one of the most promising biofuels because it grows quickly and has a higher calorific value. Steam gasification is an alternative method to convert biomass into syngas with higher H_2 content and lower CO_2 content compared to other thermochemical conversion processes. In the present work, the downdraft gasifier model was developed using Aspen Plus® simulation software, which is capable of investigating the performance of microalgae gasification. Prior to the gasification performance evaluation, the validity of the model was tested with the results of an experimental study conducted with a different feedstock. The validation of the model was successfully completed, and it was found that the initial gas compositions of H_2, CO_2, CO and CH_4 were very similar between the experimental study and the developed model. The effects of the main process parameters, such as the steam/biomass ratio and the gasification temperature, on the syngas composition and the higher heating value (HHV) of the syngas were evaluated. The results obtained with Aspen Plus® showed that increasing the temperature had a great effect on the H_2 and CO composition of the syngas. They increased from 50.72% to 56.47% and from 28.11% to 28.84%, respectively. The simulation results also showed that the increasing S/B ratio favored the steam-related reactions and increased the H_2 content in the syngas. However, a decreasing trend in CH_4 content also decreased the HHV of the syngas as a function of temperature and steam.

Keywords: Gasification; Biomass; Microalgae; Downdraft Gasifier; Aspen Plus®

1. INTRODUCTION

Enlarging energy demand due to the growing population causes considerable economic problems and global climate change [1, 2]. Renewable sources provide a more sustainable and economical method to prevent the detrimental effect of fossil fuels on energy production [3]. Fossil fuel consumption needs to be reduced and its application methods must be changed because of the emissions of carbon dioxide (CO_2) [4]. Biomass is considered a carbon-neutral feedstock that can substitute fossil fuels [5, 6]. Microalgae, as the third-generation biomass feedstock, efficiently capture CO_2 [7] through photosynthetic recirculation and are used for synthetic fuel via various conversion processes such as biochemical [8], hydrothermal [9], combustion [10], thermochemical [11, 12]. Thermochemical conversion of microalgae is seen as more preferable to biochemical conversion because the biochemical process needs a longer reaction time and has less conversion efficiency than thermochemical processes [13]. Furthermore, the use of microalgae does not compete with traditional food crops. Therefore, microalgae is a very promising feedstock for thermochemical conversion methods because of their high growth rate (up to 20 g dry algae per m^2 per day) and widespread availability [14].

The increasing desire to promote the use of biomass as a renewable energy source is giving new momentum to the development of gasification technologies. Gasification is one of the most favorable thermochemical routes that produces syngas mostly composed of methane (CH_4), carbon monoxide

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(CO), hydrogen (H_2), and CO_2 with varying characteristics can be obtained by altering the feedstock [15, 16]. Gasification under steam atmosphere is gaining momentum as it can obtain high-quality syngas [17] at a relatively low operating expense. Moreover, it can generate more H_2 yield than all the gasification agents (air, O_2, CO_2) [18].

The syngas composition can be varied concerning the physicochemical structure of fuel, operational conditions of the gasification process, and gasifier type [19]. The downdraft gasifier is a common technique for biomass gasification among the present three types of gasifiers [20]. Related to capacity and feedstock type, the downdraft gasifier is one of the fixed bed gasifiers and is the most compatible type due to its low construction cost, low tar content in syngas, and simpler and more compact design compared with the entrained and fluidized bed reactors [21, 22].

The modeling and simulation of downdraft gasifier performance by using simulation tools like an equation-driven simulation program based on mass and energy balance are valuable for better gasifier design [23]. Aspen Plus® is one of the most popular equation-oriented simulation programs that can make successful thermodynamic approaches in line with mathematical models to simulate the biomass gasification process more healthily, saving time and money is a very common technology today [24-26]. The optimization of the syngas composition and the obtained syngas with the desired quality are the most important concerns in gasification. Investigation of the optimal values of the gasification parameters like pressure, gasification temperature, and amount of gasifying agent is conducted in the Aspen Plus® program very fast and reliably. On the other hand, there are a few studies for the modeling of downdraft gasifiers by using Aspen Plus® [27, 28].

In this study, we elucidated the HHV and syngas composition of microalgae gasification under steam atmosphere from a downdraft gasifier by using Aspen Plus®. The results and adopted method in this paper give a point of reference to properly designing downdraft gasifiers for high-valued gasifier products.

2. METHODS

2.1. Sample Characterization

The microalgae as a marine biomass sample were chosen as a feedstock in this study, and the physicochemical properties of it were taken from the biomass database of ECN [29]. Microalgae do not have a stem, root, and leave like plants, however it uses CO_2, sunlight, and water to grow. Depending on their growth status and species, microalgae generally consist of protein (20–50%), lipid (9.5–42%), and carbohydrate (17–57%) [30]. According to the energetic characteristics, the microalgae sample that had a HHV (dry basis) of 23.48 MJ/kg was preferred for the gasification process. The ultimate and proximate analysis results of the microalgae are given in Table 1. The nitrogen, sulfur, hydrogen and carbon content of microalgae were determined experimentally, whereas oxygen content was calculated by difference.

Table 1. Proximate and ultimate analyses results of the microalgae sample

Proximate Analysis (dry basis)	***Value (wt.%)***
Fixed Carbon	15.68
Volatile Matter	81.80
Ash	2.52
Moisture Content	5.22
Ultimate Analysis (dry basis)	***Value (wt.%)***
Carbon	52.73
Oxygen	29.03
Sulphur	0.49
Hydrogen	7.22
Nitrogen	8.01

2.2. Downdraft Gasifier Model

Aspen Plus® is an equation-oriented program that is used to simulate several chemical, physical and biological processes based on phase equilibrium and energy and mass balances [23]. Aspen Plus® software is preferred by many researchers and industrial facilities instead of experimental studies due to its high capability to measure and examine operating parameters and analyze system performance in a very short time. Aspen Plus® has a wide database for calculation of physical properties of streams and components. Another advantage of Aspen Plus® is that solid components such as biomass, coal can be correctly handled in the well-designed model for gasification applications [31, 32]. The steady-state and equilibrium-based model of the downdraft gasifier for microalgae gasification has been developed using Aspen Plus® V11 [33]. The flow chart of the downdraft gasifier in the Aspen Plus® software was presented in Figure 1.

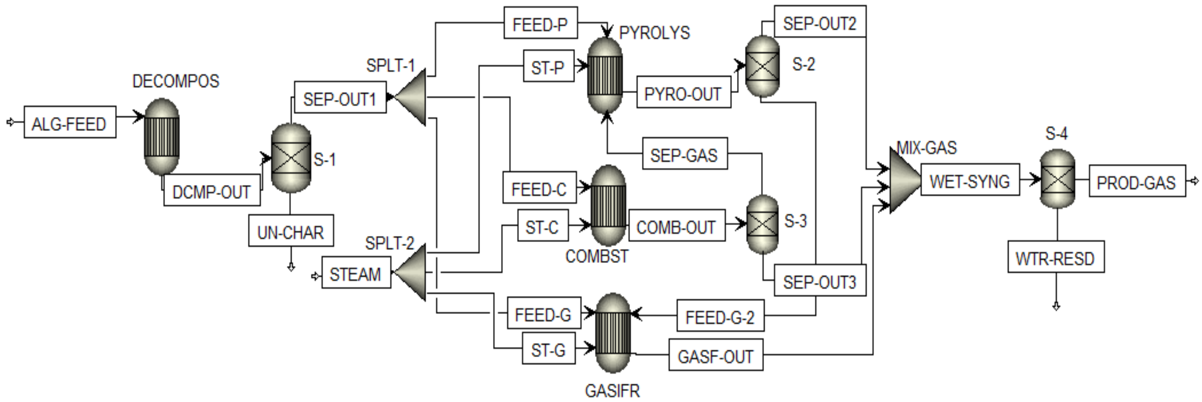

Figure 1. Flowsheet of the downdraft gasifier model

The Soave-Redlich-Kwong (SRK) that is recommended by the Aspen Plus® user manual for this type of application has been selected as the equation of state to determine the physical properties of the conventional components with STEAMNBS as the free-water method. The property methods have been selected as DCOALIGT and HCOALGEN to calculate density and enthalpy values, respectively for biomass as a nonconventional component [34]. The components which are possible to be formed as a result of gasification steps have been identified in the Aspen Plus® database.

In a downdraft gasifier, many complex reactions can occur, but they cannot be simulated with a zero-dimensional model, thus the main parts of gasification have been simulated considering some assumptions as mentioned below:

- The gasification system is operated in a steady state.
- The entire system is isothermal.
- There is no pressure drop in streams and blocks.
- All reactions reach chemical equilibrium and occur fast.
- Ash is considered an inert material and does not contribute to the reaction.
- Char consists of only carbon.
- Heavy hydrocarbons are omitted from the syngas composition.

Three Gibbs reactors have been used to simulate the pyrolysis, combustion, and gasification parts of the downdraft gasifier. Gibbs reactors work based on Gibbs free energy minimization principle, this method is also called non-stoichiometric and any information about the reaction steps and conversion rates are not needed to model reactors [35].

The blocks and reactors have been selected and formed the downdraft gasifier model. The microalgae has been defined as nonconventional solid and fed to the system, then decomposition, pyrolysis, and gasification steps have occurred consecutively. Water and other residual components have been separated and syngas containing H_2, CO, CH_4, and CO_2 has been produced.

3. RESULTS

3.1. Model Validation

Before investigating the performance of this model for the selected microalgae, the accuracy of the developed downdraft gasifier model should be validated with the experimental study. For the model validation, a gasification system was performed in the same condition as the experimental study that was selected from the literature. The syngas composition was compared for H_2, CO, CH_4, and CO_2. The results of the comparison of the model and the literature study were presented with the operational conditions in Table 2.

Table 2. Comparison of experimental and model results

Sample	Karanja Press Seed Cake	
Gasification Temperature	800 °C	
Gasification Pressure	1 atm	
Syngas Composition (%v/v.dry)	**Experimental [36]**	**Model**
H_2	37.26	37.92
CO	48.70	50.93
CO_2	4.20	4.29
CH_4	2.3	4.42

In the experimental work [36], Karanja Press Seed Cake was selected as the feedstock, and the experiment was conducted under atmospheric pressure with the gasification temperature at 800 °C. Working conditions and feedstock in the experimental study were defined identically to the Aspen Plus® model. Comparison of results depicts that the H_2, CO, and CO_2 compositions were obtained with a small difference. The deviation in CH_4 composition between the model and the experimental study can be explained with some assumptions and calculations of the Gibbs reactors in the Aspen Plus® model. Unlike the model that works based on the chemical equilibrium in the real case, conversion rates of the reaction depend on the kinetics and residence time. This situation was discussed by some researchers who studied it with the equilibrium model [26, 37-39]. Hereby, the validation of the downdraft gasifier model was completed successfully, and the newly developed model was found to be reasonably acceptable.

3.2. Parametric Study

The gasification properties of microalgae under a steam atmosphere in terms of HHV of syngas and gas composition were investigated according to change of gasification temperature and steam/biomass ratio (S/B) by using the sensitivity analysis tool in Aspen Plus®.

3.2.1. Investigation of gasification temperature on syngas composition

Temperature is one of the key parameters that influences the syngas composition due to temperature promoted endothermic and exothermic reactions. As shown in Figure 2, the change of the syngas composition with respect to gasification temperature varied between 600-1000 °C while the S/B ratio was kept constant at 1.5.

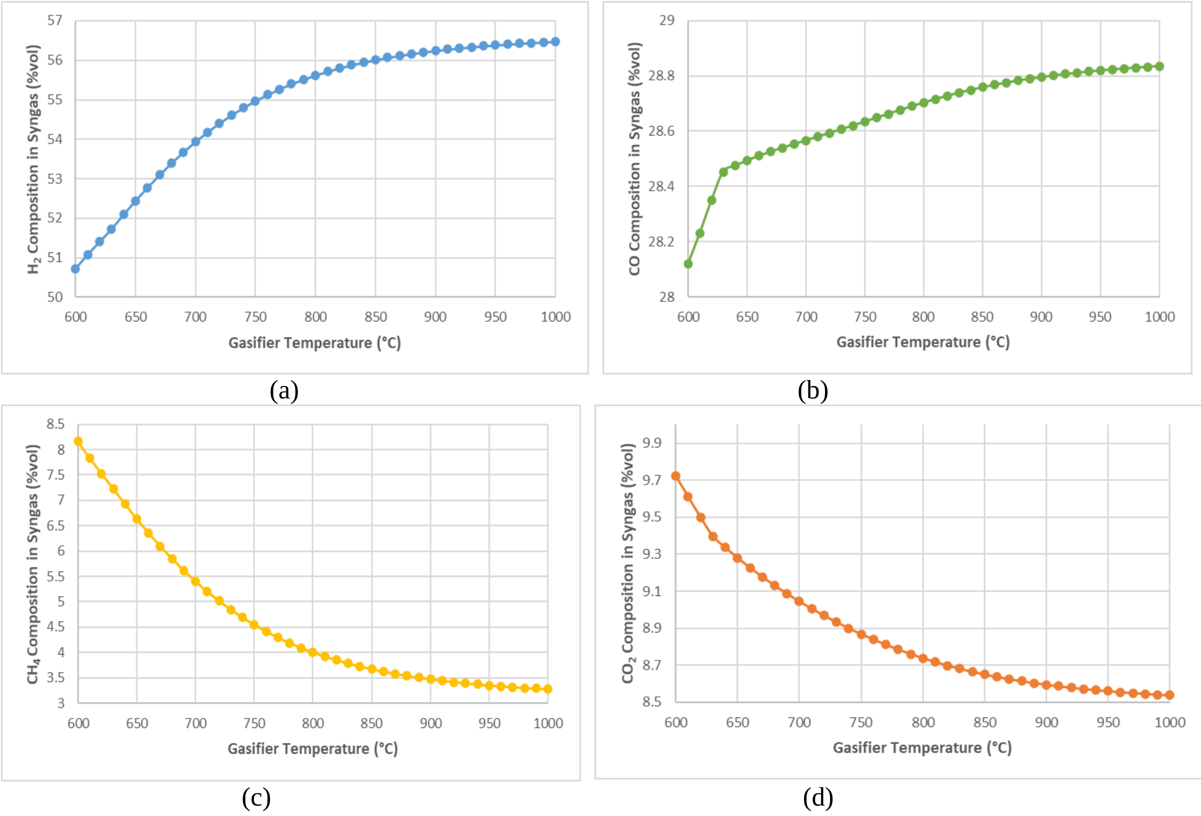

Figure 2. Effect of the temperature on syngas composition (a) H_2, (b) CO, (c) CH_4, (d) CO_2

In general, solid fuel decomposes effectively and a higher amount of syngas is produced at relatively higher temperatures [24]. As illustrated in Figure 2.a, the H_2 content in syngas rises sharply between 600 and 800 °C but the increase continues slower after the temperature point at 800°C. While the temperature reached 1000 °C, the H_2 content fluctuated between 50.72% and 56.47%. The change of CO content in syngas showed a similar trend to H_2 and it increased from 28.11% to 28.84% at a temperature between 600-1000 °C as seen in Figure 2.b. These trends can be explained by endothermic reactions such as heterogenous, water-gas ($C + H_2O \leftrightarrow CO + H_2$) and gas phase, steam-methane reforming ($CH_4 + H_2O \leftrightarrow CO + 3H_2$). The percentage increase in H_2 is higher than in CO because of the stoichiometric coefficients of H_2 in the reactions. Furthermore, a reverse trend of the CO and CO_2 can be explained by the Boudouard reaction ($C + CO_2 \leftrightarrow 2CO$) that occurs in the downdraft gasifier after the temperature of 800 °C. The decreasing behavior was observed in the CH_4 and CO_2 contents in syngas while the temperature increased in the same range. Considering all these endothermic reactions, the tendency of the components showed good agreement with the literature studies based on Le Chatelier's principle which states that high temperatures shift the reaction side to products. However, exothermic reactions approach the reactant side [32, 40-42]. The desired components which are H_2 and CO in the gasifier increased significantly until the temperature reached 800 °C, after that point the increase continued very slowly. Taking into account the energy consumption, the optimum gasifier temperature was determined as 800 °C.

3.2.2. Investigation of gasification temperature on HHV of syngas

The higher heating value (HHV) states the heat produced from the combustion of the unit mass or volume of syngas [43]. The combustible characteristics of the syngas vary depending on the calorific values of each component and the syngas composition accordingly. Thus, the HHV is an important criterion for evaluating the quality of the syngas [44]. The HHV of syngas can be provided from the property sets section as stream properties in Aspen Plus® program without needing extra calculation. The influence of gasification temperature on the HHV of syngas was investigated at the same temperature range as the syngas composition and sensitivity analysis results are presented in Figure 3.

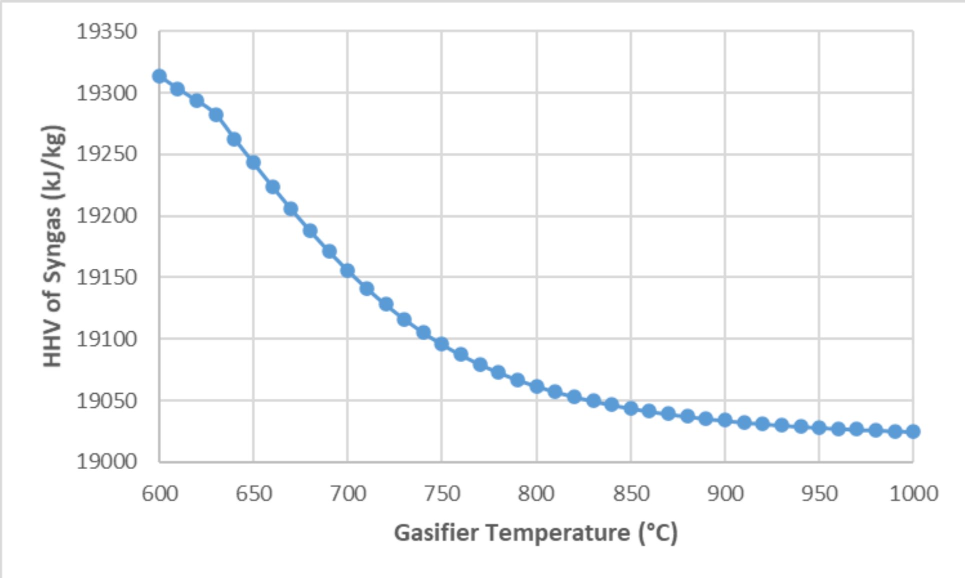

Figure 3. Effect of the temperature on HHV of syngas

The change in HHV of syngas corresponding to increased gasification temperature showed a decreasing tendency, as seen in Figure 3. The calorific value of each component is different; therefore, syngas composition directly affects the HHV of syngas. The decline slowed after 800 °C, this showed similar behavior with the change of CH_4 contents in syngas. Compared to H_2 and CO, CH_4 is three times more effective in terms of energy content and its decreasing content in syngas with enhancement of the gasification temperature caused the drastic reduction in HHV of syngas [45, 46].

3.2.3. Investigation of S/B ratio on Syngas Composition

The S/B ratio is the most influential parameter for steam promoted gasification processes and is determined as the feed rate of the steam divided by the biomass mass flow rate. Steam gasification is preferred due to its advantage of enriching the fraction of H_2 in syngas. The effect of S/B ratio on syngas composition was observed when the gasification temperature fixed at 800 °C in Figure 4.

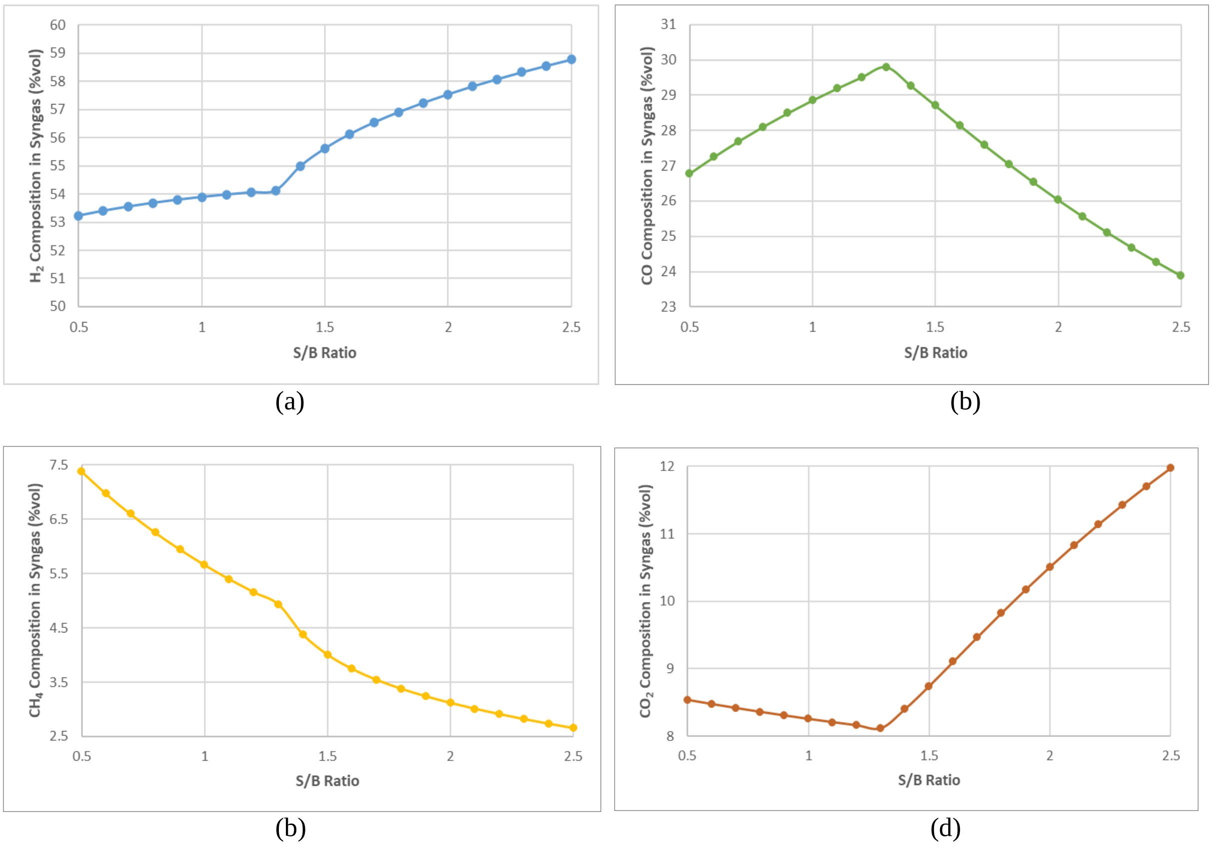

Figure 4. Effect of the S/B ratio on syngas composition (a) H_2, (b) CO, (c) CH_4, (d) CO_2

As seen in Figure 4, syngas composition remarkably changed as a function of the S/B ratio. Increasing the S/B ratio between 0.5 and 2.5 increased the H_2 content in syngas from 53.22% to 58.77% owing to an increase in the partial pressure of steam which encourages the steam methane reforming, water-gas, and water-gas shift ($CO + H_2O \leftrightarrow CO_2 + H_2$) reactions inside the gasifier [47]. From Figure 4.b and 4.d, CO composition increased and CO_2 composition decreased until the S/B ratio is 1.3, after this point, their behaviors reversed and CO composition decreased while CO_2 composition increased. H_2 composition showed an opposite tendency with the CH_4 composition because the steam methane reforming reaction uses CH_4 to produce H_2. The results depicted that the composition change in syngas was consistent with the literature studies [23, 48-50]. The optimal S/B ratio was determined as 1.5 considering the higher amounts of H_2 and CO compositions and the lower amount of CO_2.

3.2.4. Investigation of S/B ratio on HHV of Syngas

The proportion of H_2, CH_4, CO_2, and CO in syngas significantly influenced the HHV of syngas as the performance indicator of the gasification process. Thus, the HHV of syngas is affected by the S/B ratio in the gasification processes that use steam as the gasifying agent. The HHV of syngas was directly obtained from the property sets, and sensitivity analysis was conducted as a function of the S/B ratio in Aspen Plus®.

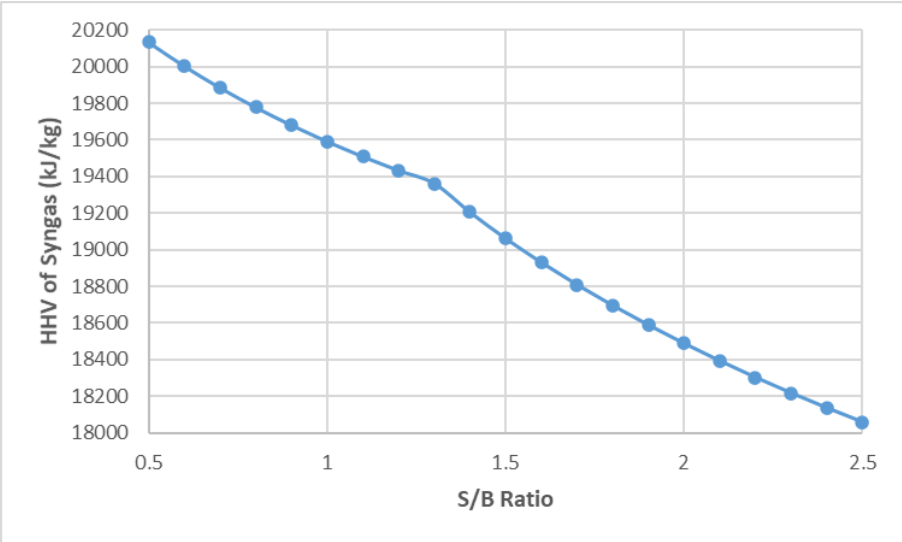

Figure 5. Effect of the S/B ratio on HHV of syngas

The HHV of syngas ratio diminished from 20132 kJ/kg to 18059 kJ/kg while the S/B changed between 0.5 and 2.5, seen in Figure 5. The HHV of syngas sharply dropped, which is similar to CH_4 trend with respect to increasing S/B ratio, because the effect of CH_4 on HHV of syngas is more active than other components as reported in the literature [48, 51]. Considering the syngas composition that desires higher H_2 content and the HHV of syngas, S/B ratio was selected 1.5 as the optimal value.

CONCLUSION

Using the developed downdraft gasifier model, the gasification of the microalgae sample under the steam atmosphere and the production of synthesis gas with high H_2 content were simulated using Aspen Plus® software. The compositions of H_2 and CO in the syngas reached their optimal values of 55.62% and 28.70%, respectively, when the operating conditions were a gasification temperature of 800 °C and S/B ratio of 1.5. With the increase of gasification temperature and S/B ratio, the H_2 composition increased appropriately from 50.72% to 56.47% with the increase of gasification temperature and from 53.22% to 58.77% with the increase of S/B ratio. In addition to the syngas composition, the HHV of the syngas was also investigated and showed a decreasing trend with the increase of gasification temperature and S/B ratio due to the CH_4 components, which mainly affect the syngas quality. The presented results of the simulation model, which are in agreement with the literature study, prove that the downdraft gasifier model was properly designed for microalgae gasification.

CONFLICT OF INTEREST

The authors stated that there are no conflicts of interest regarding the publication of this article.

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