Investigation of Process Parameters Influence on Municipal Solid Waste Gasification with CO₂ Capture via Process Simulation Approach

Fadilla Noor Rahma*, Cholila Tamzysi, Arif Hidayat, Muflih Arisa Adnan

Department of Chemical Engineering, Universitas Islam Indonesia, Indonesia

ABSTRACT: Integration of gasification with CO₂ capture using CaO sorbent is proposed as an alternative treatment to convert municipal solid waste (MSW) into energy. Aspen Plus process simulator was employed to study the process. Two models were built to represent the non-sorbent and the sorbent-enabled MSW gasification. The model validation against available experimental data shows high accuracy of the simulation result. The effect of CO₂ capture using CaO sorbent on the syngas composition and lower heating value (LHV) was observed by comparing the two models, and sensitivity analysis was performed on both models. Several process parameters affecting the syngas composition and LHV were investigated, including CaO/MSW ratio, temperature, equivalence ratio, and steam/MSW ratio. The addition of CaO sorbent for CO₂ capture was found to successfully reduce the CO₂ content in the syngas, increase the H₂ composition, and improve the syngas LHV at the temperature below 750 °C. The maximum H₂ composition of 56.67% was obtained from the sorbent-enabled gasification. It was found that increasing equivalence ratio leads to a higher H₂ concentration and syngas LHV. Raising steam/MSW ratio also increases the H₂ production, but also reduces the LHV of the syngas. Observation of the temperature effect found the highest H₂ production at 650 °C for both non-sorbent and sorbent-enabled gasification.

Keywords: CaO sorption, CO₂ capture, gasification, municipal solid waste, syngas

How to Cite This Article: Rahma, F. N., Tamzysi, C., Hidayat, A., Adnan, M. A. (2021) Investigation of Process Parameters Influence on Municipal Solid Waste Gasification with CO₂ Capture via Process Simulation Approach. Int. Journal of Renewable Energy Development, 10(1), 1-10

https://doi.org/10.14710/ijred.2021.31982

1. Introduction

As the fourth most populated country in the world, Indonesia produces a vast amount of municipal solid waste (MSW). In 2019, around 176,000 t of MSW was produced daily, making up a total of 64 Mt annual MSW generation. Due to the lack of infrastructure and human resources, waste processing is not yet available on large scale. Around 70% of the generated MSW end up in open landfills and the rest are burnt, buried, left unmanaged, or even dumped into the country’s rivers (Khalil et al. 2019). A lot of environmental problems have arisen due to this poor waste management, including land pollution, water pollution, and emission of greenhouse gases (Korai et al. 2016). MSW in the landfills is the third largest contributor of methane emission, accounting for around 550 Tg of global methane emission per year (Zuberi and Ali 2015). This number raises serious concerns since methane is a powerful greenhouse gas with 21-23 times higher global warming potential than carbon dioxide (Eggleston et al. 2006).

On the other hand, the rapid growth of population and economy in Indonesia also leads to energy security problems. Indonesia’s energy consumption has risen significantly from 893.76 million barrel of oil equivalent (BOE) in 2009 to 936.33 million BOE in 2018 (Sutijastoto et al. 2010, Adi et al. 2019) and is predicted to grow continuously in the upcoming years. Since 2004, Indonesia’s local oil production has been unable to meet this high fossil fuel demand, forcing the country to meet its energy requirement by importing oil. The majority of Indonesia’s energy share comes from fossil fuel-based energy while renewable energy sources contribute to less than 5% of the energy mix (Khalil et al. 2019). Indonesia Presidential Decree No. 79 of 2014 has stated a policy for national energy mix, requiring 23% total contribution of new and renewable fuels as the main energy source by 2025 (Putro et al. 2020). Rigorous and strategic effort for renewable energy development is urgently required to achieve this target.

Waste-to-energy (WTE) conversion is a promising solution to solve both the overproduced waste and energy security problems at once. MSW can be regarded as a potential source of energy due to its high calorific value (Zhao and Wang 2018), with HHV of around 19-20 MJ/kg depending on the composition (Jingxia 2018). A range of processing technology is available to convert MSW into energy, including several means of thermochemical and biochemical conversion (Mishra and Mohanty 2018, Chen and Wang 2016). Although biochemical conversion technology generally offers lower treatment cost, it is not
preferred for large volume of waste due to the difficulty to control the growth of the bacteria (Sudibyo et al. 2017). Therefore, the option narrows down to thermochemical conversion technologies, including incineration, pyrolysis, and gasification.

In incineration is basically an oxidation reaction of a combustible material, during which energy is recovered in the form of heat (Aフト et al. 2007). Although the technology is widely implemented around the world, it has a major drawback of producing hazardous by-products such as dioxins and furans, especially for feedstocks containing chlorine (Al-Salem et al. 2010). In addition, incineration can only produce heat and electricity without recovery of any value-added chemicals. In contrast, gasification produces valuable chemicals and fuels while also recovers energy in the form of heat and electricity (Consonni and Vigano 2012). Gasification also has other advantages regarding its cleaner emission and higher energy recovery efficiency (Dong et al. 2018), which makes it a more environmentally friendly option (Luo et al. 2012).

Gasification is a thermochemical conversion process where biomass is converted into gaseous products in the presence of a gasification agent (Molino et al. 2018). The process comprises several steps including feedstock drying, pyrolysis or decomposition, combustion, and gasification. This technology enhances the calorific value of the feedstock by reducing the C/H mass ratio of the biomass. Some of the commonly used gasification agents are air, steam, oxygen, and carbon dioxide (Sikarwar et al. 2016). The selection of the gasification agent determines the calorific value of the product. Other parameters affecting the gasification process and product include the gasification temperature, type of feedstock, amount of the gasifying agent, and the presence of catalyst and sorbent (Parthasarathy and Narayanan 2014).

The main product of biomass gasification is syngas, which is a mixture of gases containing H₂, CO, CO₂, and CH₄. The syngas can be utilized to generate electricity by combustion in gas turbines or by using fuel cell (Toonssen et al. 2011). Alternatively, it can be converted through Fischer-Tropsch synthesis to produce liquid transportation fuels (Dos Santos and Alencar 2020). Syngas is also utilized as basic raw material for production of chemicals such as methanol and a wide range of other products (Doranehgard et al. 2017). In addition, syngas contains hydrogen, which is often considered as its most important constituent (Moghaddam et al. 2014).

Hydrogen is well known as a clean fuel with high energy density. It can be utilized for production of electricity, vehicles fuel, without generating toxic emissions (Hosseini and Wahid 2016). Compared to conventional hydrocarbon fuels, hydrogen energy density is 2.75 times higher at around 122 kJ/g (Kapdan and Kargi 2006). Currently, the main pathway for commercial hydrogen production uses fossil fuels as the feedstock, which makes it a carbon-intensive process. Alternative routes for hydrogen production include water electrolysis, biological methods, and nuclear production (Doranehgard et al. 2017). However, hydrogen production from biomass gasification is highly regarded as the more promising alternative due to safety, economic, and environmental factors, therefore it has been extensively studied in the literature (Salkuyeh et al. 2018; Shayan et al. 2018; Peng et al. 2017).

According to Doranehgard et al. (2017), the production of CO₂ emission remains one of the main barriers in the development of biomass gasification. The CO₂ emission also affects hydrogen production by lowering its concentration in the syngas. However, the syngas hydrogen concentration can be enriched using CO₂ capture technology which removes some of the CO₂ from the mixture, therefore producing hydrogen-enriched syngas. Among several technological options, CO₂ removal using CaO sorbent currently gaining attention due to its relatively low cost and high efficiency (Manovic and Anthony 2010). This technology captures CO₂ from gaseous mixture by CaO carbonation reaction where CaO reacts with CO₂ to form CaCO₃.

Several experimental works have been conducted on CO₂ capture using CaO sorbent for biomass gasification. The previous studies used different biomass feedstocks such as corn stalk (Li et al. 2017), sugarcane leaves (Bunma and Kuchonthara 2018), palm kernel shell (Shahbaz et al. 2017), sewage sludge (Chen et al. 2017), and saw dust (Acharya et al. 2010). The results of all the previous studies agree that CaO sorbent works effectively to remove CO₂ and enhance hydrogen concentration in the syngas. However, only a limited number of works has been reported on MSW gasification with CO₂ capture using CaO sorbent (Hu et al. 2015).

A systematic understanding of the gasification characteristic is crucial in the process design and development. With the lack of experimental data, simulation-based study can be a feasible approach to provide additional insights regarding the process. Simulation modelling-based research has an advantage of reduced time, cost, and resources compared to experimental work, while still providing high accuracy results (Rupesh et al. 2016). Several simulation studies on biomass gasification with CO₂ capture using CaO sorbent have been published. The reported studies mostly utilized Aspen Plus process simulation, which successfully simulated the process and generated results with high validity compared to available experimental data (Rupesh et al. 2016, Shahbaz et al. 2017, Zhou et al. 2019, Gao et al. 2018). However, none of the previous simulation studies used MSW as the feedstock.

Aspen Plus is an extensive process modelling software which is capable to simulate complex industrial processes and generate accurate results. The software is equipped with unit operation blocks with built-in mathematical models. Aspen Plus contains a wide database of various chemical compounds and their thermodynamic, physical, and chemical properties. User can also select the suitable thermodynamic model according to the nature of the simulated process. In addition, Aspen Plus is equipped with powerful analysis tools such as sensitivity analysis and optimization (Begum et al. 2014).

In this study, process simulation is employed to understand the effect of CaO sorption on syngas production via MSW gasification. The simulation model is built in Aspen Plus software and validated against experimental data to ensure the model’s accuracy. The composition and calorific value of the produced syngas from non-sorbent and sorbent-enabled gasification are compared. Furthermore, several parameters affecting the syngas composition and calorific value were also investigated, including CaO/MSW ratio, temperature, equivalence ratio, and steam/MSW ratio.
understanding of how these key parameters affect gasification is a substantial key in developing MSW gasification process integrated with CuO sorbent for CO₂ capture.

2. Methods

The gasification of MSW with sorbent-enabled CO₂ capture was modelled using Aspen Plus v8.6 process simulator. The simulation was built with several assumptions (Rupesh et al. 2016, Shahbaz et al. 2017):

a. The process is in steady-state condition.

b. The gasifier and CaO carbonation reactors are isothermal and operate at atmospheric pressure.

c. Tar and higher hydrocarbons production is neglected.

d. The catalytic activity and capacity reduction of CaO are neglected.

e. Char is considered as graphite carbon.

f. Sulfur is only converted to H₂S and nitrogen is only converted to NH₃.

Peng-Robinson equation of state with Boston-Mathias alpha function was chosen for this simulation as this property package estimated thermophysical properties of processes, including gasification (Ramzan et al. 2011). The property package estimated thermophysical properties of the conventional components such as H₂, CO, CO₂, CH₄, H₂O, O₂, N₂, NH₃, H₂S, and other gases included in the simulation.

Table 1 Municipal solid waste proximate analysis

| Component          | % Mass |
|--------------------|--------|
| Fixed Carbon       | 12.82  |
| Volatile Matters   | 77.66  |
| Moisture Content   | 20.00  |
| Ash                | 9.51   |

Source: Khuriati et al. (2018)

Table 2 Municipal solid waste ultimate analysis

| Component | % Mass |
|-----------|--------|
| Carbon    | 43.71  |
| Hydrogen  | 7.74   |
| Nitrogen  | 1.95   |
| Sulfur    | 0.40   |
| Oxygen    | 36.69  |

Source: Khuriati et al. (2018)

Table 3 Aspen Plus equipment for simulation

| Block ID | Aspen Plus ID | Description |
|----------|---------------|-------------|
| DRIER    | RStoic        | A unit used to lower the moisture content in MSW feedstock. The output is calculated using a calculator block. |
| DECOMP   | RYield        | A reactor decomposing MSW (non-conventional component) into its constituents (conventional components). The output is calculated using a calculator block. |
| GASIF    | RGibbs        | A reactor converting MSW constituents into syngas. The output is calculated using Gibbs energy minimization. |
| CO₂CAPT  | RGibbs        | A reactor capturing CO₂ through CaO carbonation reaction. The output is calculated using Gibbs energy minimization. |

Biomass and ash were classified as non-conventional components, thus the enthalpy model DCOALGEN and density model DCOALIGT were selected for their thermophysical properties calculation. CaO, CaCO₃, and C were described as solid components with available thermophysical properties stored in Aspen Plus data.

The sorbent-enabled gasification process block diagram is presented on Figure 1. Since gasifier is not included in the Aspen Plus default unit operations, the actual gasification process was divided into several stages in the simulation, each one represented by a unit operation available in Aspen Plus. The gasification stages comprise drying, decomposition, and gasification. The feedstock’s proximate and ultimate analysis are listed on Table 1 and 2, while the main equipment used in the simulation are detailed on Table 3.

The feedstock enters the process through stream MSW into DRIER, where early heating and drying process take place to reduce the moisture content of the MSW. Since MSW is specified as a single non-conventional component, the drying process is modelled using RStoic reactor with a calculator block which specifies the percentage of water removal. The dried MSW enters the decomposition stage where it is decomposed into C, H, O, N, and S elements. This decomposition occurs in RYield reactor DECOMP, which is specified using FORTRAN statement.

The decomposed elements are fed to the gasification reactor GASIF, modelled by RGibbs reactor in the Aspen Plus simulation. This type of reactor uses minimization of Gibbs free energy to calculate syngas composition, assuming complete chemical equilibrium. The syngas produced from gasifier is fed to CO₂ capture reactor CO₂CAPT, also modelled using RGibbs reactor. In this reactor, removal of CO₂ through CaO carbonation into CaCO₃ takes place, removing a portion of CO₂ from the syngas mixture. The reactions inside the gasifier and CO₂ capture reactor are displayed in Table 4.

The simulated model was validated by comparing the syngas composition obtained from the simulation with that of experimental data published by Mahishi and Goswami (Mahishi and Goswami 2007). The deviation of the model from the experimental result is calculated using root mean square error (RMSE) as expressed on equation 1. An accurate model is indicated by a small RMSE value.
The validated model was used to investigate the effect of sorbent-enabled CO₂ capture on syngas composition and lower heating value (LHV) at different operating conditions. The LHV of the syngas is calculated based on the composition of combustible gases including H₂, CO, and CH₄ (Sittisun et al. 2019). The calculation formula for LHV is shown in Equation (2) (Rupesh et al. 2016). The simulation was performed as two cases: the non-sorbent case which excludes the CO₂ capture reactor system and the sorbent-enabled case. The syngas composition and LHV of the two cases were compared as the effect of parameters including CaO/MSW ratio, temperature, equivalence ratio, and steam/MSW ratio were studied. The base case was simulated at CaO/MSW ratio of unity, temperature of 600 °C, equivalence ratio of 0.5, and zero steam flow. Using sensitivity analysis feature in Aspen Plus, the parametric study was performed by varying CaO/MSW ratio from zero to unity, temperature from 500 to 1500 °C, equivalence ratio from 0.05 to 1, and steam/MSW ratio from 0.05 to unity. Each sensitivity analysis was run by changing only one parameter while keeping the other conditions at the base case value.

3. Results and Discussion

3.1. Model Validation

The simulated model (Figure 2) was validated against available experimental data of biomass gasification using CaO sorbent for CO₂ capture (Mahishi and Goswami 2007). The composition of the syngas obtained from the simulation model was compared to the experimental data. The validation results are displayed on Figure 3 for non-sorbent gasification model and Figure 4 for sorbent-enabled gasification model. The accuracy of the model results is quantified statistically by calculating the root mean square error (RMSE) as shown in Equation 1. Compared to previous publications (Rupesh et al. 2016; Al Amoudi et al. 2019), the result shows better agreement between simulation and experimental data, with acceptable RMSE of 4.07% for non-sorbent gasification and 5.63% for sorbent-enabled gasification. The sorbent-enabled gasification model demonstrates higher RMSE compared to the non-sorbent case, as it includes more complex process model which increases the possibility of deviation. However, the validation result proved the ability of both models to predict the process output with a high accuracy. Therefore, the models can be used to further investigate the effect of process parameters on MSW gasification with CaO sorbent for CO₂ capture.

![Fig. 2 Process flowsheet of sorbent-enabled MSW gasification](image-url)
3.2 Effect of CaO/MSW Ratio

One of the main purposes of this study is to observe the effect of CO₂ capture using CaO sorbent on MSW gasification product. Therefore, the effect of CaO/MSW ratio on syngas composition was investigated. The addition of CaO sorbent is intended to remove CO₂ content in the syngas and enhance H₂ composition.

Increasing CaO/MSW ratio means providing more sorbent for CO₂ carbonation reaction (R9). Figure 5 demonstrates that CO₂ removal performance is improved as the CaO/MSW ratio is varied from 0.05 to unity, indicated by the notable drop of CO₂ percentage from 14.54% to 0.43%. As a result, H₂ mole fraction increases from 20.00% to 23.31%, CO mole fraction from 9.41% to 10.97%, and CH₄ mole fraction from 0.95% to 1.10%. Since the addition of CaO sorbent improved the concentration of H₂, CO, and CH₄, the lower heating value of the syngas increases accordingly as shown on Figure 6. The trends observed here agree with the results from previous study (Acharya et al. 2010).

3.3 Effect of Temperature

Gasification temperature is an important parameter affecting equilibrium and rate of the chemical reactions (R1-R9). The effect of temperature can be explained by basic law of chemical reactions: Lower temperature favours the exothermic reactions, and higher temperature favours the endothermic reactions. Meanwhile, the reaction rate gets higher as the temperature increases. Combination of these effects causes variation of syngas composition over temperature as observed in this simulation study.

In this study, CaO sorbent is utilized to remove a portion of CO₂ in the syngas through CaO carbonation reaction (R9), thus improving the syngas H₂ composition. The optimal operating temperature of the carbonator is 580-700 °C, which is caused by the trade-off between the reaction equilibrium and kinetics. Above this temperature range, the efficiency of CO₂ capture drops significantly and approaches zero at around 775 °C (Hanak et al. 2015). The addition of CaO sorbent can no longer affect syngas composition when the operating temperature is over this limit. The result of this study strongly agrees with theory. Comparison of the syngas composition for non-sorbent case (Figure 7) and sorbent-enabled case (Figure 8) suggested that CaO sorbent affects the syngas composition only at temperature range of 500-750 °C. This conclusion is also supported by Figure 9 which suggested that LHV of the syngas produced from non-sorbent and sorbent-enabled gasification only differs at the temperature below 750 °C.
The effect of temperature on H₂ composition is similar for non-sorbent and sorbent-enabled cases. At the temperature below 650 °C, both trends demonstrate that temperature raise increases H₂ composition to a maximum value, which is observed at 650 °C for both cases. This is mainly attributed to the increasing rate of the water-gas (R5) and steam-methane reforming (R7, R8) reactions. In addition, at lower temperature the equilibrium of water-gas shift reaction (R6) is favoured towards the right side to produce H₂. However, above 650 °C, the temperature starts to favour the reverse direction of water-gas shift reaction (R6), causing H₂ composition to decrease as the temperature increases. The maximum H₂ composition for sorbent-enabled case is observed to be higher at 23.52% compared to 20.58% for non-sorbent case.

The production of CO is contributed mainly by the endothermic boudouard reaction (R4), water-gas reaction (R5), and steam-methane reforming reaction (R7). For both non-sorbent and sorbent-enabled cases, the graphs indicate a consistent increase of CO composition as temperature gets higher. This can be attributed to the increasing rate of the three reactions and the nature of endothermic reactions which is favoured by higher temperature. On the contrary, CH₄ production for both cases consistently decreases as the temperature raises. This is attributed to the methane-consuming steam-methane reforming reaction (R6, R7) which is also favoured by the higher temperature.

For non-sorbent case, the graph shows consistent reduction of CO₂ composition as temperature increases. This can be explained by the endothermic boudouard reaction (R4) and exothermic water-gas shift reaction (R6). CO₂ production from both reactions is more favourable at lower temperature, whereas higher temperature drives the reactions equilibrium to the other side which consumes CO₂ instead. Composition of CO₂ for the sorbent-enabled case is affected by gasification reactions (R1-R8) and CaO carbonation reaction (R9). The trend appears to be more complex as higher temperature inhibits CO₂ production from gasification, but also promotes desorption of CaCO₃ and releases additional CO₂ to the syngas mixture. At 500-600 °C, temperature increase lowers CO₂ composition down to its lowest point. This is the combined effect of the reduced CO₂ production and the increasing CaO sorption activity at this temperature range. However, when the temperature is raised above 600 °C, the notable drop in CaO sorption activity causes CO₂ composition to increase up to its maximum point at 750 °C. The CO₂ composition around 600-750 °C is nonetheless still lower compared to non-sorbent case, indicating that CO₂ removal reaction still takes place. The CO₂ capture activity is no longer detected above 750 °C, as the CO₂ composition obtained beyond this temperature is identical with that of the non-sorbent case.

Figure 9 compares the lower heating value of syngas produced from non-sorbent gasification and sorbent-enabled gasification. The syngas LHV for the non-sorbent case gets higher along with temperature raise, which is mainly contributed by the increase of CO content in the syngas. However, a different trend is observed for the sorbent-enabled case. Raising the temperature between 500-600 °C causes significant rise on H₂ and CO content in the syngas, therefore a steep ascent of the lower heating value is observed. The lower heating value reaches its peak at 4.26 MJ/Nm³ at the temperature of 600 °C. Between 600-750 °C, temperature rise affects the LHV negatively, as the H₂ and CO composition are decreasing
at this temperature range. Beyond 750 °C, no CaO sorption activity is detected as indicated by the identical value of syngas LHV from both models. It can be concluded from the graph that CaO sorption activity can significantly increase the LHV of the syngas.

Similar trends are observed in other works. Experimental study of Acharya et al. (2010) found that maximum H₂ composition was obtained at 670 °C, while Hu et al. (2015) reported highest composition of H₂ at 750 °C. Both studies also observed similar trends for CO and CH₄ composition. In addition, a simulation study by Rupesh et al. (2016) generated similar trend result for H₂, CO, CO₂, and CH₄ composition for both non-sorbent and sorbent-enabled cases.

3.4 Effect of Equivalence Ratio

The equivalence ratio (ER) represents the ratio of oxygen to biomass. A higher ER value means more oxidizing agent is present, promoting more oxidation reactions (R1-R3). This will lead to an increase of CO₂ and H₂O compositions, which will consequently reduce the amount of CO and H₂ (Niu et al. 2013). The result on both Figure 10 for non-sorbent case and Figure 11 for sorbent-enabled case agree with this theory. On both cases, compositions of CO and H₂ consistently decrease as ER and CO₂ composition increase.

The main difference between the two graphs is that the sorbent-enabled case has significantly lower amount of CO₂, which is attributed to the CO₂ capture. The reduced CO and H₂ contents also affect the syngas lower heating value negatively. As seen on Figure 12, syngas LHV decreases significantly as the ER value is raised. It is also observed that the LHV of the syngas generated from the sorbent-enabled gasification is generally higher than that from the non-sorbent gasification, which is mainly attributed to the lower CO₂ content and higher concentration of H₂ and CO in the sorbent-enabled gasification. The trends obtained here are highly consistent with previously published results (Rupesh et al. 2016, Chen et al. 2013).

3.5 Effect of Steam/MSW Ratio

Addition of steam affects gasification by promoting water-gas reaction (R5), water-gas shift reaction (R6), and steam-methane reforming reactions (R7, R8). Higher steam/MSW ratio drives these reactions equilibrium to the right side, increasing H₂ and CO₂ production while simultaneously reducing CO and CH₄ composition. This is consistent with the result presented on Figure 13 for the non-sorbent case. Composition of CO₂ rises from 14.12% to 19.37% and H₂ mole fraction increases from 18.19% to 25.85% as the steam/MSW ratio is varied from zero to unity.
4. Conclusion

Gasification of municipal solid waste integrated with CO₂ capture using CaO sorbent was successfully simulated using Aspen Plus process simulator. Two models were developed to compare the non-sorbent and the sorbent-enabled gasification. Comparison of both model’s results with available experimental data showed good agreement with acceptable root mean square error, indicating reliability of the model for predicting the actual process. The CaO addition was found to significantly reduce CO₂ content and improve H₂ concentration and LHV of the syngas. The sorbent activity is limited below the temperature of 750 °C, with optimum hydrogen concentration at 650 °C for both non-sorbent and sorbent-enabled cases. The increase of equivalence ratio and steam/MSW ratio positively affect the hydrogen production. A maximum hydrogen composition of 56.67% was obtained using sorbent-enabled gasification. Overall, this study provides a significant insight regarding the influence of key parameters on the investigated process. However, the assumption of complete chemical equilibrium does not always apply to the actual process. Therefore, future work should focus on representing the actual condition more accurately by taking the reaction kinetics into consideration.

Acknowledgments

The authors would like to express gratitude to the Department of Research and Community Service (DPPM) Universitas Islam Indonesia for providing the funding to carry out this study (Contract number: 07/Dnr/DPPM/70/Pen.Pemula/PII/XI/2019).

References

Acharya, B., Dutta, A. & Basu, P. (2010). An investigation into steam gasification of biomass for hydrogen enriched gas production in presence of CaO. *International Journal of Hydrogen Energy*, 35, 1582-1589.

Adi, A. C., Lasnawatin, F., Prananto, A., Suzanti, V., Anutomo, I., Anggreani, D. & Yuannigrat, H. (2019). *Handbook of Energy and Economic Statistics of Indonesia 2018*. Ministry of Energy and Mineral Resources Republic of Indonesia.

Al-Salem, S., Lettieri, P. & Baeyens, J. (2010). The valorization of plastic solid waste (PSW) by primary to quaternary routes: From re-use to energy and chemicals. *Progress in Energy and Combustion Science*, 36, 103-129.

Al Amoodi, N., Kannan, P., Al Shoaili, A. & Srinivasakannan, C. (2013). Aspen Plus simulation of polyethylene gasification under equilibrium conditions. *Chemical Engineering Communications*, 200, 977-992.

Aubret, E., Berthier, F., Laszuniew, A. & Nicolas, F. (2007). Incineration of municipal and assimilated wastes in France: Assessment of latest energy and material recovery performances. *Journal of Hazardous Materials*, 139, 569-574.

Begum, S., Rasul, M. & Akbar, D. (2014). A numerical investigation of municipal solid waste gasification using aspen plus. *Procedia engineering*, 90, 710-717.

Bumma, T. & Kuchonthara, P. (2018). Synergistic study between CaO and MgO sorbents for hydrogen rich gas production from the pyrolysis-gasification of sugarcane leaves. *Process Safety and Environmental Protection*, 118, 188-194.

Meanwhile, the mole fraction of CO decreases from 10.71% to 4.07%, and CH₄ composition is also reduced from 1.18% to 0.15%. Similar result was obtained by Niu et al. (2013). However, for the sorbent-enabled case (Figure 14), the addition of CO₂ capture system inhibits the raise of CO₂ composition. Consequently, the highest CO₂ composition is limited to 5.75% at steam/biomass ratio of unity, while the hydrogen composition is higher at 30.21%. This result agrees with the previous work published by Rupesh et al. (2016).

The effect of steam addition on the syngas LHV is presented on Figure 15. For the observed range, it can be seen that syngas LHV from sorbent-enabled gasification is always higher than that from non-sorbent gasification. For both cases, the increase of steam/MSW ratio causes a decrease of the syngas LHV. This is attributed to the declining CO composition as previously discussed. Although H₂ composition increases with steam addition, it cannot compensate for the reduced calorific value due to the decrease of CO₂ production.

**Fig. 14** Effect of steam/MSW ratio on syngas mole fraction for sorbent-enabled case

**Fig. 15** Effect of steam/MSW ratio on syngas LHV

Citation: Rahma, F.N., Tamzysi, C., Hidayat, A., Adnan, M.A. (2021) Investigation of Process Parameters Influence on Municipal Solid Waste Gasification with CO₂ Capture via Process Simulation Approach. *Int. Journal of Renewable Energy Development*, 10(1), 1-10, doi: 10.14710/ijred.2021.31982
Chen, C., Jin, Y.-Q., Yan, J.-H. & Chi, Y. (2013). Simulation of municipal solid waste gasification in two different types of fixed bed reactors. *Fuel*, 103, 58-63.

Chen, H. & Wang, L. (2016). *Technologies for biochemical conversion of biomass*, Academic Press.

Chen, S., Sun, Z., Zhang, Q., Hu, J. & Xiang, W. (2017). Steam gasification of sewage sludge with CaO as CO2 sorbent for hydrogen-rich syngas production. *Biomass and bioenergy*, 107, 52-62.

Consonni, S. & Viganò, F. (2012). Waste gasification vs. conventional Waste-To-Energy: A comparative evaluation of two commercial technologies. *Waste management*, 32, 653-666.

Dong, J., Tang, Y., Xizhou, A., Chi, Y., Weiss-Hortala, E., Ni, M. & Zhou, Z. (2018). Comparison of waste-to-energy technologies of gasification and incineration using life cycle assessment: Case studies in Finland, France and China. *Journal of Cleaner Production*, 203, 287-300.

Doranehgard, M. H., Samadayar, H., Mesbah, M., Haratipour, P. & Samiezade, S. (2017). High-purity hydrogen production with in situ CO2 capture based on biomass gasification. *Fuel*, 202, 29-35.

Dos Santos, R. G. & Alencar, A. C. (2020). Biomass-derived syngas production via gasification process and its catalytic conversion into fuels by Fischer Tropsch synthesis: a review. *International Journal of Hydrogen Energy*, 45, 18114-18152.

Eggleston, S., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. (2006). 2006 IPCC guidelines for national greenhouse gas inventories, Institute for Global Environmental Strategies Hayama, Japan.

Gao, W., Yan, L., Tahmoures, M. & Asgari Safdar, A. H. (2018). Hydrogen Production from Co-Gasification of Coal and Biomass in the Presence of CaO as a Sorbent. *Chemical Engineering & Technology*, 41, 447-453.

Hanak, D. P., Anthony, E. J. & Manovic, V. (2015). A review of developments in pilot-plant testing and modelling of calcium looping process for CO2 capture from power generation systems. *Energy & Environmental Science*, 8, 2199-2249.

Hosseini, S. E. & Wahid, M. A. (2016). Hydrogen production from renewable and sustainable energy resources: promising green energy carrier for clean development. *Renewable and Sustainable Energy Reviews*, 57, 850-866.

Hu, M., Guo, D., Ma, C., Hu, Z., Zhang, B., Xiao, B., Luo, S. & Wang, J. (2015). Hydrogen-rich gas production by the gasification of wet MSW (municipal solid waste) coupled with carbon dioxide capture. *Energy*, 90, 857-863.

Jingxia, Y. (2018). Municipal solid waste (MSW)-to-energy in China: challenges and cost analysis. *Energy Sources, Part B: Economics, Planning, and Policy*, 13, 116-120.

Kapdan, I. K. & Kargi, F. (2006). Bio-hydrogen production from waste materials. *Enzyme and microbial technology*, 38, 569-582.

Khaliil, M., Berawi, M. A., Horyanto, R. & Rizalie, A. (2019). Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia. *Renewable and Sustainable Energy Reviews*, 105, 323-331.

Khuriati, A., Purwanto, P., Huboyo, H. S., Suryono, S. & Putro, A. B. (2018). Application of aspen plus for municipal solid waste plasma gasification simulation: case study of Jatibarang Landfill in Semarang Indonesia. *Journal of Physics: Conference Series*, 012006.

Korai, M. S., Mahar, R. B. & Uqaili, M. A. (2016). Optimization of waste to energy routes through biochemical and thermochemical treatment options of municipal solid waste in Hyderabad, Pakistan. *Energy Conversion and Management*, 124, 333-343.

Li, B., Yang, H., Wei, L., Shao, J., Wang, X. & Chen, H. (2017). Absorption-enhanced steam gasification of biomass for hydrogen production: Effects of calcium-based absorbents and NiO-based catalysts on corn stalk pyrolysis-gasification. *International Journal of Hydrogen Energy*, 42, 5840-5848.

Lin, S., Kiga, T., Wang, Y. & Nakayama, K. (2011). Energy analysis of CaCO3 calcination with CO2 capture. *Energy Procedia*, 4, 356-361.

Luo, S., Zhou, Y. & Yi, C. (2012). Syngas production by catalytic steam gasification of municipal solid waste in fixed-bed reactor. *Energy*, 44, 391-395.

Maahachi, M. R. & Goswami, D. (2007). An experimental study of hydrogen production by gasification of biomass in the presence of a CO2 sorbent. *International Journal of Hydrogen Energy*, 32, 2803-2808.

Manovic, V. & Anthony, E. J. (2010). Lime-based sorbents for high-temperature CO2 capture—a review of sorbent modification methods. *International journal of environmental research and public health*, 7, 3129-3140.

Mishra, R. K. & Mohanty, K. (2018). An Overview of Techno-economic Analysis and Life-Cycle Assessment of Thermochemical Conversion of Lignocellulosic Biomass. *Recent Advancements in Biofuels and Bioenergy Utilization*, 363-402.

Mohgadam, R. A., Yusup, S., Uemura, Y., Chin, B. L. F., Lam, H. L. & Al Shoaibi, A. (2014). Syngas production from palm kernel shell and polyethylene waste blend in fluidized bed catalytic steam co-gasification process. *Energy*, 75, 40-44.

Molino, A., Larocca, V., Chiannese, S. & Musmarra, D. (2018). Biofuels production by biomass gasification: A review. *Energies*, 11, 811.

Niu, M., Huang, Y., Jin, B. & Wang, X. (2013). Simulation of syngas production from municipal solid waste gasification in a bubbling fluidized bed using Aspen Plus. *Industrial & Engineering Chemistry Research*, 52, 14768-14775.

Parthasarathy, P. & Narayanan, K. S. (2014). Hydrogen production from steam gasification of biomass: influence of process parameters on hydrogen yield—a review. *Renewable energy*, 66, 570-579.

Peng, W., Wang, L., Mirzaee, M., Ahmadi, H., Esfahani, M. & Fremaux, S. (2017). Hydrogen and syngas production by catalytic biomass gasification. *Energy Conversion and Management*, 135, 270-273.

Punzo, F. A., Pranolo, S. H., Waluyo, J. & Setyawan, A. (2020). Thermodynamic Study of Palm Kernel Shell Gasification for Aggregate Heating in an Asphalt Mixing Plant. *International Journal of Renewable Energy Development*, 9, 311-317.

Ramzan, N., Ashraf, A., Naveed, S. & Malik, A. (2011). Simulation of hybrid biomass gasification using Aspen plus: A comparative performance analysis for food, municipal solid and poultry waste. *Fuel and Biomass and Bioenergy*, 35, 3962-3969.

Rupesh, S., Muraleedharan, C. & Arun, P. (2016). ASPEN plus modelling of air–steam gasification of biomass with sorbent enabled CO2 capture. *Resource-efficient technologies*, 2, 94-103.

Salkuyeh, Y. K., Saville, B. A. & Maclean, H. L. (2018). Techno-economic analysis and life cycle assessment of hydrogen production from different biomass gasification processes. *International Journal of Hydrogen Energy*, 43, 9514-9528.

Shahbaz, M., Yusup, S., Inayat, A., Patrick, D. O., Ammar, M. & Pratama, A. (2017). Cleaner production of hydrogen and syngas from catalytic steam palm kernel shell gasification using CaO sorbent and coal bottom ash as a catalyst. *Energy & Fuels*, 31, 13924-13933.

Shayan, E., Zare, V. & Mirzaee, I. (2018). Hydrogen production from biomass gasification; a theoretical comparison of using different gasification agents. *Energy Conversion and management*, 159, 30-41.

Sikarwar, V. S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M. Z., Shah, N., Anthony, E. J. & Fennell, P. S. (2016). An overview of advances in biomass gasification. *Energy & Environmental Science*, 9, 2939-2977.

Sittisun, P., Tippayawong, N. & Shimpa, S. (2019). Gasification of pelleted corn residues with oxygen enriched air and steam. *International Journal of Renewable Energy Development*, 8, 215.
Sudibyo, H., Majid, A.I., Pradana, Y.S., Budhijanto, W., Deendarlianto, and Budiman, A. (2017). Technological evaluation of municipal solid waste management system in Indonesia. *Energy Procedia*, 105, 263-269.

Sutijastoto, A. R., Suharyati, I. R., Kurniawan, F., Kurniawan, A., Suzanti, V. & Ajiwhanto, N. (2010). *Handbook of energy & economic statistics of Indonesia 2009*. Ministry of energy and mineral resources republic Indonesia.

Toonssen, R., Sollai, S., Aravind, P., Woudstra, N. & Verkooijen, A. H. (2011). Alternative system designs of biomass gasification SOFC/GT hybrid systems. *International journal of hydrogen energy*, 36, 10414-10425.

Zhao, H. & Wang, J. (2018). Chemical-looping combustion of plastic wastes for in situ inhibition of dioxins. *Combustion and Flame*, 191, 9-18.

Zhou, L., Yang, Z., Tang, A., Huang, H., Wei, D., Yu, E. & Lu, W. (2019). Steam-gasification of biomass with CaO as catalyst for hydrogen-rich syngas production. *Journal of the Energy Institute*, 92, 1641-1646.

Zuberi, M. J. S. & Ali, S. F. (2015). Greenhouse effect reduction by recovering energy from waste landfills in Pakistan. *Renewable and Sustainable Energy Reviews*, 44, 117-131.

© 2021. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution-ShareAlike 4.0 (CC BY-SA) International License (http://creativecommons.org/licenses/by-sa/4.0/)