Research Article

Investigation of Process Parameters Influence on Municipal Solid Waste Gasification with CO_2 Capture via Process Simulation Approach

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ABSTRACT. Integration of gasification with CO_2 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 CO_2 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 CO_2 capture was found to successfully reduce the CO_2 content in the syngas, increase the H_2 composition, and improve the syngas LHV at the temperature below 750 ºC. The maximum H_2 composition of 56.67% was obtained from the sorbent-enabled gasification. It was found that increasing equivalence ratio leads to a higher H_2 concentration and syngas LHV. Raising steam/MSW ratio also increases the H_2 production, but also reduces the LHV of the syngas. Observation of the temperature effect found the highest H_2 production at 650 ºC for both non-sorbent and sorbent-enabled gasification.

Keywords: CaO sorption, CO_2 capture, gasification, municipal solid waste, syngas

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

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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.

Incineration is basically an oxidation reaction of a combustible material, during which energy is recovered in the form of heat (Autret *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 Viganò 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 biomass 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 H_2, CO, CO_2, and CH_4. 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 (Moghadam *et al.* 2014).

Hydrogen is well known as a clean fuel with high energy density. It can be utilized for production of electricity or 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 CO_2 emission remains one of the main barriers in the development of biomass gasification. The CO_2 emission also affects hydrogen production by lowering its concentration in the syngas. However, the syngas hydrogen concentration can be enriched using CO_2 capture technology which removes some of the CO_2 from the mixture, therefore producing hydrogen-enriched syngas. Among several technological options, CO_2 removal using CaO sorbent is currently gaining attention due to its relatively low cost and high effectivity (Manovic and Anthony 2010). This technology captures CO_2 from gaseous mixture by CaO carbonation reaction where CaO reacts with CO_2 to form $CaCO_3$.

Several experimental works have been conducted on CO_2 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 CO_2 and enhance hydrogen concentration in the syngas. However, only a limited number of works has been reported on MSW gasification with CO_2 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 CO_2 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. The

understanding of how these key parameters affect gasification is a substantial key in developing MSW gasification process integrated with CaO sorbent for CO_2 capture.

2. Methods

The gasification of MSW with sorbent-enabled CO_2 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 H_2S and nitrogen is only converted to NH_3.

Peng-Robinson equation of state with Boston-Mathias alpha function was chosen for this simulation as this property package is suitable for high temperature processes, including gasification (Ramzan *et al.* 2011). The property package estimated thermophysical properties of the conventional components such as H_2, CO, CO_2, CH_4, H_2O, O_2, N_2, NH_3, H_2S, 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 *at 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 *at 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 CO_2 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 HCOALGEN and density model DCOALIGT were selected for their thermophysical properties calculation. CaO, $CaCO_3$, 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 CO_2 capture reactor CO2CAPT, also modelled using RGibbs reactor. In this reactor, removal of CO_2 through CaO carbonation into $CaCO_3$ takes place, removing a portion of CO_2 from the syngas mixture. The reactions inside the gasifier and CO_2 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.
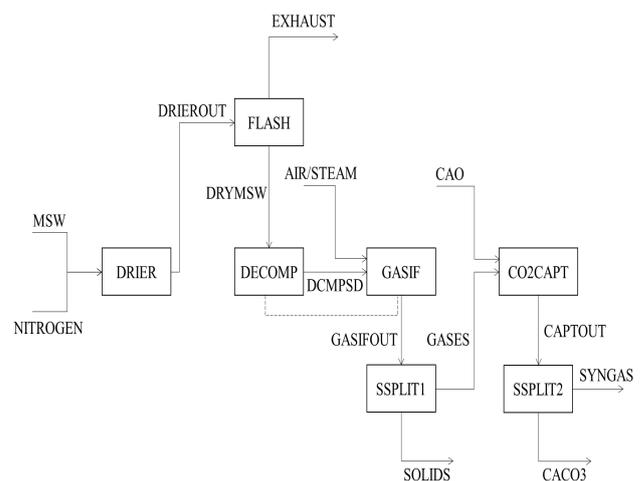
Fig. 1 Block diagram of sorbent-enabled MSW gasification

Table 4
Description of reactions in gasifier and CO_2 capture reactor

No	Reaction Equation	$\Delta H_{R\,25}$ kJ/mol	Reaction Name
R1	$C + 0.5O_2 \rightarrow CO$	-111	Char partial combustion
R2	$CO + 0.5O_2 \rightarrow CO_2$	-283	CO partial combustion
R3	$H_2 + 0.5O_2 \rightarrow H_2O$	-242	H_2 partial combustion
R4	$C + CO_2 \leftrightarrow 2CO$	+172	Boudouard reaction
R5	$C + H_2O \leftrightarrow CO + H_2$	+131	Water-gas reaction
R6	$CO + H_2O \leftrightarrow CO_2 + H_2$	-41	Water-gas shift reaction
R7	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206	Steam-methane reforming
R8	$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2$	+165	Steam-methane reforming
R9	$CO_2 + CaO \leftrightarrow CaCO_3$	-178	CaO carbonation

Source: Niu *et al.* (2013), Lin *et al.* (2011)

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(\hat{y}_i - y_i)^2}{n}} \qquad (1)$$

Where:

- RMSE is the root mean square error
- $\hat{y}_i$ is the model result
- y_i is the experimental result
- n is the number of data

$$LHV_{gas} = 10.79\, Y_{H_2} + 12.26\, Y_{CO} + 35.81\, Y_{CH_4} \qquad (2)$$

Where:

- LHV_{gas} is the lower heating value of syngas (MJ/Nm³)
- Y_{H_2} is the mole fraction of H_2
- Y_{CO} is the mole fraction of CO
- Y_{CH_4} is the mole fraction of CH_4

The validated model was used to investigate the effect of sorbent-enabled CO_2 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 H_2, CO, and CH_4 (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 CO_2 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 ºC, 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 ºC, 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 CO_2 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 Amoodi *et al.* 2013), 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 CO_2 capture.
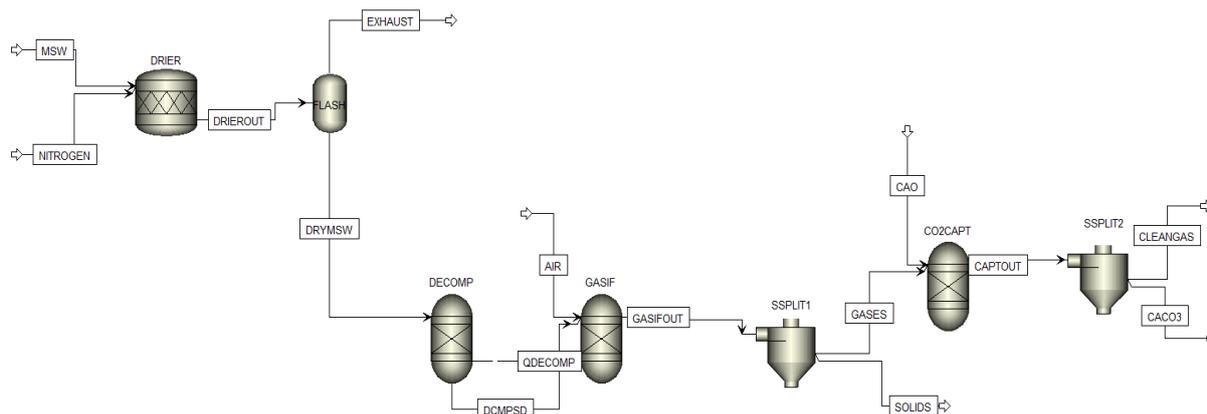
Fig. 2 Process flowsheet of sorbent-enabled MSW gasification
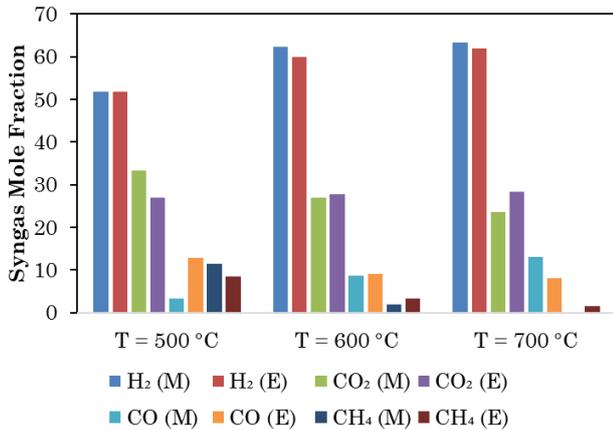
Fig. 3 Validation of syngas mole fraction for non-sorbent gasification (Mahishi and Goswami 2007)
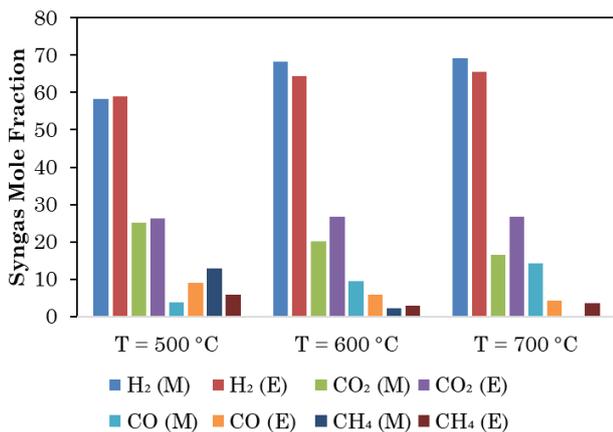
Fig. 4 Validation of syngas mole fraction for sorbent-enabled gasification (Mahishi and Goswami 2007)

3.2 Effect of CaO / MSW Ratio

One of the main purposes of this study is to observe the effect of CO_2 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 CO_2 content in the syngas and enhance H_2 composition.
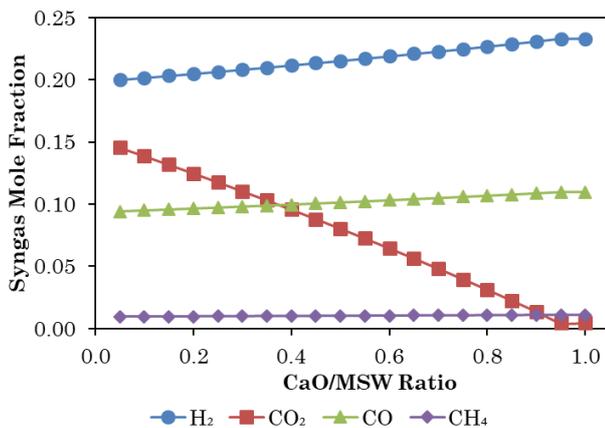
Fig. 5 Effect of CaO/MSW ratio on syngas mole fraction
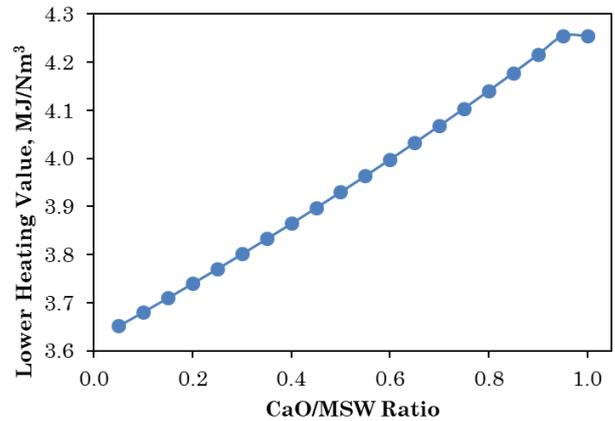
Fig. 6 Effect of CaO/MSW ratio on syngas LHV

Increasing CaO/MSW ratio means providing more sorbent for CO_2 carbonation reaction (R9). Figure 5 demonstrates that CO_2 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, H_2 mole fraction increases from 20.00% to 23.31%, CO mole fraction from 9.41% to 10.97%, and CH_4 mole fraction from 0.95% to 1.10%. Since the addition of CaO sorbent improved the concentration of H_2, CO, and CH_4, 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 CO_2 in the syngas through CaO carbonation reaction (R9), thus improving the syngas H_2 composition. The optimal operating temperature of the carbonator is 580-700 ºC, which is caused by the trade-off between the reaction equilibrium and kinetics. Above this temperature range, the efficiency of CO_2 capture drops significantly and approaches zero at around 775 ºC (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 ºC. 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 ºC.
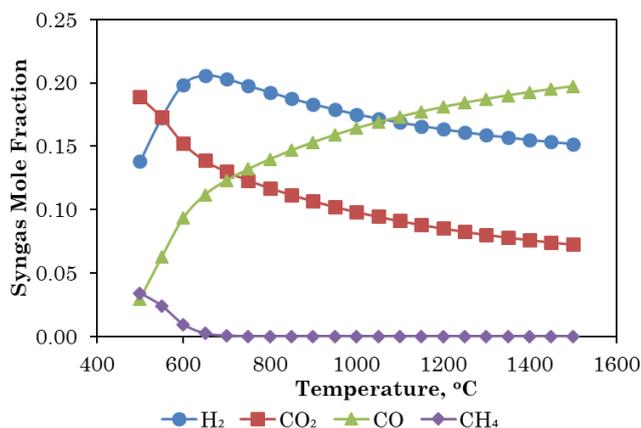
Fig. 7 Effect of temperature on syngas mole fraction for non-sorbent case
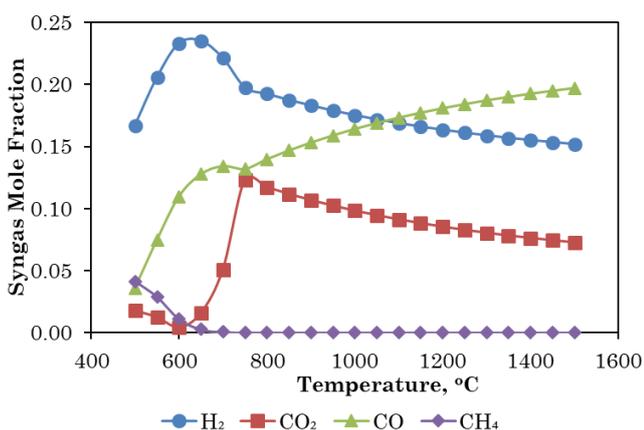
Fig. 8 Effect of temperature on syngas mole fraction for sorbent-enabled case
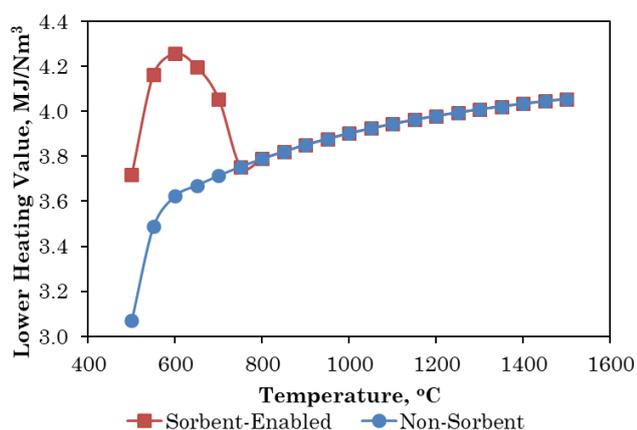
Fig. 9 Effect of temperature on syngas LHV

Observation of syngas composition and LHV at higher temperature shows no difference between the non-sorbent case and sorbent-enabled cases, indicating the absence of CO_2 removal reaction.

The effect of temperature on H_2 composition is similar for non-sorbent and sorbent-enabled cases. At the temperature below 650 °C, both trends demonstrate that temperature raise increases H_2 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 H_2. However, above 650 °C, the temperature starts to favour the reverse direction of water-gas shift reaction (R6), causing H_2 composition to decrease as the temperature increases. The maximum H_2 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, CH_4 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 CO_2 composition as temperature increases. This can be explained by the endothermic boudouard reaction (R4) and exothermic water-gas shift reaction (R6). CO_2 production from both reactions is more favourable at lower temperature, whereas higher temperature drives the reactions equilibrium to the other side which consumes CO_2 instead. Composition of CO_2 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 CO_2 production from gasification, but also promotes desorption of $CaCO_3$ and releases additional CO_2 to the syngas mixture. At 500-600 °C, temperature increase lowers CO_2 composition down to its lowest point. This is the combined effect of the reduced CO_2 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 CO_2 composition to increase up to its maximum point at 750 °C. The CO_2 composition around 600-750 °C is nonetheless still lower compared to non-sorbent case, indicating that CO_2 removal reaction still takes place. The CO_2 capture activity is no longer detected above 750 °C, as the CO_2 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 H_2 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/Nm^3 at the temperature of 600 °C. Between 600-750 °C, temperature rise affects the LHV negatively, as the H_2 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 H_2 composition was obtained at 670 °C, while Hu *et al.* (2015) reported highest composition of H_2 at 750 °C. Both studies also observed similar trends for CO and CH_4 composition. In addition, a simulation study by Rupesh *et al.* (2016) generated similar trend result for H_2, CO, CO_2, and CH_4 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 CO_2 and H_2O compositions, which will consequently reduce the amount of CO and H_2 (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 H_2 consistently decrease as ER and CO_2 composition increase.
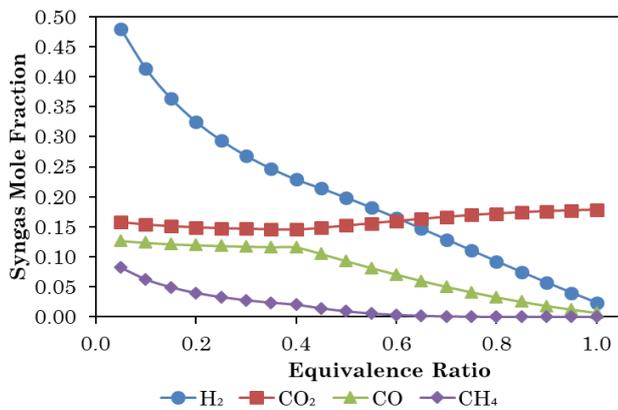
Fig. 10 Effect of ER on syngas mole fraction for non-sorbent case
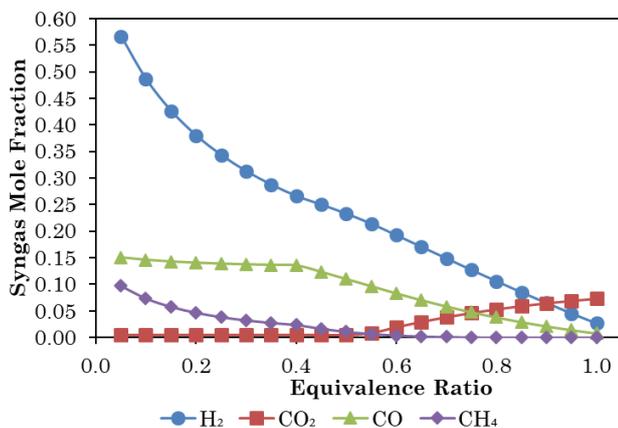
Fig. 11 Effect of ER on syngas mole fraction for sorbent-enabled case
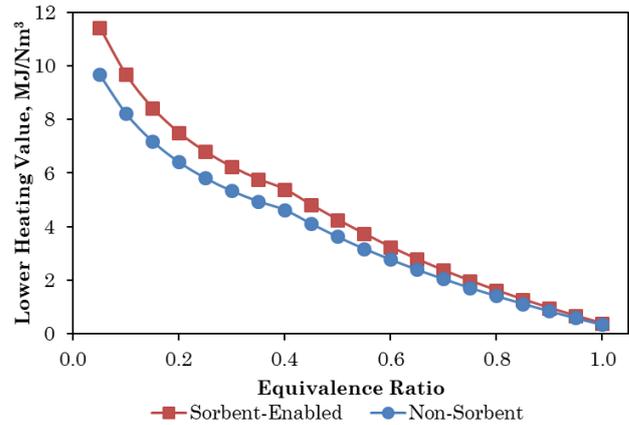
Fig. 12 Effect of ER on syngas LHV

The main difference between the two graphs is that the sorbent-enabled case has significantly lower amount of CO_2, which is attributed to the CO_2 capture. The reduced CO and H_2 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 case is generally higher than that from the non-sorbent gasification, which is mainly attributed to the lower CO_2 content and higher concentration of H_2 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 H_2 and CO_2 production while simultaneously reducing CO and CH_4 composition. This is consistent with the result presented on Figure 13 for the non-sorbent case. Composition of CO_2 rises from 14.12% to 19.37% and H_2 mole fraction increases from 18.19% to 25.85% as the steam/MSW ratio is varied from zero to unity.
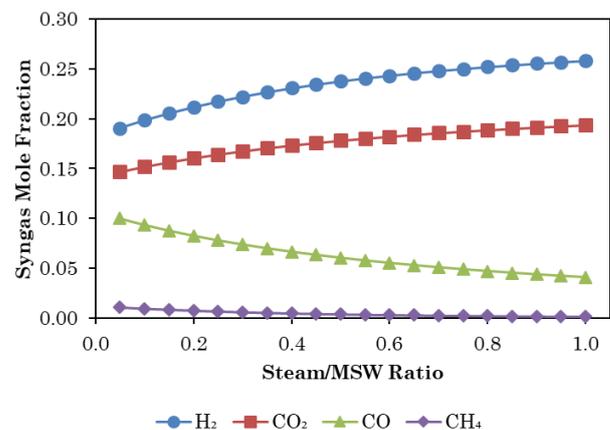
Fig. 13 Effect of steam/MSW ratio on syngas mole fraction for non-sorbent case
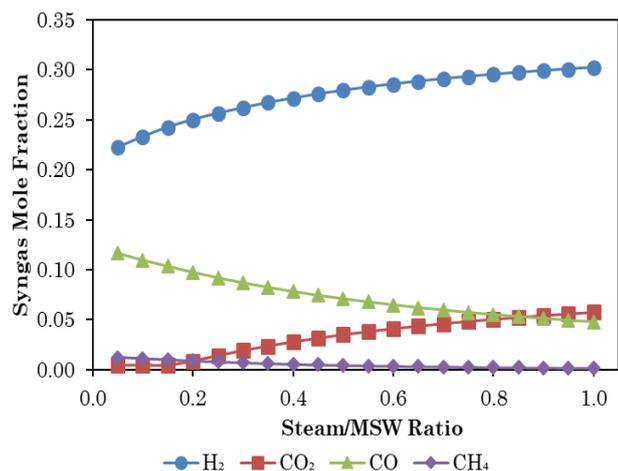
Fig. 14 Effect of steam/MSW ratio on syngas mole fraction for sorbent-enabled case
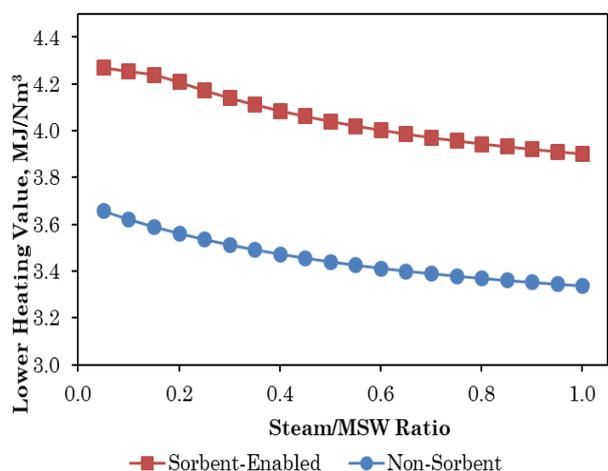
Fig. 15 Effect of steam/MSW ratio on syngas LHV

Meanwhile, the mole fraction of CO decreases from 10.71% to 4.07%, and CH_4 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 CO_2 capture system inhibits the raise of CO_2 composition. Consequently, the highest CO_2 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 H_2 composition increases with steam addition, it cannot compensate for the reduced calorific value due to the decrease of CO production.

4. Conclusion

Gasification of municipal solid waste integrated with CO_2 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 CO_2 content and improve H_2 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

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