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Article

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Gasification of plastic waste for synthesis gas production

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Abstract

This work presents the synthesis gas production from gasification of plastic waste, i.e. polyethylene (PE) and polypropylene (PP). The steam gasification is modeled by using AspenPlusTM simulation software. The effects of gasifier temperature and steam to feed (S/F) mass ratio were examined to determine the suitable synthesis gas mole flow rate. The simulation results showed that gasifier should be operated at 900 °C with optimal S/F mass ratio as 1.5. Considering the influence of PE/PP mass ratio, the results indicated that the PE/PP mass ratio of 100/0 or pure PE can provide the maximum synthesis gas flow rate of 21 kmol/hr and H₂/CO ratio of 2.1.

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Keywords: Synthesis gas; Gasification; Plastic; Waste

1. Introduction

Increasing population leads to an increase in plastic waste which is a big issue in every country. The dominant plastics produced worldwide are 29.6% polyethylene, 18.9% polypropylene and the others [1]. The plastic waste can be managed by landfill and incinerating. The disadvantages of landfill and incinerating are carbon dioxide emission. Although plastic waste can be reused and recycled, in the end it will be garbage or become non-recyclable. In order to add value of plastic waste, the conversion of plastic waste to other products has received much attention [2–5].

Nowadays, there are two technologies, i.e., pyrolysis and gasification, for converting plastic waste to an energy carrier. In case of pyrolysis, plastic waste is heated at temperature around 300–650 °C in the absence of O₂ and then, oil fuel can be provided. In gasification, plastic waste is reacted with gasifying agent (e.g., steam, oxygen and

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air) at high temperature around 500–1300 °C, which can produce synthesis gas or syngas. It can be observed that the main difference of these methods is the obtained product. Gasification of plastic waste has been focused in this work since syngas can be further used to produce many products and fuel for fuel cell to generate electricity.

Although there are a few experimental studies concentrated on gasification of plastic waste, theoretical calculation based on Aspen plus simulator is an essential task. The obtained results can be guideline in the real operation. The simulation of whole process can provide the possibility of using this process in large-scale application.

2. Process description

Fig. 1 shows the schematic of gasification of plastic waste designed in Aspen Plus simulator. Plastic wastes considered in this work consist of polyethylene (PE) and polypropylene (PP). In the real practice, the plastic waste can be directly supplied to the gasifier where it is reacted with steam as a gasifying agent. Since the plastic waste is a non-conventional component and thus, it must be decomposed into each element before occurring the reaction. In the simulation, the gasification consists of two parts: decomposition of plastic waste (DECOMP) and reaction of plastic waste with steam (GASIFIER). As seen in Fig. 1, plastic waste (PLASTIC) is firstly heated through the heater (HEATER1) before feeding to the decomposition unit (DECOMP). Then, the DE-PLA stream is sent to the gasifier (GASIFIER) simultaneously with steam (STEAM) which water (WATER) is preheated via heater (HEATER2). When the chemical reactions are accomplished in the gasifier, the gas product (PRODUCT) can be provided. Table 1 presents the specification of each unit model in gasification of plastic waste.

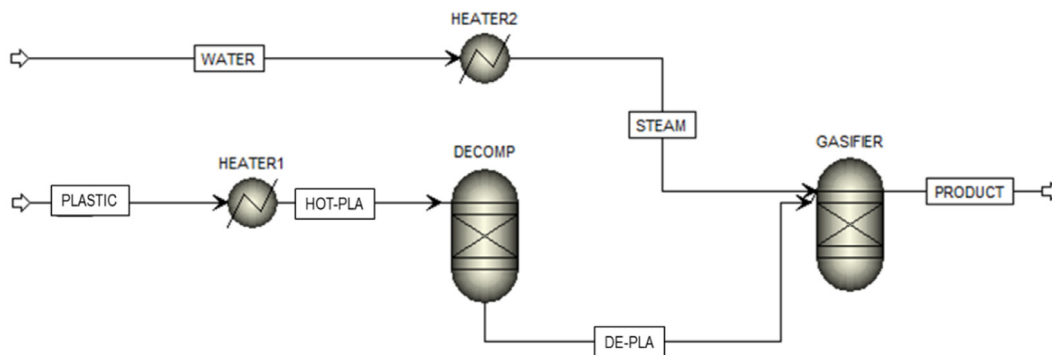


Fig. 1. Gasification of plastic waste.

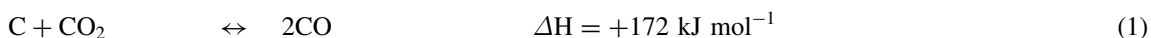
Table 1. Specification of each unit models in gasification of plastic waste.

Name	Unit model	Initial condition	Operation range
HEATER1	Heater	T = 300 °C, P = 1 atm	–
HEATER2	Heater	T = 300 °C, P = 1 atm	–
DECOMP	RYield	T = 650 °C, P = 1 atm	T = 650–1100 °C
GASIFIER	RGibbs	T = 300 °C, P = 1 atm	T = 650–1100 °C

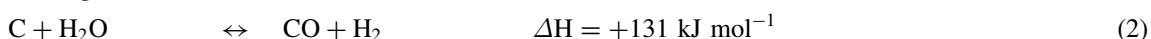
Note T = Temperature and P = Pressure.

In this work, *RYield* reactor model is used to represent the decomposition of plastic waste as non-conventional component into element. Gasifier is modeled by *RGibbs* reactor model since there are many reactions possible to occur in the gasifier. The chemical reactions that are possible to occur in the steam gasification are listed below:

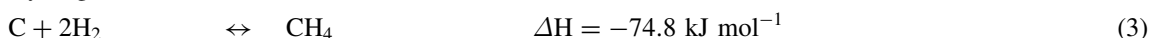
- Boudouard Reaction



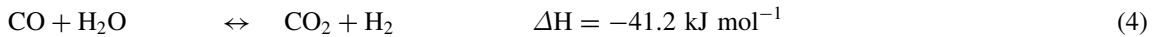
- Water-gas Reaction



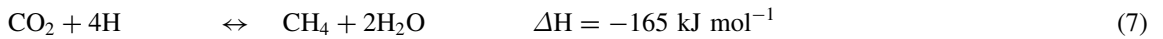
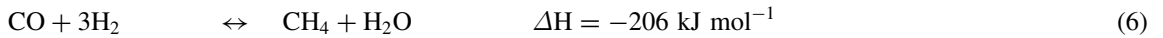
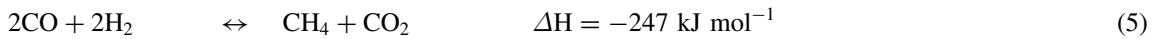
- Hydrogasification



- Water-gas shift Reaction



- Methanation Reaction



- Reforming Reaction



3. Methodology

This work performs thermodynamic calculation through Aspen plus simulator in which Soave–Redlich–Kwong is used as the equation of state. The proximate and ultimate analysis of PE [3] and PP [4] which is extracted from the literature is shown in Table 2. When the temperature and pressure of each unit model are specified as Table 1 and steam to feed (S/F) mass ratio is set as 1, the gas composition can be determined by the total Gibbs free energy minimization method. Effect of gasifier temperature and S/F mass ratio on syngas production is determined. Not only the syngas fraction is used to consider the favorable operating condition but also lower heating value (LHV) of syngas as expressed in Eq. (9) is considered.

$$\text{LHV}_{\text{syngas}} = (y_{\text{CO}} \times 12.636) + (y_{\text{H}_2} \times 10.798) \quad (9)$$

where y_{CO} and y_{H_2} represent the mole fraction of CO and H₂, respectively. The unit of LHV_{syngas} is MJ/Nm³.

Table 2. The proximate and ultimate analysis of PE and PP used in the simulation.

	PE [3]	PP [4]
Moisture Content (wt%)	0.02	0
Proximate analysis, wt% dry basis		
Fixed carbon	0	0
Volatile matter	99.85	99.30
Ash	0.15	0.70
Ultimate analysis, wt% dry basis		
Carbon	85.81	86.42
Hydrogen	13.86	12.28
Oxygen	0	0
Nitrogen	0.12	0.72
Sulfur	0.06	0.17

4. Model validation

To ensure that the proposed model can be used in this study, the simulated results of steam gasification from PP are compared with the experimental data extracted from literature [5]. From the experiment of C. Wu and P.T. Williams [5], PP which has the proximate and ultimate analysis according to Table 2 is fed into the reactor with 1 g. The steam is introduced into the gasifier as flow rate of 4.7 ml/h. Table 3 presents the comparison results obtained from experiment and simulation when the gasifier operates at temperature of 800 °C and 1 atm. It can be seen that under the same operating condition with the experiment, the simulation results agree with the experimental data.

5. Results and discussion

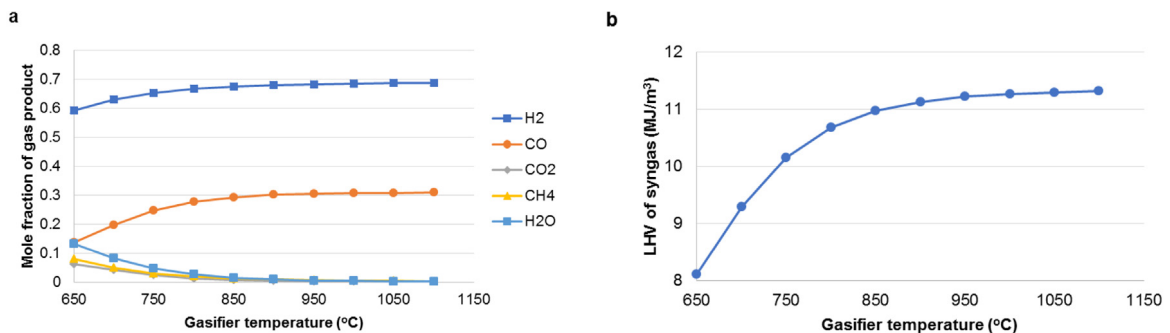
This section presents the effect of gasifier temperature and S/F mass ratio on syngas production and LHV_{syngas} under atmospheric pressure. In addition, the use of different type of plastic waste, i.e., pure PE, pure PP and mixed PE and PP, is also investigated.

Table 3. The comparison between experimental data from the literature [5] and simulated result in this study.

Gas composition (% mole)	Experimental result [5]	This study
Hydrogen	64.0	67.25
Carbon monoxide	25.7	25.24
Carbon dioxide	6.40	7.33
Methane	3.30	0.18
C2+	0.60	–

5.1. Gasifier temperature effect

Fig. 2 shows the effect of gasifier temperature on mole fraction of gas product and LHV_{syngas} obtained from steam gasification of pure PE. In this study, the gasifier temperature is varied from 650 to 1100 °C whereas S/F mass ratio is fixed as 1. From Fig. 2a, it can be seen that increasing gasifier temperature leads to increases in mole fraction of H_2 and CO. In the contrast, the increment of gasifier temperature causes the reduction of CO_2 , CH_4 and H_2O fraction. Since increasing gasifier temperature can promote the endothermic reaction, i.e., Boudouard (Eq. (1)), water-gas (Eq. (2)) and reforming reactions (Eq. (3)) and thus, the production of H_2 and CO is higher whereas the generation of CO_2 , CH_4 and H_2O is lower. However, it can be observed from Fig. 2a that both H_2 and CO fraction will stable when the gasifier is operated at temperature higher than 900 °C. Since the gas production is equilibrium limited at this temperature.

**Fig. 2.** Effect of gasifier temperature on (a) mole fraction of gas product and (b) LHV_{syngas} obtained from steam gasification of pure PE at S/F mass ratio of 1.

Considering LHV_{syngas} according to Fig. 2b, it is found that LHV_{syngas} is higher when the gasifier operates at higher temperature. This is due to the fact that the LHV_{syngas} is calculated from mole fraction of CO and H_2 and thus, it has similar trend of CO and H_2 mole fraction profile. Nevertheless, when the gasification reaction tends to be completed at temperature of 900 °C, the LHV_{syngas} becomes stable at about 11.36 MJ/m³. From the simulation result, it can be concluded that the optimal operating temperature of gasifier is 900 °C.

5.2. S/F mass ratio effect

Next, the impact of the S/F mass ratio which was varied between 0.25 and 3 on mole fraction of gas product and LHV_{syngas} is investigated at gasifier temperature of 900 °C. Since this system uses steam as gasifying agent, adding steam into the gasifier can shift the reaction toward. There are three reactions affected to adding steam: water-gas (Eq. (2)), water-gas shift (Eq. (4)) and reforming (Eq. (8)) reactions. Therefore, H_2 can be more produced with increasing S/F mass ratio. Like H_2 production, the generation of CO is more pronounced when S/F mass ratio increases from 0.5 to 1.25 and then, the molar flow rate of CO is reduced. This is because an excess steam will react with CO to generate more CO_2 resulting in a decrease in CO molar flow rate. Because the results as shown in Fig. 3a are reported in mole fraction, the mole fraction of H_2 will be decreased; although, mole flow rate of H_2 is higher. From the simulation results, it is found that the optimal S/F mass ratio is 1.25 which can provide the suitable mole fraction of H_2 and CO.

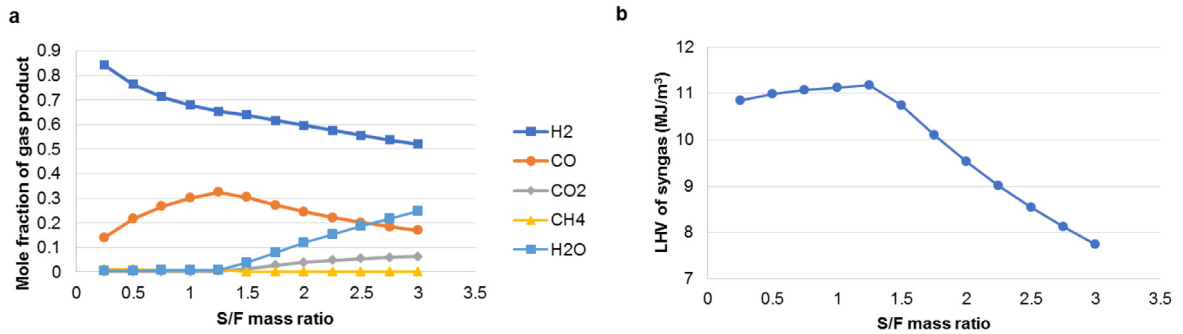


Fig. 3. Effect of S/F mass ratio on (a) mole fraction of gas product and (b) LHV_{syngas} obtained from steam gasification of PE at gasifier temperature of 900 °C.

From Fig. 3b, it can be seen that LHV_{syngas} will increase and reach to maximum value $\sim 11.40 \text{ MJ/m}^3$ at S/F mass ratio of 1.25. Then, the LHV_{syngas} is dropped because excess steam in system affects to not only the dilution of H_2 with steam but also the conversion of CO to CO_2 .

5.3. Energy consumption

Fig. 4 presents the effect of S/F mass ratio on energy consumption at gasifier temperature of 900 °C. Since the gasifying agent used in this work is steam, it is known that steam gasification is allothermal process and thus, it always requires the external heat source. From Fig. 4, it can be found that at constant gasifier temperature of 900 °C, increasing S/F mass ratio requires more energy input to drive the reaction. Adding higher steam in feed causes highly endothermic reaction. In addition, more steam in the reactor uses more heat to vaporize steam. The selection of S/F mass ratio as 1.5 is compromise between syngas production and energy consumption.

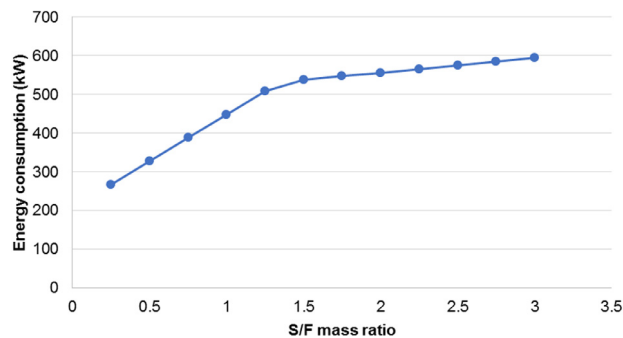


Fig. 4. Effect of S/F mass ratio on energy consumption at gasifier temperature of 900 °C.

5.4. PE/PP mass ratio effect

In order to determine the suitable types and amount of plastic waste for syngas production, the influence of PE/PP mass ratio as 100/0, 75/25, 50/50, 25/75 and 0/100 are considered as a function of different gasifier temperature and S/F mass ratio as illustrated in Fig. 5. It is noted that PE/PP mass ratio of 100/0 and 0/100 is referred to the use of pure PE and pure PP, respectively.

As seen in Fig. 5, it is found that the results of all PE/PP mass ratios have the similar trend with the results as discussed in Sections 5.1 and 5.2. Both increases of gasifier temperature and S/F mass ratio can improve the syngas molar flow rate. However, it can be observed that the use of different PE/PP mass ratios in feed has a slight effect on syngas molar flow rate. From Fig. 5, it can be seen that pure PE can produce more syngas compared with other ratios. This is since the component of hydrogen and carbon in PE is higher than that in PP, the use of pure

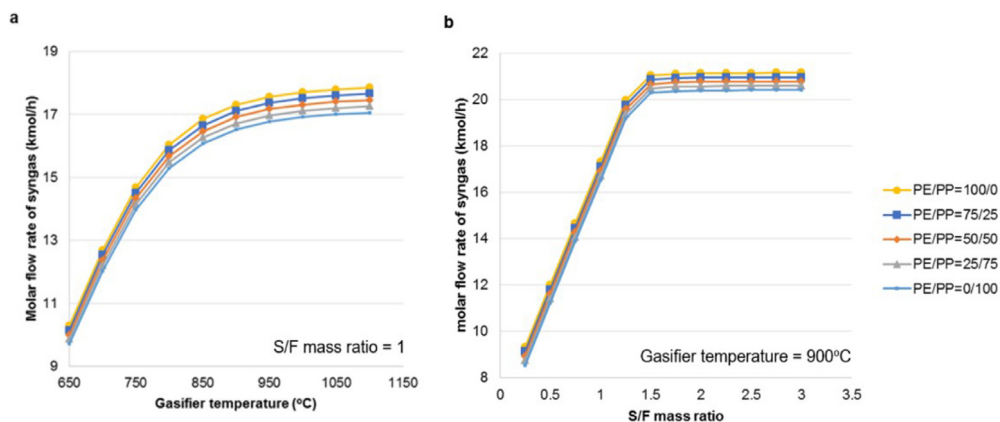


Fig. 5. Effect of (a) gasifier temperature and (b) S/F mass ratio on molar flow rate of syngas with using different mass ratio of PE/PP.

PE can obtain the highest syngas production. From the simulation results, it can be concluded that the favorable operating condition providing the optimum syngas molar flow rate is at 900 °C and S/F mass ratio of 1.5. Under this operating condition, the syngas flow rate of 21 kmol/h and H_2/CO ratio of 2.1 can be provided when pure PE is used. In case of using pure PP, it can be obtained the syngas molar flow rate and H_2/CO as 20.3 kmol/h and 2, respectively.

6. Conclusions

In this work, the plastic wastes which include polyethylene (PE) and polypropylene (PP) are used as feed to convert into syngas through steam gasification. Theoretical calculation based on Aspen plus simulator is performed. Gas composition at equilibrium can be computed by using the minimization of Gibbs free energy. The simulation results indicated that the favorable operating condition of syngas production is at 900 °C with S/F mass ratio of 1.5. Considering the mixed PE and PP, it was found that the highest syngas production can be obtained when pure PE is used. Under this operating condition, the syngas flow rate of 21 kmol/h and H_2/CO ratio of 2.1 can be provided.

Acknowledgment

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