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Simulation of municipal solid waste gasification for syngas production in fixed bed reactors*

Chong CHEN, Yu-qi JIN†‡, Jian-hua YAN, Yong CHI
(*State Key Laboratory of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, China*)
†E-mail: jinyuqi@zju.edu.cn

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Abstract: This study proposes a model of syngas production from municipal solid waste (MSW) gasification with air in fixed bed reactors. The model (using Aspen plus simulator) is used to predict the results of MSW gasification and to provide some process fundamentals concerning syngas production from MSW gasification. The effects of gasification temperature, air equivalence ratio and moisture concentration on the composition of syngas, lower heating value (LHV) of syngas, heat conversion efficiency, and carbon conversion are discussed. The results indicate that higher temperature improves gasification, and higher air equivalence ratio increases the carbon conversion while decreasing syngas LHV. Heat conversion efficiency increases and reaches the maximum and then decreases with the increase of air equivalence ratio. Higher moisture concentration increases the carbon conversion and increases the heat conversion efficiency at lower ratios. Higher temperature and a lower equivalence ratio are favorable for obtaining a higher LHV of syngas at the same moisture concentration.

Key words: Municipal solid waste (MSW), Gasification, Syngas, Aspen plus, Fixed bed
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1 Introduction

Municipal solid waste (MSW) incineration has advantages of energy recovery and weight/volume reduction. It has rapidly developed in the last decade in China. However, as environmental protection becomes more and more important, the emission control on MSW incineration is also increasingly important. To provide a more energy efficient and environmentally friendly solution, the study of a novel MSW thermal treatment (gasification of MSW) has gained importance in China. Gasification has the advantage of lower dioxins, compared to other disposal options, such as incineration (Calaminus and Stahlberg, 1998). To many analysts, gasification is expected to be the future method of producing an energy carrier, and the production of syngas from biomass or waste would require gasification as an essential part of the overall process (Thamavithya and Dutta, 2008).

There are mainly two kinds of gasifier: fluidized bed gasifier and fixed bed gasifier. Fluidized bed gasification is often adopted for larger capacity MSW disposal (Warnecke, 2000). Fluidized bed gasification is more complicated in constructing and operating, and also requires a higher investment. However, in the counties or towns of China, the output of MSW is not large enough to match the capacity of the fluidized bed. As a result, for disposing MSW, it is more advisable to choose fixed bed gasification, which requires a lower investment, and matches the small output of MSW in these places. Fixed bed gasification also has the advantage of a small amount of fly ash, and the syngas from MSW gasification can be used in various areas as clean energy.

Much work has been done on gasification in

‡ Corresponding author
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fixed bed reactors. However, most of these fixed bed reactors are used to deal with biomass. Lv *et al*. (2007) developed a self-heated downdraft gasifier for hydrogen production from gasification of biomass with air and oxygen/steam. It was concluded that the content of H_2 and CO reaches 63.27%–72.56% for biomass oxygen/steam gasification, while the content reaches 52.19%–63.31% for biomass air gasification. Niu *et al*. (2001) studied straw gasification in an updraft gasifier (household-type). The results showed that the lower heating value (LHV) of the syngas produced was 7.6–9.1 MJ/Nm^3. Saravanakumar *et al*. (2007) developed an updraft gasifier for wood gasification. Friberg and Blasiak (2002) studied the effect of air flow rate on the gasification of three different sizes of wood. The results indicated that, although a controlled constant primary air flow is applied, the batch conversion of wood fuels is very dynamic. Dogru *et al*. (2002) studied the gasification of hazelnut shells in a downdraft gasifier. The optimum operation of the gasifier was found to be between 1.44 and 1.47 Nm^3/kg of air fuel ratios at the values of 4.06 and 4.48 kg/h of wet feed rate, which produces gas (at a volumetric flow of 8–9 Nm^3/h) with a good gross calorific value (GCV) of about 5 MJ/m^3. However, little has been done on MSW gasification in fixed bed reactors. To study MSW gasification in real fixed bed reactors, the first step is to simulate the process to understand the characteristics of MSW gasification. Many scholars have worked on simulation of gasification in fixed bed reactors (Kayal *et al*., 1997; Di Blasi *et al*., 2003; Gobel *et al*., 2007; Jarungthammachote and Dutta, 2007; Gerun *et al*., 2008; Sharma, 2008). Aspen plus has been widely used to simulate biomass gasification and MSW incineration in fluidized beds (Khoshnoodi and Lim, 1997; Sotudeh-Gharebaagh *et al*., 1998; Slapak *et al*., 2000; Mathieu and Dubuisson, 2002; de Jong *et al*., 2003; Zheng and Furimsky, 2003; Cimini *et al*., 2005; Zheng and Furimsky, 2005; Zhao *et al*., 2006; Chen *et al*., 2007; Jannelli and Minutillo, 2007; Nikoo and Mahinpey, 2008; Shen *et al*., 2008).

In this study, a novel process of air gasification of MSW in a fixed bed reactor is proposed. Aspen plus is adopted to simulate the entire process. The process simulation is conducted to demonstrate the possibly available efficiencies of a fixed bed, and evaluate the effects of air equivalence ratio, moisture concentration and gasifier temperature on the LHV of syngas, the composition of syngas, heat conversion efficiency, and carbon conversion of MSW.

2 Technical and modeling approach

A fixed bed was designed for syngas production from MSW gasification (Fig. 1). It is divided into four sections: drying, pyrolysis, gasification, and combustion. It resembles an updraft fixed bed without injecting the flue gas (mainly CO_2) from the combustor back into the gasifier.

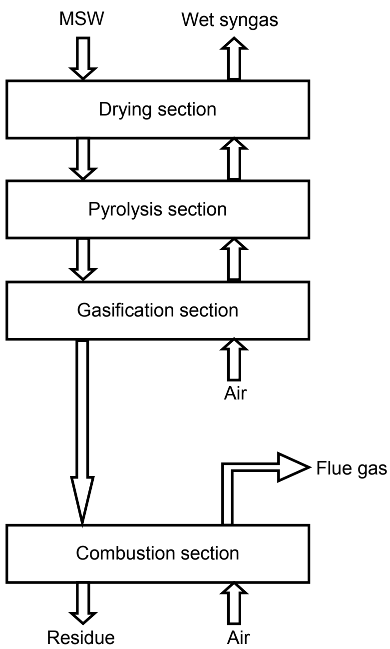

Fig. 1 Process flowchart of municipal solid waste gasification in fixed bed

In the process of MSW gasification, the temperature of pyrolysis and gasification sections will vary from 500 to 700 °C, and the temperature of combustion section is 900 °C. MSW is fed from the top of the fixed bed into the drying section, while one part of the air is fed directly into the gasification section from the bottom of the gasifier, and the other part of the air is fed into the combustion section for the combustion of char (in the residue from the bottom of the gasifier). Firstly, MSW is dried in the drying section, where part of the moisture of MSW evaporates, and the need of heat is provided by the heat exchange of syngas produced from the gasifier. Secondly, the dried MSW is decomposed in the pyrolysis section, where volatile compounds in MSW evaporate, and the carbon content of MSW is converted into char and syngas. Then in the gasification section, char is partly gasified with air and reacted with other gaseous compounds. Finally, the residue (unreacted char) from the bottom of gasifier is passed into the combustion section, where it is burned out to generate part of the heat needed for this reactor.

In this study, to simulate the processes of drying, pyrolysis, gasification and combustion, the software of Aspen plus is adopted. Aspen plus is widely accepted in the chemical industry as a design tool because of its ability to simulate a variety of steady-state processes ranging from single unit operation to complex processes involving many units (Sotudeh-Gharebaagh *et al.*, 1998). It is based on a minimization of the Gibbs free energy at equilibrium. This implies that the residence time is long enough to allow the chemical reactions to reach an equilibrium state.

The flow chart of simulation for MSW gasification in a fixed bed is shown in Fig. 2. The simulation for the process of MSW gasification is set up based on balance of mass and energy, and chemical equilibrium among the overall process. The Aspen plus stoichiometric reactor, RSTOIC, was used to simulate the evaporation of moisture in the drying section. In this step, the moisture of the MSW is partly evaporated and then separated by the SSPLIT: the dried MSW is put into the next section, while the evaporated moisture is separated from it together with the syngas produced from the gasifier. The gasifier is composed of a pyrolysis section and a gasification section. The pyrolysis section is just a decomposer, so the block of RYIELD in Aspen plus was used. In this simulation of the pyrolysis section, MSW is decomposed into its constituting components, including hydrogen, carbon, oxygen, sulfur, nitrogen, and ash, by specifying the yield distribution according to the MSW ultimate analysis. The Aspen plus Gibbs reactor, RGIBBS, is based on the minimization of the Gibbs free energy at equilibrium; the whole simulation of drying, pyrolysis, gasification and combustion processes is based on the principle of minimization of Gibbs free energy, as a result, the block of RGIBBS in Aspen plus was used for gasification and combustion. The following assumptions are considered in the simulation of the whole process:

1. The whole process is in steady state and the reactions reach chemical equilibrium.

2. The heat exchange in a fixed bed is ideal and it is isothermal in the same section.

3. Char only contains carbon and ash; ash is inert and does not participate in chemical reactions.

4. The syngas produced from MSW gasification consists of H_2, CH_4, H_2O, CO, CO_2, SO_2, N_2, NO, and NO_2; tar was not taken into account in the simulation.

Operating conditions and primary parameters in the simulation were as follows: ambient temperature 25 °C, gasifier temperature at the range of 500–700 °C, combustor temperature 900 °C, drying section heat duty 0 kJ/h, MSW flow rate 1.0 kg/h, air flow rate varies with the air equivalence ratio which ranges from 0.2 to 0.8, and system pressure 1.013×10^5 Pa. As shown in Table 1, the characteristic (the proximate analysis and ultimate analysis) of MSW used in this study was an average value of that of MSW from different provinces in China.

3 Results and discussion

The effects of gasification temperature, air equivalence ratio and moisture concentration on the composition of syngas, LHV of syngas, heat conversion efficiency, and carbon conversion are discussed.

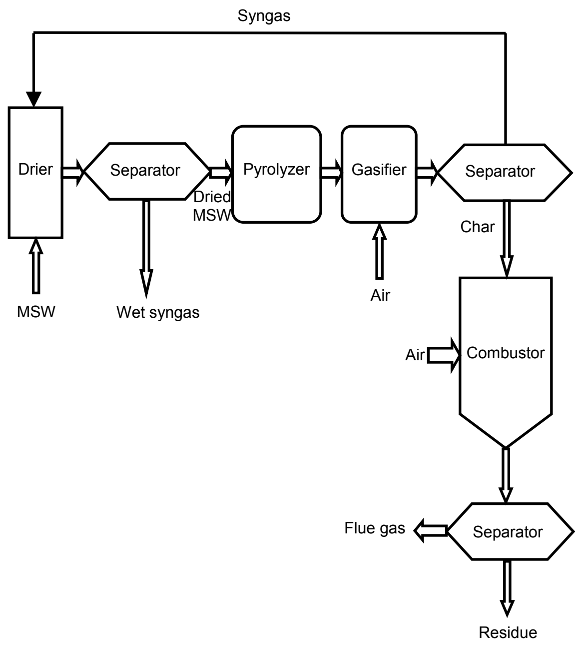

Fig. 2 Simulation of municipal solid waste gasification in fixed bed

Table 1 Characteristics of MSW

Property		Value
Proximate analysis (%, w/w, dry basis)	Volatile matter	46.15
	Fixed carbon	7.70
	Ash	46.15
Ultimate analysis (%, w/w, dry basis)	C	30.77
	H	4.62
	O	17.3
	N	0.77
	S	0.39
High heating value (dry basis, kJ/kg)		13016
Moisture (%, w/w)		48

3.1 Effect of gasifier temperature on syngas production

The gasifier temperature was one of the most important factors on syngas production from MSW gasification in a fixed bed. It influences the equilibrium of the chemical reactions (Cimini *et al.*, 2005). In this study, the gasifier temperature was varied between 500 and 700 °C. The results referring only to an air equivalence ratio of 0.4 are studied to analysis the effect of gasifier temperature on the MSW gasification. The composition of the syngas produced from gasification of MSW versus the gasifier temperature is shown in Fig. 3.

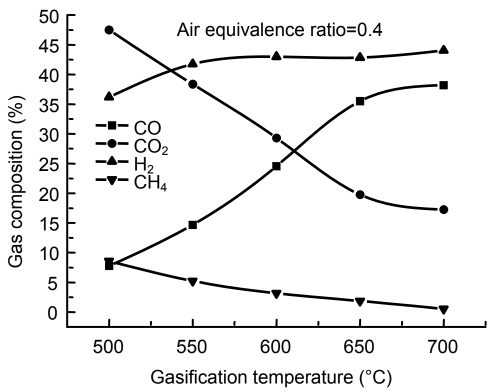

Fig. 3 Effect of gasification temperature on gas composition

It can be clearly seen that H_2 concentration was maintained around 35%–44% (mol/mol). It increased slightly as the gasifier temperature rose from 500 to 550 °C, and remained nearly invariable from 550 to 700 °C; while on the other hand, CH_4 decreased with an increase in temperature. Additionally, CO in the syngas increased observably as the gasifier temperature increased, whilst CO_2 decreased correspondingly. These trends can be attributed to the chemical reaction laws: higher temperatures favoured the products in endothermic reactions, and favoured the reactants in exothermic reactions. The concentration of each component of the syngas from MSW resulted from a series of chemical reactions in the gasifier (reactions (1)–(6)). Therefore, a simplified gasification mechanism could be explained by the following reactions (Skoulou *et al.*, 2008):

$$C+H_2O=CO+H_2, \quad -132\ \text{kJ/mol}, \tag{1}$$
$$CH_4+H_2O=CO+3H_2, \quad -206\ \text{kJ/mol}, \tag{2}$$
$$C+CO_2=2CO, \quad -173\ \text{kJ/mol}, \tag{3}$$
$$C+O_2=CO_2, \quad +393\ \text{kJ/mol}, \tag{4}$$
$$CH_4+2H_2O=CO_2+4H_2, \quad -165\ \text{kJ/mol}, \tag{5}$$
$$C+1/2O_2=CO, \quad +110\ \text{kJ/mol}. \tag{6}$$

Therefore, as the temperature increased, CH_4 concentration would decrease following endothermic reactions (2) and (5). H_2 concentration would increase following endothermic reactions (1), (2), (5) and CO concentration would increase according to endothermic reactions (1), (2), (3) that prevail over exothermic reaction (6). Although endothermic reaction (5) releases CO_2 (and the CO_2 concentration should increase), the CO_2 concentration decreased as the temperature increased. This is because endothermic reaction (3) was more dominant, placing the reaction toward the right, and resulting in the increase of CO and decrease of CO_2 as the temperature increased.

Fig. 4 shows the LHV of syngas from MSW gasification. The LHV increases as temperature rises. The LHV calculation is shown below:

$$\text{LHV} = (119950.4\times n_{H_2} + 10103.9\times n_{CO} + 50009.3\times n_{CH_4})/V, \tag{7}$$

where n_{CO}, n_{H_2} and n_{CH_4} are the molar yields of those gases in syngas, V is the volume of syngas, m^3, and the unit of LHV is kJ/Nm^3.

The LHV of syngas increased as temperature rose from 500 to 650 °C (the maximum value was about 4500 kJ/Nm^3, and then it remained nearly constant from 650 to 700 °C.

Variation of heat conversion efficiency of syngas and carbon conversion of MSW could be used to investigate the effect of temperature on MSW gasification. The definitions of those two parameters were respectively defined in Eqs. (8) and (9).

$$q=\frac{m_1}{m_2}, \quad (8)$$

$$\theta=\frac{Q\times V}{m_{\mathrm{MSW}}}, \quad (9)$$

where q is the carbon conversion of MSW, m_1 is the weight of carbon in the syngas, kg, m_2 is the weight of carbon of MSW fed into the system, kg, θ is heat conversion efficiency of syngas, kJ/kg, Q is the LHV of the syngas (dry) yield in the gasifier, kJ/Nm^3, and m_{MSW} is the weight of MSW fed into the system, kg.

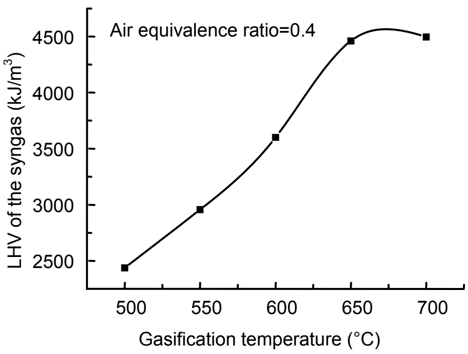

Fig. 4 Effect of gasification temperature on LHV of the syngas

Carbon conversion and heat conversion efficiency of MSW versus the gasifier temperature is shown in Fig. 5. Carbon conversion and heat conversion efficiency of MSW appeared almost the same in terms of variation with the gasifier temperature. There was an obvious increase in heat conversion efficiency of the syngas, from 2500 to 5000 kJ/kg MSW at the temperature range of 500 to 650 °C. Heat conversion efficiency reached its maximum of 5000 kJ/kg MSW at 650 °C, and then remained almost constant. With an increase in temperature, more carbon of MSW reacted in the gasifier, and consequently resulted in an increase of carbon transferred into syngas. And there was no fixed carbon left in the residues at 650 °C. It can be concluded from the results of Figs. 3–5 that the favorable gasifier temperature for syngas production should be 650 °C for the air equivalence ratio of 0.4.

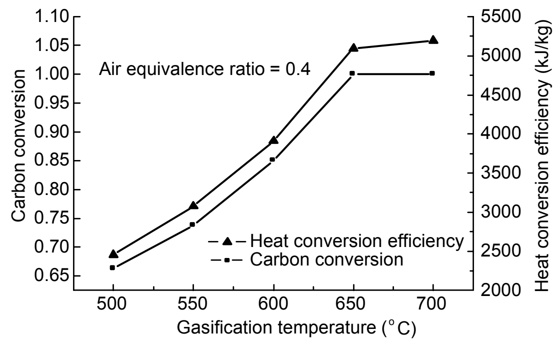

Fig. 5 Effect of gasification temperature on carbon conversion and heat conversion efficiency

3.2 Effect of air equivalence ratio on syngas production

The effect of air equivalence ratio on syngas yield from MSW gasification in a fixed bed was also studied. In this study, air equivalence ratio is defined as the ratio of the amount of air (oxygen) needed per weight of MSW for complete combustion (under stoichiometric conditions). Thus, the change of the amount of air that supplied in the gasifier would have a strong affect on the process that leads to two extreme operating conditions: one to full gasification towards CO and another to full combustion towards CO_2 (Skoulou *et al.*, 2008), and it would have a strong effect on the gas composition. The air equivalence ratio was varied between the ranges of 0.2–0.8 by varying flux of air while keeping MSW flux constant. Fig. 6 indicates the influence of air equivalence ratio on gas composition according to a gasifier temperature of 600 °C. H_2 content decreased smoothly as the air equivalence ratio increased. CO_2 and CO contents increased smoothly while the air equivalence ratio rose from 0.2 to 0.5, and then as the ratio kept increasing, CO content dropped while CO_2 content presented an opposite trend. CO concentration reached a maximum of 26% at the air equivalence ratio of 0.5. This can be explained by reactions (4) and (6): CO_2 and CO contents increased as the ratio rose in a lower range, as the ratio increased higher enough, reaction (4) would prevail over reaction (6) (higher equivalence ratios means that there is more oxygen supply in the reactor and favors consequently the oxidation reactions), and this would cause a decrease of CO content and an increase of the CO_2 content. The decrease of CH_4 content was much smaller.

The influence of air equivalence ratio on the LHV of syngas is given in Fig. 7. The LHV decreased remarkably as the equivalence ratio increased. The maximum LHV of syngas achieved at 600 °C is 4974 kJ/Nm^3 at the equivalence ratio of 0.2. LHV of syngas would decrease according to a further increase of the equivalence ratio, which can be probably explained by oxidation reactions (4) and (6) and the increasing volume of noncombustible gas (especially N_2 in the air).

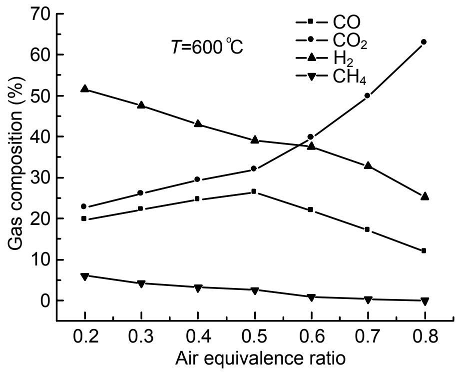

Fig. 6 Effect of air equivalence ratio on gas composition

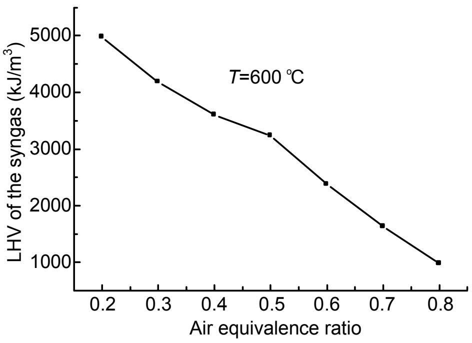

Fig. 7 Effect of air equivalence ratio on LHV of the syngas

The influence of the air equivalence ratio on carbon conversion and heat conversion efficiency of MSW is shown in Fig. 8. Heat conversion efficiency of MSW increased as the equivalence ratio increased, and reached the maximum heat conversion efficiency (4116 kJ/kg) at the equivalence ratio of around 0.5 at 600 °C. Then it followed an opposite trend as the ratio continued increasing. This can be explained by the fact that as the equivalence ratio increases, exothermic reactions (4) and (6) are favored, which will provide more heat to the decomposition and gasification sections. However, the heating value of syngas will become lower due to further oxidation reaction (reaction (4)), which leads to more CO_2 production but less combustible gases. As a result, it is very important to choose a proper equivalence ratio at a certain gasifier temperature to get higher heat conversion efficiency. Lower or higher air equivalence ratios result in lower gasification temperatures or deterioration of heating values of syngas due to combustible gas consumption (Yang *et al.*, 2006). At higher temperatures (700 °C) it seemed that a lower equivalence ratio (around 0.3) was more favorable towards achieving higher heat conversion efficiency (maximum of 5779 kJ/kg).

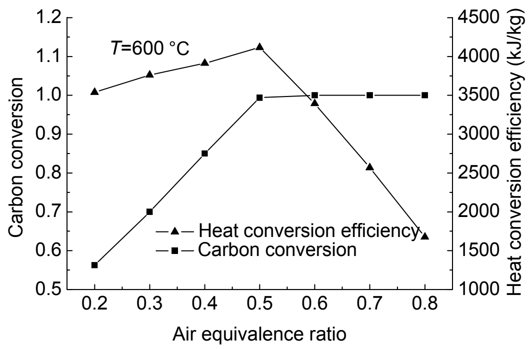

Fig. 8 Effect of air equivalence ratio on heat conversion efficiency and carbon conversion

As shown in Fig. 8, carbon conversion increased linearly and reached a maximum value of 1 at the ratio of 0.5 with an increase of air equivalence ratio. This means that the carbon of MSW had already completely reacted as the ratio increased to 0.5. This can be explained by the oxidation reactions (3), (4), and (6).

To summarize, from the results shown in Figs. 6–8, the conclusion can be made that the favorable air equivalence ratio for syngas production should be 0.5 for the temperature of 600 °C in the gasifier. Considering the higher moisture concentration of Chinese MSW, it is necessary to study the influence of moisture concentration of dried MSW on syngas production.

3.3 Effect of moisture concentration on syngas production

Considering that the moisture concentration in the MSW in China is very high (around 40%), it is necessary to demonstrate the effect of the moisture concentration on syngas production from gasification of MSW. In this study, the moisture concentration was varied by changing the dry efficiency (the ratio of moisture that vaporized from MSW input) in the dry reactor (RSTOIC). The air equivalence ratio varied in the range of 0.2–0.8 at different gasifier temperatures of 500, 600, and 700 °C, respectively. Moisture concentration of the dried MSW as the input of the gasifier was set at 5%, 20%, and 30%, respectively.

It can be clearly seen that moisture strengthened the carbon conversion due to reaction (1) (Fig. 9). The higher moisture concentration (that means higher H_2O concentration) prohibited the reactants in reaction (1), and as a result, the carbon decreased and carbon conversion increased.

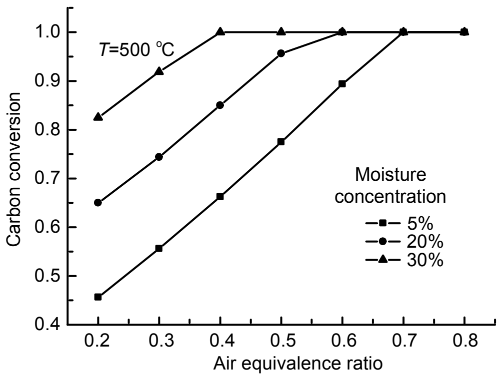

Fig. 9 Carbon conversion at different moisture concentrations according to air equivalence ratio

From Fig. 10, it can be seen that the LHV of syngas produced from MSW gasification had a decreasing trend as the equivalence ratio increased at different settings of the gasifier temperature. As shown in Fig. 10a, a higher moisture concentration contributed to a higher LHV of syngas at the lower equivalence ratio (below 0.5) with the gasifier temperature of 500 °C. This can be explained by reactions (1) and (2); the increase of H_2O would promote the reactions towards the right direction. As a result, the increase of CO and H_2 would improve the LHV of syngas. As the ratio continued increasing, the effect of moisture concentration was the opposite, i.e., a higher moisture concentration resulted in a lower LHV of syngas. This was achieved mainly due to the increase in the incombustible gas H_2O (mainly moisture concentration) that diluted the syngas, and the increase in CO_2 (reactions (4) and (5)). The same trend can be seen in Figs. 10b and 10c, and the higher the gasifier temperature, the less positive the effect of the moisture concentration on improving the syngas LHV. This is more obvious in Fig. 11, showing that a further increase of the ratio at 600 °C resulted in nearly the same heat conversion efficiency at different moisture concentrations, so the LHV decreased as the moisture concentration increased. As the gasifier temperature

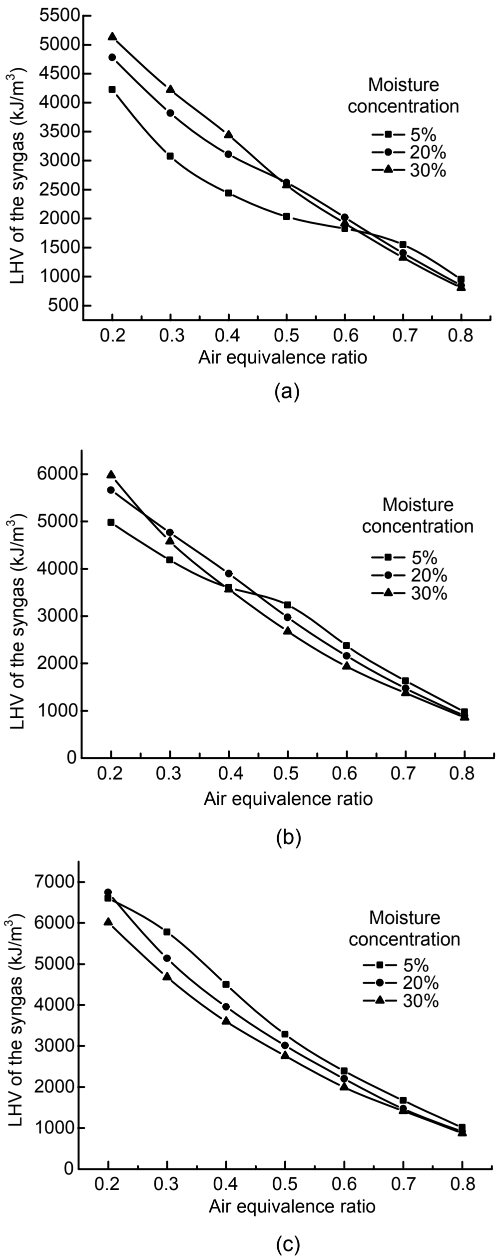

Fig. 10 LHV of the syngas at different moisture concentrations according to air equivalence ratio
(a) T=500 °C; (b) T=600 °C; (c) T=700 °C

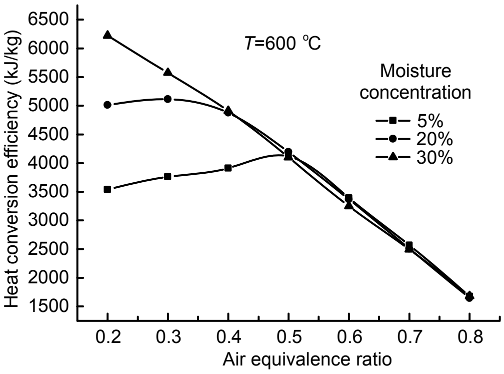

Fig. 11 Heat conversion efficiency at different moisture concentrations according to air equivalence ratio

increased to 700 °C, syngas LHV was lower at a moisture concentration of 30% compared to a moisture concentration of 5%. The maximum value of LHV (6741 kJ/Nm^3) was achieved at the moisture concentration of 20% (700 °C, 0.2), which was a little higher than that (6598 kJ/Nm^3) achieved at the moisture concentration of 5% (700 °C, 0.2). The higher moisture concentration required more heat for evaporation, thus a lower moisture concentration is more favorable. The increase of moisture concentration might thus not result in an increase of LHV of syngas produced from the gasification of MSW. This depends on the gasifier temperature and the air equivalence ratio. A higher temperature and lower equivalence ratio is favorable for achieving a higher LHV of syngas at a given moisture concentration. However, the increase of the moisture concentration provides a higher LHV at lower temperatures (below 700 °C). On the other hand, it increases the requirements of heat in gasifier for the vaporization of H_2O: latent heat of H_2O was higher in the gasifier than that in the dry reactor (the temperature is lower than that of the gasifier).

4 Conclusions

In this paper, the simulation of MSW gasification for syngas production in a fixed bed reactor was developed using the Aspen plus simulator. The simulation was used to predict the results of MSW gasification, and to provide some process fundamentals about syngas production from MSW gasification. The effects of gasification temperature, air equivalence ratio, and moisture concentration on the composition of syngas, lower heating value of syngas, carbon conversion, and heat conversion efficiency are evaluated. The simulation results from this paper can be summarized as follows:

1. High temperatures increased the LHV, heat conversion efficiency, and carbon conversion. The effective temperature of the gasifier for syngas production should be 650 °C for the air equivalence ratio of 0.4.

2. A high air equivalence ratio increased the carbon conversion, while decreasing the LHV. Heat conversion efficiency increased and reached a maximum, then decreased while the ratio increased. The favorable air equivalence ratio of the gasifier for syngas production should be 0.5 for the gasifier temperature of 600 °C.

3. High moisture concentration might not improve the gasification process. The increase of moisture concentration might not result in the increase of LHV of syngas produced from the gasification of MSW; it depends on the gasifier temperature and the air equivalence ratio: the maximal LHV (5976 kJ/Nm^3) at 600 °C was achieved at the moisture concentration of 30% while the maximal LHV (6598 kJ/Nm^3) at 700 °C was achieved at 5%. High moisture concentration increased the carbon conversion and the heat conversion efficiency at lower ratio. A higher temperature and a lower equivalence ratio is most favorable for achieving a higher LHV of syngas at a given moisture concentration.

The results of the simulation indicate that gasification of MSW in fixed bed reactors is a feasible method of producing syngas. Since the whole process of the simulation was proposed under many ideal conditions, there are considerable demands to improve real operations. In real operations, the heat conduction should be greatly improved in the fixed bed reactors and MSW should be well pretreated to achieve the assumptions that are considered in the simulation process, while the gasification should be controlled under the conditions that were concluded from the results of the simulation.

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