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Thermodynamic Analysis of the Gasification of Municipal Solid Waste

Pengcheng Xu, Yong Jin, Yi Cheng*

Beijing Key Laboratory of Green Chemical Reaction Engineering and Technology, Department of Chemical Engineering, Tsinghua University, Beijing 100084, China

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ABSTRACT

This work aims to understand the gasification performance of municipal solid waste (MSW) by means of thermodynamic analysis. Thermodynamic analysis is based on the assumption that the gasification reactions take place at the thermodynamic equilibrium condition, without regard to the reactor and process characteristics. First, model components of MSW including food, green wastes, paper, textiles, rubber, chlorine-free plastic, and polyvinyl chloride were chosen as the feedstock of a steam gasification process, with the steam temperature ranging from 973 K to 2273 K and the steam-to-MSW ratio (STMR) ranging from 1 to 5. It was found that the effect of the STMR on the gasification performance was almost the same as that of the steam temperature. All the differences among the seven types of MSW were caused by the variation of their compositions. Next, the gasification of actual MSW was analyzed using this thermodynamic equilibrium model. It was possible to count the inorganic components of actual MSW as silicon dioxide or aluminum oxide for the purpose of simplification, due to the fact that the inorganic components mainly affected the reactor temperature. A detailed comparison was made of the composition of the gaseous products obtained using steam, hydrogen, and air gasifying agents to provide basic knowledge regarding the appropriate choice of gasifying agent in MSW treatment upon demand.

1. Introduction

In recent years, municipal solid waste (MSW) has become a major environmental concern all over the world [1,2]. In the United States, the yield of MSW reached 2.54×10^8 t in 2013, only 34.3% of which was recycled [3]. As a comparison, the yield of MSW in China was approximately 1.8×10^8 t in 2014 and is expected to reach 2×10^8 t by 2020 [4]. Thus, the disposal of MSW is one of the most important and urgent problems in the world because of its huge volume and severe environmental impact.

Traditional landfill disposal is not a long-term solution because it requires a large amount of land and results in serious environment pollution of air, water, and soil [5]. Incineration is preferred to landfill disposal because it has the advantage of reducing the weight and volume of MSW, and because it can recover energy in the forms of heat and electricity [6]. However, incineration produces harmful emissions of acidic gases, dioxins, and toxic heavy metals, which have a great impact on the environment and human health [7]. Increasing attention is being paid to the gasification process of MSW, which is considered to be an energy efficient, environmentally friendly, and economically sound technology [8].

Gasification is defined as the thermochemical conversion of carbon-containing materials to syngas through gas-forming reactions in an oxygen-deficient environment, using gasifying agents such as air, hydrogen, steam, and their mixtures [9,10]. MSW gasification can prevent dioxin formation and reduce acidic gas emission due to the higher temperature and reduction conditions [11]. The products of the gasification of MSW are ash, oils, and gases, which are mainly carbon monoxide, hydrogen, carbon dioxide, and hydrocarbons [9]. Many researchers have investigated this process to evaluate the influences of operating parameters (i.e., temperature, steam-to-MSW ratio (STMR), residence time, feedstock particle size, addition of catalyst, etc.), types of feedstock, and gasifying agents on the gasification performance [12–20]. In order to develop an efficient and economic MSW gasification process, it is necessary to understand how these factors influence the gasification reactions, which can provide

* Corresponding author.
E-mail address: yicheng@tsinghua.edu.cn

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valuable information for the better design of the MSW gasification process. Thermodynamic analysis can deliver information on the composition and concentration of target species under specific conditions; this form of analysis is especially suitable for systems with precise chemical composition and unknown reaction mechanisms, such as MSW [21,22]. In the present work, thermodynamic analysis of MSW gasification was carried out for different types of MSW for a large range of temperatures and STMRs. Furthermore, three different types of gasifying agent were taken into account: air, steam, and hydrogen. The purpose of this study is to obtain knowledge of the gasification process of MSW by means of thermodynamic analysis.

2. Methodology

2.1. Model assumptions

A thermodynamic equilibrium model was developed to calculate the gasification performance of MSW. The model assumptions are listed below.

- The gasification reactions take place at the thermodynamic equilibrium condition.
- In this system, the process is completely adiabatic and there is no heat loss. The reactor temperature is not given and is determined by the temperature and amount of the gasifying agent(s) based on the energy balance.
- In addition to the organic components of MSW, such as carbon (C), hydrogen (H), oxygen (O), nitrogen (N), sulfur (S), and chlorine (Cl) content, other mineral components are considered because they affect the energy balance and reactor temperature, and thus have a significant influence on the gaseous products.
- Fixed carbon is accounted for, and the main syngas product is composed of hydrogen gas (H_2), carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), hydrogen sulfide (H_2S), and hydrochloric acid (HCl). Other higher hydrocarbons are neglected because they occur in negligible amounts.

2.2. Thermodynamic equilibrium model

On the basis of the above assumptions, the thermodynamic equilibrium model [23] was used to calculate the equilibrium of the gasification of MSW.

First, according to the mass conservation law, the total atom number is constant. Therefore, we can determine that

$$\begin{cases} \sum_{j=1}^{s} n_{ij}\overline{N}x_j = p_i,\ i=1,\ 2,\ \cdots,\ c \\ \sum_{j=1}^{s} x_j = 1 \end{cases} \tag{1}$$

where $\overline{N}$ is the total mole number of all species, x_j is the mole fraction of species j, n_{ij} is the number of atom i per species j, p_i is the total mole number of atom i, s is the number of species types, and c is the number of atom types. In addition, x_j must be a non-negative value, that is

$$x_j \geq 0,\ j=1,\ 2,\ \cdots,\ s \tag{2}$$

Second, the total Gibbs free energy can be expressed as follows:

$$G = \sum_{j=1}^{s} \overline{g}_j \overline{N} x_j \tag{3}$$

where G is the total Gibbs free energy and $\overline{g}_j$ is the partial molar Gibbs free energy of species j. $\overline{g}_j$ is given by

$$\overline{g}_j = g_j(T,P) + RT\ln x_j \tag{4}$$

where $g_j(T, P)$ is the Gibbs free energy of pure species j under reactor temperature T and pressure P, and R is the universal gas constant, 8.314 J·(mol·K)$^{-1}$.

Since we only know the initial temperature of the MSW (T_0) and of the gasifying agent (T_1), the reactor temperature T can be acquired by the energy balance:

$$G(\text{product},\ T) = G(\text{MSW},\ T_0) + G(\text{gasifying agent},\ T_1) \tag{5}$$

Finally, the equilibrium mole fraction of all species and the reactor temperature can be calculated by solving the above equations.

2.3. Model components

MSW is comprised of many heterogeneous materials; thus, the composition of MSW is very complicated and is impacted by a number of factors such as time, region, and type. As per Zhou et al. [24], we can classify MSW into two main categories: organics, which include food, green wastes, paper, textiles, rubber, and plastic (chlorine-free plastic and polyvinyl chloride (PVC)); and inorganics, which include ash, tiles, glass, metal, and other inert materials.

To better understand the gasification of MSW, we chose seven typical materials as our model components: food, green wastes, paper, textiles, rubber, chlorine-free plastic, and PVC. Table 1 lists the statistical results of the proximate and ultimate analysis of these seven materials [24]. Because the gaseous products are mainly formed from the organics, we analyze these materials based on seven model components, as shown in Table 2.

2.4. Model parameters

First, we will analyze the steam gasification of MSW. The initial temperature of the MSW is 300 K and the mass flowrate is 1000 kg·h^{-1} on a received basis. Table 3 shows the detailed logistics data of seven types of MSW, where water (H_2O) refers to moisture

Table 1
The proximate analysis and ultimate analysis of seven types of MSW.

Model components	Proximate analysis (wt%)				Ultimate analysis (wt%)						HHV_{daf} (MJ·kg^{-1})
	M_w	A_d	V_d	FC_d	C_{daf}	H_{daf}	O_{daf}	N_{daf}	S_{daf}	Cl_{daf}	
Food	69.85	20.98	66.79	12.23	47.22	7.04	41.15	3.86	0.49	1.06	15.39
Green wastes	42.95	6.84	75.87	17.29	51.35	6.39	40.50	1.59	0.18	0.29	19.46
Paper	13.15	12.20	76.14	11.66	45.62	6.01	47.78	0.34	0.22	0.28	15.89
Textiles	13.75	3.56	82.69	13.75	54.08	5.84	38.09	1.70	0.22	0.36	20.16
Rubber	0.89	15.64	64.70	19.67	84.52	8.62	4.31	0.86	1.56	1.62	43.45
Chlorine-free plastic	0.13	0.48	99.44	0.08	86.22	12.97	0.73	0.08	0.05	0.00	29.79
PVC	0.21	4.18	85.94	9.87	40.59	5.00	0.59	0.08	0.20	53.53	21.17

HHV_{daf}: higher heating value of MSW on a dry, ash-free basis; M_w: moisture content on a wet basis; A_d: ash content on a dry basis; V_d: volatile content on a dry basis; FC_d: fixed carbon content on a dry basis; C_{daf}: carbon content on a dry, ash-free basis; H_{daf}: hydrogen content on a dry, ash-free basis; O_{daf}: oxygen content on a dry, ash-free basis; N_{daf}: nitrogen content on a dry, ash-free basis; S_{daf}: sulfur content on a dry, ash-free basis; and Cl_{daf}: chlorine content on a dry, ash-free basis.

content, silicon dioxide (SiO_2) is the ash content of MSW, and the model components are shown in Table 2.

The given temperature is specifically referred to as the steam temperature. The STMR is determined as the mass ratio of the steam to MSW with moisture. The yield of the gaseous product is defined as the volume of the gas produced per kilogram of MSW. The conversion of fixed carbon can be expressed as shown in Eq. (6).

$$\alpha_{\text{fixed carbon}} = \frac{\text{Total carbon of the gaseous products}}{\text{Total carbon of MSW}} \tag{6}$$

Since the gaseous products are a mixture of various types of gases, the lower heating value (LHV) of the gaseous products can be calculated from Eq. (7) once the gas compositions are determined from the thermodynamic analysis [25].

$$\begin{aligned}\text{LHV} = (&\text{CO\%} \times 126.36 + \text{H}_2\% \times 107.98 \\ &+ \text{CH}_4\% \times 358.18)/1000\end{aligned} \tag{7}$$

where CO%, H_2%, and CH_4% are the volume percentages of these components in the gaseous products.

3. Results and discussion

Calculations for the steam gasification of MSW were performed by applying the thermodynamic equilibrium model developed above. Seven types of MSW were considered with steam temperature ranging from 973 K to 2273 K and STMR ranging from 1 to 5.

3.1. Effect of temperature

Fig. 1 presents the effect of steam temperature on the yields of main gaseous products (CH_4, CO, CO_2, H_2), reactor temperature, and LHV for food. The steam temperature ranges from 973 K to 2273 K and the STMR is 2.

As indicated in Fig. 1, the yields of the species produced from food versus the steam temperature can be generally grouped into two different regions. When the steam temperature is below 1650 K, a rise in temperature is found to increase H_2 yield from 0 $Nm^3 \cdot kg^{-1}$ to 0.45 $Nm^3 \cdot kg^{-1}$ and CO_2 yield from 0.09 $Nm^3 \cdot kg^{-1}$ to 0.19 $Nm^3 \cdot kg^{-1}$. The trend is opposite for CH_4, which decreases from 0.12 $Nm^3 \cdot kg^{-1}$ to 0 $Nm^3 \cdot kg^{-1}$. The yield of CO remains unchanged, with little CO being produced. However, when the temperature is above 1650 K, the yields of H_2 and CO_2 decrease slightly, while that of CO increases slightly. The reactor temperature increases linearly with the increase in steam temperature. The LHV starts at a very large value and drops to the saturation value at about 7.5 $MJ \cdot m^{-3}$.

It is easy to understand the trend of the reactor temperature increasing with steam temperature. As shown in Eq. (5), the reactor temperature is determined by the energy balance. When the steam temperature is higher, more energy is brought into the system via steam. Therefore, the reactor temperature increases linearly with the increase of steam temperature. The reactor temperature reaches about 750 K when the steam temperature is 1650 K.

The yield of CO is very small throughout because the H_2O content is large in the steam gasification of food. CO_2 is more stable than CO when sufficient oxygen is present. When the reactor temperature is lower than 750 K, Reaction (I) takes place, leading to a decrease in CH_4 and an increase in H_2 and CO_2. When the reactor temperature is higher than 750 K, CH_4 is completely converted to CO_2 and Reaction (II) takes place instead. Thus, the yields of H_2 and CO_2 decrease slightly and the yield of CO increases slightly in the second situation.

$$\text{CH}_4 + 2\text{H}_2\text{O} \longrightarrow \text{CO}_2 + 4\text{H}_2 \tag{I}$$

$$\text{CO}_2 + \text{H}_2 \longrightarrow \text{CO} + \text{H}_2\text{O} \tag{II}$$

LHV is affected by the volume percentages of CO, H_2, and CH_4. When the steam temperature is above 1650 K, the main gaseous products are H_2 and CO_2, and the volume percentage of H_2 remains about the same. The value of 7.5 $MJ \cdot m^{-3}$ based on our results above is determined by the composition of the food.

3.2. Effect of steam-to-MSW ratio

The effect of STMR on the yields of main gaseous products, reactor temperature, and LHV for food is presented in Fig. 2, where the steam temperature is 1273 K and the STMR ranges from 1 to 5. As shown in Fig. 2, the effect of the STMR is very similar to the effect of steam temperature.

As discussed above, H_2O is excessive for the steam gasification of food. Thus, an increase of STMR mainly affects the reactor temperature, rather than affecting the composition of the gaseous products. The reactor temperature increases linearly with an increase of STMR due to the energy balance. As a result, the variations in the yields of the gaseous products and the LHV that occur with changes in STMR are almost the same as those that occur with changes in steam temperature.

3.3. Effect of types of MSW

Seven types of MSW were chosen for thermodynamic analysis; their compositions are listed in Table 1 and Table 2. Here, we only compare the differences in the yields of the main gaseous products, reactor temperature, and LHV versus STMR, as shown in Fig. 3, because steam temperature has almost the same influence as STMR.

First, as indicated in Fig. 3(a), the yields of CH_4 drop to zero for food, green wastes, paper, and textiles when the STMR increases to about 5. These components are nearly the same because their compositions are almost the same, as shown in Table 2. However, the yields of CH_4 for chlorine-free plastic and rubber show different trends that increase at first and then decrease linearly. We found the oxygen content of chlorine-free plastic and of rubber to be only 0.04 and 0.006, respectively, which are much lower than the oxygen

Table 2
The chemical formula and molar mass of seven model components.

Model components	Chemical formula	Molar mass ($g \cdot mol^{-1}$)
Food	$CH_{1.79}O_{0.65}N_{0.07}S_{0.004}Cl_{0.008}$	25.62
Green wastes	$CH_{1.49}O_{0.59}N_{0.03}S_{0.001}Cl_{0.002}$	23.44
Paper	$CH_{1.58}O_{0.79}N_{0.006}S_{0.002}Cl_{0.002}$	26.37
Textiles	$CH_{1.30}O_{0.53}N_{0.03}S_{0.002}Cl_{0.002}$	22.25
Rubber	$CH_{1.81}O_{0.006}N_{0.001}S_{0.0002}$	13.92
Chlorine-free plastic	$CH_{1.22}O_{0.04}N_{0.009}S_{0.007}Cl_{0.007}$	14.41
PVC	$CH_{1.48}O_{0.01}N_{0.002}S_{0.002}Cl_{0.45}$	29.56

Table 3
The detailed logistics data of seven types of MSW ($kg \cdot h^{-1}$).

	Food	Green wastes	Paper	Textiles	Rubber	Chlorine-free plastic	PVC
H_2O	698.5	429.5	131.5	137.5	8.9	1.3	2.1
Model component	238.3	531.6	762.6	831.7	836.2	993.9	956.1
SiO_2	63.3	39.0	106.0	30.7	155.0	4.8	41.7

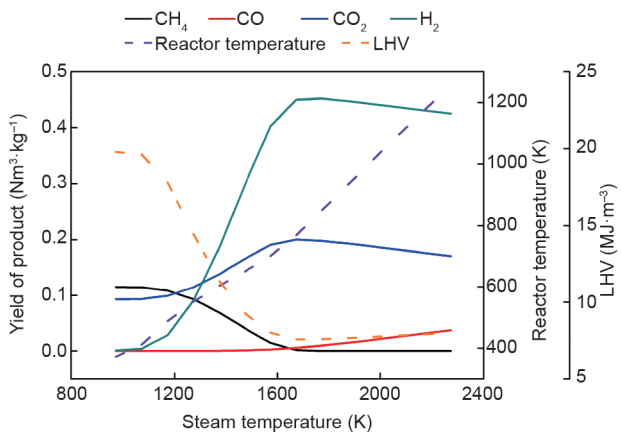

Fig. 1. Yields of main gaseous products (on a dry, ash-free basis), reactor temperature, and LHV for food versus steam temperature, with an STMR of 2.

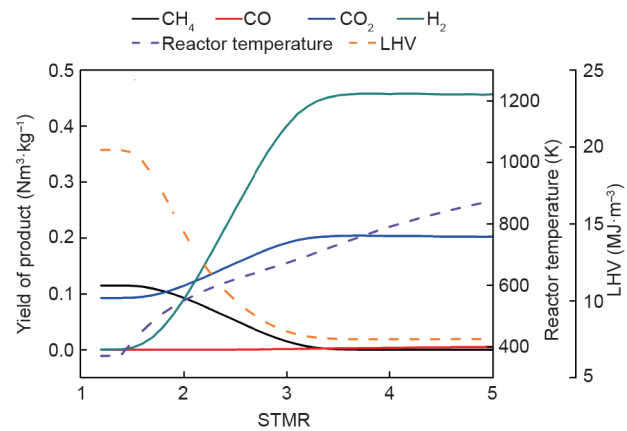

Fig. 2. Yields of main gaseous products (on a dry, ash-free basis), reactor temperature, and LHV for food versus STMR, with a steam temperature of 1273 K.

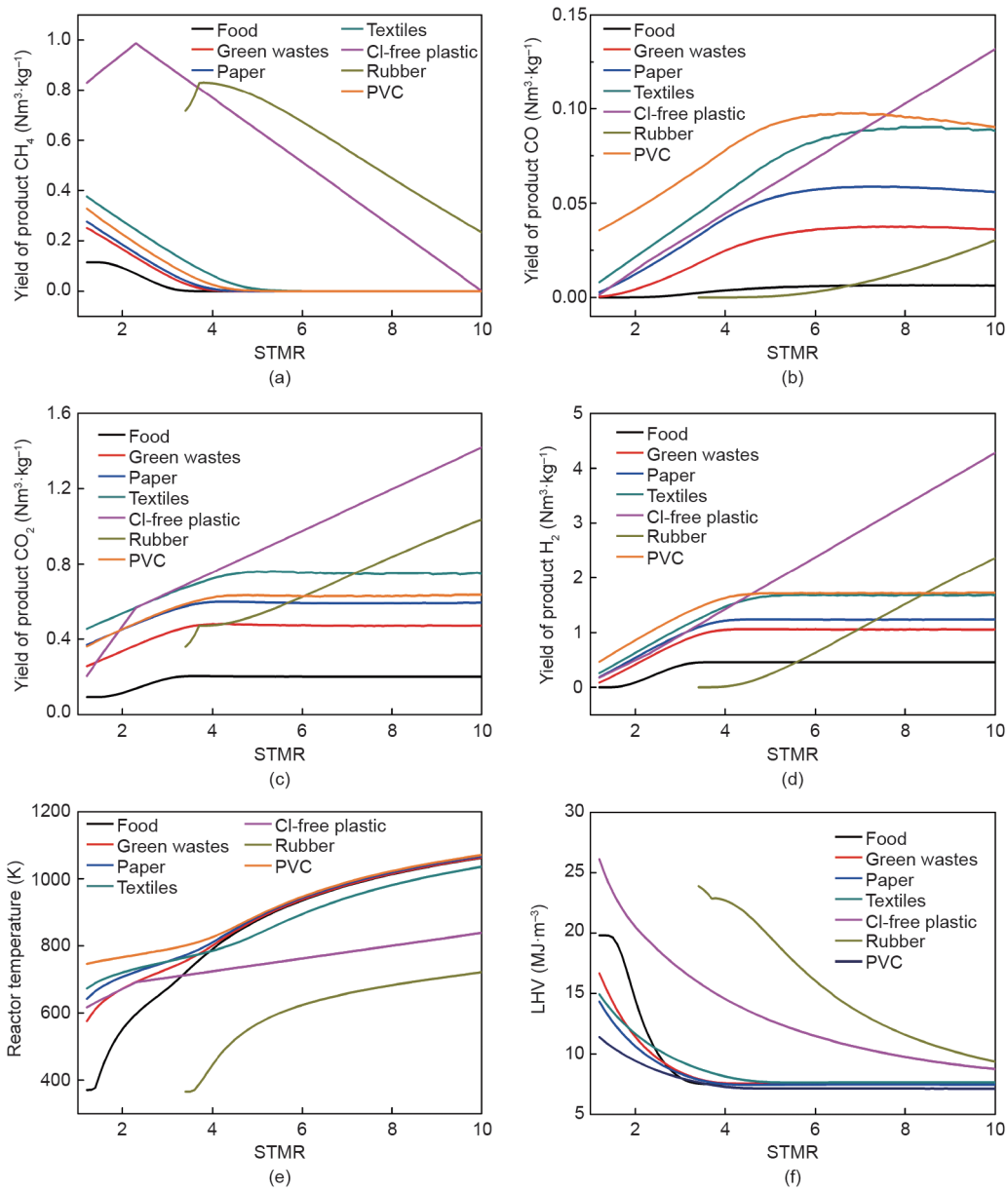

Fig. 3. Yields of main gaseous products (on a dry, ash-free basis), reactor temperature, and LHV for different MSWs versus STMR with a steam temperature of 1273 K.

content in food, green wastes, paper, and textiles, as shown in Table 2. For MSWs with low oxygen content, the conversion of fixed carbon cannot reach 100% under the condition of low STMR. Thus, with an increase of STMR, Reaction (III) takes place first, leading to an increase in CH_4. Once the fixed carbon is completely converted, Reaction (VI) and Reaction (I) take place instead, and the yield of CH_4 decreases linearly for components such as food and so on. The oxygen content of PVC is nearly the same as those of rubber and chlorine-free plastic; however, the gaseous products of PVC are more similar to those of food than to those of rubber and chlorine-free plastic because PVC has a greater chlorine content of 0.45. Chlorine is likely to form HCl, which consumes hydrogen, and it is easier for carbon to form CO in the absence of hydrogen than to form CH_4. In general, the yield of CH_4 is related to the content of oxygen and chlorine, in that larger oxygen and chlorine contents result in a smaller yield of CH_4.

$$2C + 2H_2O \longrightarrow CH_4 + CO_2 \quad \text{(III)}$$

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \quad \text{(VI)}$$

Fig. 3(b) shows that the yields of CO are lower than 0.15 $Nm^3 \cdot kg^{-1}$ for all seven types of MSW. In particular, little CO is produced from food gasification because H_2O is excessive in food and because CO_2 is more stable than CO. With an increase in STMR, the yields of CO first increase and then remain unchanged for food, green wastes, paper, textiles, and PVC. However, for chlorine-free plastic and rubber, the yields of CO continually increase. CO is mainly produced by Reaction (VI). For food and similar components, when the STMR increases to 5, CH_4 is almost completely converted to CO. For chlorine-free plastic and rubber, CH_4 is still produced, even when the STMR increases to 10, resulting in the continual increase of CO.

Fig. 3(c) shows that the yields of CO_2 first increase and then remain unchanged with an increase in STMR for food, green wastes, paper, textiles, and PVC. However, for chlorine-free plastic and rubber, the yields of CO_2 first increase sharply and then increase gently. The primary difference between the former and latter components of MSW is that fixed carbon is not completely converted for chlorine-free plastic and rubber. When fixed carbon is present, Reaction (III) and Reaction (I) take place simultaneously. If it is not present, only Reaction (I) takes place. Therefore, for chlorine-free plastic and rubber, the yields of CO_2 increase sharply at first, and more CO_2 is produced as more H_2O is consumed.

As indicated in Fig. 3(d), the yields of H_2 show the same trend as those of CO because Reaction (VI) is taking place in both cases. In Fig. 3(e), the reactor temperatures increase with an increase in STMR, and the final temperatures are mainly determined by the MSW composition. Fig. 3(f) shows that the LHVs decrease to the saturation value of about 7.5 $MJ \cdot m^{-3}$ for food and similar components.

In summary, thermodynamic analysis can show how the yields of the main gaseous products, reactor temperature, and LHV change with an increase in steam temperature and STMR for different types of MSW. It is thus possible to predict the gasification performance of MSW, mainly in terms of the gaseous products, reactor temperature, and LHV, by using thermodynamic analysis rather than by a large number of experiments. Furthermore, it is possible to conjecture how the reactions occur, even though a series of complex and competing reactions occur during the gasification of MSW. In other words, all the differing results for the seven types of MSW tested in this study are caused by the variation of their compositions.

The composition of actual MSW is very complicated and is impacted by a number of factors. It is necessary to adjust the operating conditions when the composition of MSW is changed. This is very difficult in practice; what is worse is that it also costs a considerable amount of time and money. However, it is possible to predict the performance of the steam gasification of different MSWs by thermodynamic analysis, if their compositions are known. This ability has great potential to assist with the choice of operating conditions for the gasification process of actual MSW.

3.4. Actual MSW

Actual MSW is comprised of many heterogeneous materials, including the organics discussed above and inorganics such as ash, tiles, glass, metal, and so on. Table 4 provides the composition of actual MSW collected from Nanjing, Jiangsu Province, China on rainy days. Table 5 lists the statistical results of the proximate and ultimate analysis of actual MSW.

3.4.1. Inorganics

The inorganic components of actual MSW include three main types of substance: sand, glass, and metal. The compositions of sand, glass, and metal are SiO_2, $Na_2O \cdot CaO \cdot 6SiO_2$, and Fe·Cu, respectively. To analyze the effect of inorganics on gasification performance, we compared four cases, as shown in Fig. 4. In Case 1, we considered each composition in detail. In Cases 2 and 3, we counted all inorganics as SiO_2 and Al_2O_3, respectively. In Case 4, we did not take inorganics into consideration at all. The mass flowrate of the actual MSW was 1000 $kg \cdot h^{-1}$. We used steam as the gasifying agent; the mass flowrate of the steam was 459 $kg \cdot h^{-1}$.

As shown in Fig. 4, the mole fractions of the gaseous products (CO, CO_2, H_2, and H_2O) and the reactor temperature were nearly the same in Cases 1, 2, and 3. It is well known that no significant difference exists between the specific enthalpy of SiO_2 and that of Al_2O_3. Thus, these components consume nearly the same amount of energy to reach the same reactor temperature. The mole fractions of gaseous products are nearly the same because they are affected mainly by the

Table 4
The composition of actual MSW from Nanjing on rainy days (as-received basis).

Components	Inorganics (wt%)			Organics (wt%)						Moisture (wt%)
	Sand	Glass	Metal	Paper	Plastic	Rubber	Cloth	Grass	Food	
Actual MSW	5.61	0.84	0.69	8.65	9.14	0.00	3.01	6.55	11.14	54.37

Table 5
The proximate analysis and ultimate analysis of actual MSW (as-received basis).

Components	Proximate analysis (wt%)				Ultimate analysis (wt%)						HHV_{daf} ($MJ \cdot kg^{-1}$)
	M_w	A_d	V_d	FC_d	C_{daf}	H_{daf}	O_{daf}	N_{daf}	S_{daf}	Cl_{daf}	
Actual MSW	54.37	16.04	26.77	2.82	16.45	2.12	10.51	0.35	0.05	0.10	18.48

HHV_{daf}: Higher heating value of MSW on a dry, ash-free basis; M_w: moisture content on a wet basis; A_d: ash content on a dry basis; V_d: volatile content on a dry basis; FC_d: fixed carbon content on a dry basis; C_{daf}: carbon content on a dry, ash-free basis; H_{daf}: hydrogen content on a dry, ash-free basis; O_{daf}: oxygen content on a dry, ash-free basis; N_{daf}: nitrogen content on a dry, ash-free basis; S_{daf}: sulfur content on a dry, ash-free basis; and Cl_{daf}: chlorine content on a dry, ash-free basis.

temperature. However in Case 4, the reactor temperature was 50 K higher than in Cases 1, 2, and 3. Case 4 differed slightly from the other three cases regarding the composition of the gaseous products. Therefore, the inorganic components of actual MSW mainly affect reactor temperature in that they consume some energy with the increase of their temperature. However, the small variation of the reactor temperature does not have a great influence on the composition of gaseous products. Thus, it is possible to consider all inorganics as SiO_2 or Al_2O_3 for the purpose of simplification, as in Cases 2 and 3.

3.4.2. Gasifying agent

In this study, we considered three gasifying agents: steam, hydrogen, and air. The mass flowrate of the actual MSW was still 1000 kg·h^{-1}, and we counted the inorganic components as SiO_2 for the purpose of simplification. To better compare the differences in these three gasifying agents, we set the reactor temperature at 1273 K. Fig. 5 and Fig. 6 show the results. The gasifying agents in Cases 2, 5, and 6 are steam, hydrogen, and air, respectively.

As shown in Fig. 5, the mass flowrate of the hydrogen gasifying agent is the lowest, at 45.4 kg·h^{-1}, while that of the air gasifying agent is the highest, at 890 kg·h^{-1}. This result indicates that the lowest mass flowrate is consumed to reach the same reactor temperature for the hydrogen gasifying agent. The reason for this finding is that the temperature of the hydrogen gasifying agent is the highest, and this gasifying agent has the largest energy density. We also considered the power input required for the three gasifying agents. The power input was nearly the same for the steam and hydrogen gasifying agents. However, the power input for the air gasifying agent was much smaller—less than half of the power input of the steam or hydrogen gasifying agents. The reason for this finding is that many combustion reactions take place with the use of an air gasifying agent, which release a considerable amount of energy.

Fig. 6 presents the mole fractions of the gaseous products for different gasifying agents. The hydrogen gasifying agent had the largest mole fractions of CO and H_2 and the smallest mole fractions of CO_2 and H_2O of the three gasifying agents. The steam gasifying agent had larger mole fractions of H_2 and H_2O and a smaller mole fraction of CO_2 than the air gasifying agent. These results are easy to understand because the oxygen content is lowest for the hydrogen gasifying agent, followed by the steam gasifying agent, and is highest for the air gasifying agent. When sufficient oxygen is present, the gaseous products are mainly composed of CO_2 rather than CO and H_2. Similarly, the mole ratio of H_2/CO is highest for the hydrogen gasifying agent and lowest for the air gasifying agent.

Steam, hydrogen, and air are three different gasifying agents, so it is very difficult to compare their advantages and disadvantages using experimental means. However, our study demonstrates that it is possible to set the reactor temperature to the same value and then analyze the differences among these gasifying agents in detail using thermodynamic analysis. In summary, the greatest amounts of H_2 and CO are obtained and the lowest mass flowrate is required when using the hydrogen gasifying agent. The air gasifying agent has the greatest energy efficiency, so if the goal is to deal with MSW using the lowest amount of energy, without considering the products, the air gasifying agent is the best choice. The steam gasifying agent falls between the other two agents because its oxygen content is higher than that of the hydrogen gasifying agent but lower than that of the air gasifying agent. Thus, it is possible to choose different kinds of gasifying agents based on demand by means of thermodynamic analysis, rather than in practice by means of a large number of experiments.

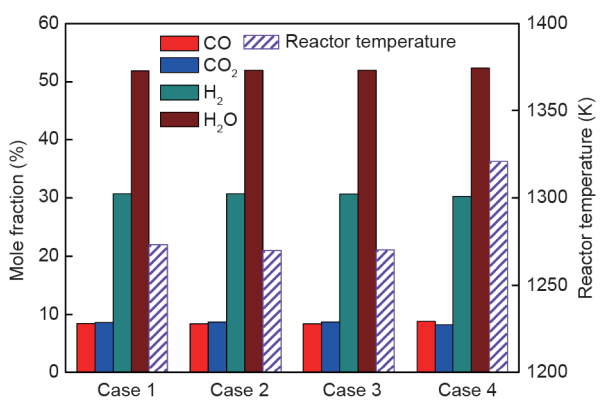

Fig. 4. The composition of gaseous products and reactor temperature for different inorganic components.

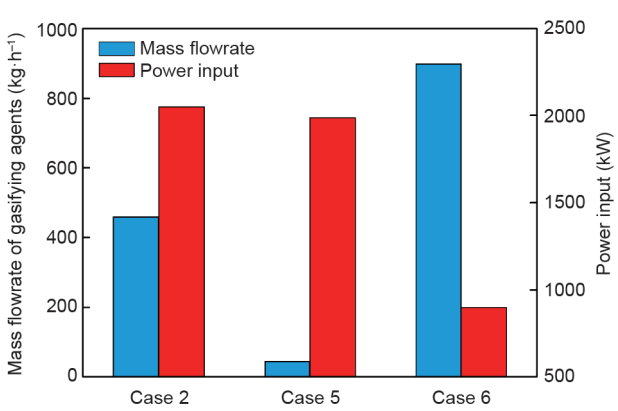

Fig. 5. The mass flowrate and power input for different gasifying agents.

4. Conclusions

A thermodynamic equilibrium model was developed in this paper with the aim of understanding the gasification performance of MSW. The composition of MSW is very complicated, so we first analyzed the steam gasification of seven typical components of MSW: food, green wastes, paper, textiles, chlorine-free plastic, rubber, and PVC. We discussed the effects of steam temperature, STMR, and different types of MSW on the yields of the main gaseous products, reactor temperature, and LHV. In summary, the reactor temperature increased linearly with an increase of steam temperature, due to the energy balance. When H_2O was excessive, the effect of STMR on the gasification performance was almost the same as the effect of steam temperature. All the differences among the seven types of MSW were caused by the variation in their compositions.

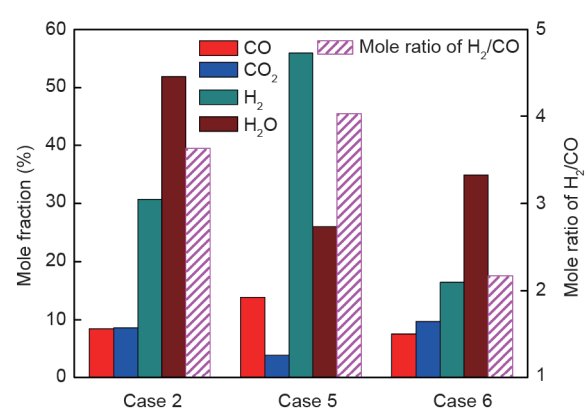

Fig. 6. The composition of gaseous products for different gasifying agents.

Actual MSW consists of a series of heterogeneous materials, including inorganic and organic components. As discussed above, inorganic components of actual MSW mainly affected the reactor temperature rather than the compositions of the gaseous products. Thus, it was possible to count all inorganic components as SiO_2 or Al_2O_3 for the purpose of simplification. We compared three different types of gasification using the gasifying agents of steam, hydrogen, and air, respectively. The hydrogen gasifying agent had the greatest energy density and produced the greatest amounts of H_2 and CO due to the reductive atmosphere. The energy efficiency of the air gasifying agent was the highest due to many combustion reactions taking place, so it consumed the lowest amount of power to reach the same reactor temperature. The steam gasifying agent ranked between the other two agents because of its composition. In summary, this study demonstrates that thermodynamic analysis can be used to choose between different kinds of gasifying agent based on demand, rather than performing a large number of experiments in practice.

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Compliance with ethics guidelines

Pengcheng Xu, Yong Jin, and Yi Cheng declare that they have no conflict of interest or financial conflicts to disclose.

Nomenclature

c	Total number of atom types present in the system
g	Gibbs free energy of the pure species
$\overline{g}$	Partial molar Gibbs free energy
G	Gibbs free energy of the system
M	Molar mass
n_{ij}	Number of the atom i that appears in the species j
N	Number of moles
$\overline{N}$	Total number of moles of all species in the phase
p_i	Total mole number of atom i
P	Pressure of the system
R	Universal gas constant
$R_{C/H}$	Effective mole ratio of C/H
s	Total number of species types
T	Reactor temperature
T_0	Initial temperature of MSW
T_1	Initial temperature of gasifying agents
x	Mole fraction of species

Subscripts

i	Atom
j	Species

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