Engineering 3 (2017) 416–422

Contents lists available at ScienceDirect

Engineering

journal homepage: www.elsevier.com/locate/eng

Research
Green Chemical Engineering—Article

Thermodynamic Analysis of the Gasification of Municipal Solid Waste

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A R T I C L E   I N F O

Article history:
Received 1 December 2016
Revised 12 March 2017
Accepted 26 March 2017
Available online 11 May 2017

Keywords:
Gasification
Waste treatment
Municipal solid waste
Thermodynamic analysis
Gasifying agents

A B S T R A C T

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

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http://dx.doi.org/10.1016/J.ENG.2017.03.004
2095-8099/

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 $J\cdot(mol\cdot K)^{-1}$.

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 $kg\cdot h^{-1}$ 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$_{daf}$ ($MJ\cdot kg^{-1}$)
	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.