Energy Conversion and Management 117 (2016) 393–399

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Experimental study on gasification performance of bamboo and PE from municipal solid waste in a bench-scale fixed bed reactor

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ARTICLE INFO

Article history:
Received 16 December 2015
Received in revised form 16 March 2016
Accepted 17 March 2016

Keywords:
MSW
Gasification
Fixed bed reactor
Hydrogen
Calcium oxide

ABSTRACT

Gasification performance of key components including polyethylene (PE) and bamboo of municipal solid waste (MSW) was examined in a bench-scale fixed bed. Effects of equivalence ratio, gasification temperature, steam/feedstock ratio, and calcium oxide (CaO) presence on syngas composition and lower heating value (LHV) were investigated. As equivalence ratio increased, both combustible gas components and LHV of syngas from bamboo and PE gasification decreased while the yield of CO_2 increased generally. Higher gasification temperature favored improving H_2 and CO production and lowering the yield of CO_2 from PE gasification while an optimal temperature of 700 °C existed for the best syngas quality and the highest LHV of syngas from bamboo gasification. Different variations of CO_2 between bamboo and PE were observed as steam/feedstock ratio increased. CaO was more effective to increase the yields of H_2, CO, and CH_4 and lower the yield of CO_2 from bamboo and PE gasification under both air and steam atmosphere, excluding the syngas composition of PE steam gasification. The work described here favors us understand the real MSW gasification process and thus facilitates the industrial application of gasification technology.

1. Introduction

Municipal solid waste (MSW) treatment, management and disposal have been common concerns in every country. The conventional landfilling method is encountering some problems including land shortage, underground water pollution, air pollution, and leachate disposal [1]. In recent years, incineration technology has been widely used with the advantages of substantial and immediate reduction of MSW volume. However, toxic dioxins emissions derived from waste incineration have been observed [2]. Therefore, both pyrolysis and gasification are regarded as feasible alternative ways to incineration for MSW disposal, due to the improved energy extraction by co-firing of syngas in large power plants or combustion of syngas in the combined cycle gas turbine, as well as better pollution control including the reduction of some pollutants as dioxins, furans and NOx [3–5].

Extensive investigations of MSW pyrolysis by thermogravimetry (TGA) under inert atmosphere were reported in literature. Fang et al. studied the co-pyrolysis characteristics of MSW, paper sludge and their blends at N_2 atmosphere. Meanwhile their kinetics were studied as well [6]. TGA study was performed under inert nitrogen atmosphere by Velghe et al. to get information on the potential of MSW pyrolysis [7]. Chen et al. investigated the pyrolysis and gasification characteristics of the most common components of MSW using TGA and analyzed their decomposed characteristics in N_2 and CO_2 atmosphere [8]. However, gasification studies under other atmosphere were rare. Gasification performance of MSW depends on many factors, like feedstock properties, reactor configurations, and reaction conditions. Investigations focused on the reaction conditions such as temperature, pressure, heating rate, and catalysts have been performed. The effect of catalyst and reactor temperature on the yield and product composition of MSW steam catalytic gasification was investigated by He et al. [9]. Hu et al. studied the effects of moisture content, [Ca]/[C], and reactor temperature on H_2 yield and gas composition, when an in-situ MSW steam gasification method was proposed using CaO as catalyst and CO_2 sorbent [10]. In order to produce tar-free fuel gas from MSW steam catalytic gasification, Guan et al. investigated the effect of catalyst, temperature, steam on the tar content, dry gas yield and composition, and carbon conversion efficiency using the gasifier composed of gasification reactor and catalytic reactor [11]. Feedstock properties have great influences on gasification performance as well. Researches have been conducted to

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http://dx.doi.org/10.1016/j.enconman.2016.03.044
0196-8904/

investigate the effect of physical properties, such as particle size and shape on gasification characteristics. Luo et al. investigated the influence of particle size on the pyrolysis and gasification performance of single component including woods, plastics, and kitchen wastes in a tubular and lab-scale fixed bed. They found that particle size had an effect on pyrolysis product yields and composition [12,13]. However, effects of chemical properties such as MSW individual component on gasification performance are limited.

In above studies, effective measures should be taken to reduce the emissions of tar and undesirable green house gas CO_2. Owing to the low cost and abundance, CaO has been widely used in coal and biomass gasification to produce hydrogen-enriched gas [14,15]. It plays a vital role as tar reforming catalysts and excellent CO_2 sorbent in the gasification process. Recently, Zhou et al. studied the influence of CaO addition on high-temperature steam gasification of MSW. CaO showed a good capacity toward CO_2 adsorption, leading to hydrogen-rich syngas production [16]. Hu et al. found CaO as CO_2 sorbent and catalyst in the gasification process of wet MSW could improve the hydrogen-rich fuel gas production [10]. Their gasification experiments were conducted in batch-type tubular fixed bed reactor. The results from this apparatus are far from the reality. Results from a bench-scale reactor present far more importance for further commercial plant. This knowledge is still lacking.

Because more tar and char can be converted into gaseous products with a high yield of H_2, steam gasification of MSW also has been thought of as a more promising technology. Zhang et al. investigated the thermal decomposition of six representative components of MSW by thermogravimetric–mass spectroscopy (TG–MS) under steam atmosphere [17].

However, due to the technical obstacle and lack of practical experience, MSW gasification still stay in the preliminary stage. Deep understanding on gasification performance of raw materials favors the proper design and operation of gasifiers. Particularly, experience from the gasification of key MSW components in a bench-scale reactor is rarely lacking. It is helpful to understand the gasification performance of real MSW.

The composition of MSW is very complex including plastics and lignocellulosic biomass, etc. According to the ultimate analysis of MSW components, the main constituents of MSW components are C, H, and O elements. Therefore, $C_xH_yO_z$ can be represented as MSW components. Their conversion to syngas progressed under the main steps that were indicated by the reactions below [10,18]:

MSW devolatilization:

$$C_xH_yO_z + \text{heat} \rightarrow \text{steam} + \text{biochar} + \text{tar} + \text{volatile}\ \Delta H^0_{298} > 0 \quad (1)$$

Biochar pyrolysis reaction:

$$\text{char} + \text{heat} \rightarrow H_2 + CO + CH_4 + CO_2 + C_nH_m\ \Delta H^0_{298} > 0 \quad (2)$$

Boudouard reaction:

$$C + CO_2 \rightarrow 2CO\ \Delta H^0_{298} = 162.4\ \text{kJ/mol} \quad (3)$$

Hydrocarbons reforming reaction:

$$C_nH_m + 2nH_2O \rightarrow \left(2n + \frac{m}{2}\right)H_2 + nCO_2\ \Delta H^0_{298} > 0 \quad (4)$$

Water gas reaction:

$$C + H_2O \rightarrow CO + H_2\ \Delta H^0_{298} = 131.3\ \text{kJ/mol} \quad (5)$$

Water–gas shift reaction:

$$CO + H_2O \rightarrow CO_2 + H_2\ \Delta H^0_{298} = -41\ \text{kJ/mol} \quad (6)$$

Methane steam reforming reaction:

$$CH_4 + H_2O \rightarrow CO + 3H_2\ \Delta H^0_{298} = 206.3\ \text{kJ/mol} \quad (7)$$

Secondary tar cracking reaction:

$$\text{Tar} \rightarrow \text{Light and Heavy hydrocarbons} + H_2 + CO + CO_2\ \Delta H^0_{298} > 0 \quad (8)$$

Methanation:

$$CO + 3H_2 \rightarrow CH_4 + H_2O\ \Delta H^0_{298} = -206.3\ \text{kJ/mol} \quad (9)$$

Carbonization:

$$CaO_{(s)} + CO_2 \leftrightarrow CaCO_{3(s)}\ \Delta H^0_{298} = -178.2\ \text{kJ/mol} \quad (10)$$

In the presence of CaO, it adsorbs CO_2 to form $CaCO_3$ (Eq. (10)), which contributes to the CO_2 partial pressure reduction in the reactor. The continuous removal of CO_2 in the gasification process enhances the reactions (1), (2), (4), (6), (8) toward the desired products. The CO_2 adsorption via CaO strongly depends on the partial pressure of CO_2 in the product and temperature. When gasification is performed below 850 °C, CO_2 is absorbed by CaO to form $CaCO_3$. Above this temperature, $CaCO_3$ decomposes into CaO and CO_2 [19].

In this study, comprehensive investigations on gasification performance of key MSW components were performed in a bench-scale fixed bed reactor. The polyethylene and bamboo were selected, which were regarded as plastics and lignocellulosic biomass in real MSW. Effects of equivalence ratio, steam/feedstock ratio, gasification temperature and CaO presence on syngas composition and LHV were examined. This knowledge would assist in gasifier design and operation, and provide basic data to facilitate the industrial application of gasification technology.

2. Experimental section

2.1. Materials

In this study, bamboo was selected as biomass for the wide use of chopsticks. PE was chosen as plastics, which was the main component in MSW in China. Both of them were purchased from local factories. They were dried and cut with a diameter of 5 mm before the experiments. Bamboo and PE were used separately in this study. Their properties were summarized in Table 1. The analytical reagent, calcium oxide (CaO), was adopted in this study with the particle size ranging from 1 to 200 μm. The deionized water was used to generate steam in this study.

2.2. Facilities and procedures

Experiments were performed in a self-designed fixed bed reactor with air or steam as gasification agent, respectively. A flow diagram of gasification process was shown in Fig. 1.

Table 1
Properties of bamboo and PE.

Proximate analysis	Bamboo[a]	PE[a]
Moisture	7.14	0.65
Volatile matter	74.35	98.87
Fixed carbon[b]	17.02	0.17
Ash	1.49	0.31
Ultimate analysis		
Carbon	44.83	83.62
Hydrogen	5.96	13.56
Oxygen[b]	40.08	1.31
Nitrogen	0.35	0.55
Sulfur	0.15	0
LHV (MJ/kg)	18.32	43.83

[a] Air dried basis, wt.%.
[b] By difference.