Energy 66 (2014) 82–89

Contents lists available at ScienceDirect

Energy

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

Plasmatron gasification of biomass lignocellulosic waste materials derived from municipal solid waste

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ARTICLE INFO

Article history:
Received 28 June 2012
Received in revised form
16 October 2013
Accepted 19 December 2013
Available online 15 January 2014

Keywords:
Syngas
Plasmatron
Gasification
Municipal solid waste
Steam mechanical heat treatment
Refuse solid biomass (RSB)

ABSTRACT

The aim of this work is to study the feasibility and operational performance of plasmatron (plasma torch) gasification of municipal solid waste mixed with raw wood (MSW/RW) derived from the pretreatment of Steam Mechanical Heat Treatment (SMHT), as the target material (MRM). A 10 kW plasmatron reactor is used for gasification of the MRM. The production of syngas (CO and H_2) is the major component, and almost 90% of the gaseous products appear in 2 min of reaction time, with relatively high reaction rates. The syngas yield is between 88.59 and 91.84 vol%, and the recovery mass ratio of syngas from MRM is 45.19 down to 27.18 wt% with and without steam with the energy yields of 59.07–111.89%. The concentrations of gaseous products from the continuous feeding of 200 g/h are stable and higher than the average concentrations of the batch feeding of 10 g. The residue from the plasmatron gasification with steam is between 0 and 4.52 wt%, with the inorganic components converted into non-leachable vitrified lava, which is non-hazardous. The steam methane reforming reaction, hydrogasification reaction and Boudouard reaction all contribute to the increase in the syngas yield. It is proved that MSW can be completely converted into bioenergy using SMHT, followed by plasmatron gasification.

1. Introduction

Energy from waste (EFW) is a sustainable and environmental friendly waste disposal and can provide better waste disposal of municipal solid waste (MSW). The transformation of waste into energy can be efficiently achieved by applying thermochemical techniques, such as torrefaction, partial oxidation, pyrolysis, gasification and synthesis [1–9]. Papageorgiou et al. [10] found that the greenhouse gas (GHG) impact highly depends on the MSW treatments and the end market of the solid recovery fuel (SRF) or refuse derived fuel (RDF). However, the quality and stability of SRF or RDF are not high enough for them to serve as supplement fuels or to derive power from combustion, especially for long distance transportation and extended storage time [9]. If the MSW is treated by steam mechanical heat treatment (MHT), the fiber and flock can be easily separated as SRF or RDF [11]. Garg et al. [12] reported that SRF has a Higher Heating Value (HHV) of about 15–18 MJ kg^{-1} (or 3585–4302 kcal/kg), and that it is a suitable co-combustion fuel for coal power plants or cement kilns.

The pyrolysis/gasification of solid waste to produce syngas offers an alternative to energy supplied by fossil fuels. Because syngas essentially contains molecular hydrogen and carbon monoxide, it has the potential for use as a high-quality fuel. Moreover, after purification, it becomes an important source of hydrogen, which is important in the context of fuel cell technology [13]. However, the purification or separation of syngas is another technology which should be developed and advanced. It will be easier to use the syngas as fuel for the power generation or cogeneration. Notably, the use of plasmatron pyrolysis or gasification offers unique advantages for solid waste conversion, such as providing high temperatures and heating rates, in comparison to conventional pyrolysis or gasification methods [7–9]. A suitable pretreatment process enhances the pyrolysis or gasification effects. Erlach et al. [14] pointed out that pre-treating the biomass with hydrothermal carbonization (HTC) produces a coal-like substance, biocoal, which is potentially better suited for entrained flow gasification than raw biomass. Byun et al. [15] developed a gasification/vitrification unit for the direct treatment of municipal solid waste (MSW), with a capacity of 10 tons/day, using an integrated furnace equipped with two nontransferred thermal plasma torches. It was successfully demonstrated that this process converted MSW into innocuous slag, with much lower levels of environmental air pollutant emissions and the syngas having a utility value as energy sources

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0360-5442/$ – see front matter
http://dx.doi.org/10.1016/j.energy.2013.12.042

(287 N m^3/MSW-ton for H_2 and 395 N m^3/MSW-ton for CO), using 1.14 MWh/MSW-ton of electricity (thermal plasma torch (0.817 MWh/MSW-ton) + utilities (0.322 MWh/MSW-ton)) and 7.37 N m^3/MSW-ton of liquefied petroleum gas [15].

In this study, the treatment of MSW mixed with raw wood (MSW/RW) via Steam Mechanical Heat Treatment (SMHT), using a thermal plasmatron reactor as the heat source, was examined. The waste, in the view of sustainable material management (SMM), is regarded as the used material. The ultimate goal of SMM is total recycling and reuse without waste, thereby achieving a green environment. In keeping with this goal, the MHT of MSW/RW focuses on the feasibility of total recovery and reutilization. SMHT is one of the alternatives for the pretreatment of MSW/RW before its further reutilization. SMHT, sometimes referred to as wet torrefaction, is an artificial coalification process which takes place in hot pressurized water between 175 and 250 °C. It involves hydrolysis, decarboxylation, dehydratization, condensation and aromatization reactions [16]. SMHT is one of the alternatives for the pretreatment of municipal solid waste (MSW) using waste steam effluent from incinerator plants before its further separation and reutilization. For the heat recycling consideration, the waste steam effluent is derived from the off-stream steam from co-generator in incinerator plant. After SMHT, the lignocellulosic in MSW becomes refuse-derived biomass (RDB), and the properties of MSW are significantly changed. For example, the mass decreases while the volume density increases. The autoclaving serves as a pre-treatment step of MHT for the better separation yielding floc/fibre or RDF of good quality. The quality of derived floc/fibre depends on the properties of the MSW [17]. The biomass of MSW/RW from SMHT (MRM), which is compost-like and primary RDF or bio-char, becomes suitable for torrefaction/pyrolysis or gasification. The main objective of this study was to assess the plasmatron gasification of MRM with different temperatures and to examine the effects of the operation parameters on the performance, with the aim of providing product distribution with different contents. The gasification was performed using a plasmatron system in a nitrogen atmosphere with a 10 kW power capacity with steam contents. The residual materials and non-condensable gases were collected and analyzed using an elemental analyzer, gas analytical instruments and gas chromatography analyzers with thermal conductivity detectors (GC–TCD).

2. Material and methods

2.1. Materials

The biomass used in this study was MRM. The MRM was taken from the MSW/RW after the pretreatment of SMHT, which was performed by a fertilizer company in I-Lan, Taiwan. The sample of MRM was dried in a recycling ventilation drier for 24 h at 378 K before use. For a comparison of the effect of steam content, the water flow rate (circulated by a 378 K heating tape for steam production) was adjusted to 1 and 3 mL min^{-1} and injected into the plasmatron reactor. The results of the proximate analysis of MRM were 57.21, 4.12, and 38.67 wt% for moisture, ash and combustibles, respectively. As shown in Table 1, the contents of C, H, N, S and Cl of dry MRM were 53.13, 7.34, 1.49, 0.37 and 0.12 wt%, respectively, and the higher heating value (HHV) and lower heating value (LHV) of dry MRM were 9.71 and 7.59 MJ kg^{-1}, respectively.

2.2. Plasmatron operational procedure

A pilot-scale apparatus was used, and the experimental procedures for the plasmatron steam gasification were similar to those in previous studies [6,7], as shown in Fig. 1. A 10 kW plasmatron was used for the gasification process. For batch feeding, a sample of known mass of about 10 g was placed on the sample apparatus for feeding the sample material; then a 10 g sample flowed through the sample apparatus at 3 min intervals. The flow rate of carrier gas N_2 (99.99%) (Q_N) was adjusted to the desired value, i.e., 10 L min^{-1} at 101.3 kPa (1 atm) and 293 K, and was controlled by a rotameter. The power supply control unit (chopper) (Taiwan Plasma Corp.) for the plasmatron reactor was set at 2.59–4.68 kW (P_L) for temperatures (T) ranging from 573 to 873 K, respectively. For the analysis of gas products, a Gas Chromatograph GC–TCD (Thermo Scientific FOCUS GC) with a Supelco packing column (60/80 carbonxen-1000, 15 ft long, 2.1 mm i.d.) was used. The operation conditions of the Gas Chromatograph GC–TCD were set as follows: injector temperature 453 K, detector temperature 513 K, column temperature (following the sampling injection) held at 513 K for 10 min, helium carrier gas flow rate of 30 mL min^{-1} for A and B columns and a sample volume of 2 mL. Several duplicate experimental runs were performed in order to verify the values.

Table 1
Elemental analysis, calorific value and BET surface area of MRM and solid residues derived from plasmatron gasification at various temperatures and steam flow rates.

	Target temperature ± 20 (K)	573 K		773 K		873 K		873 K		873 K	
	Water flow rate for steam generation (mL min^{-1}) Dry MRM[a]	0		0		0		1		3	
Element											
C	53.13	65.86[b]	17.69[c]	54.66[b]	9.93[c]	56.27[b]	7.96[c]	41.25[b]	1.86[c]	33.27[b]	2.66[c]
H	7.34	0.79[b]	0.21[c]	0.47[b]	0.09[c]	0.47[b]	0.07[c]	1.28[b]	0.06[c]	0.92[b]	0.07[c]
N	1.49	1.95[b]	0.52[c]	1.62[b]	0.30[c]	3.92[b]	0.55[c]	1.25[b]	0.06[c]	2.12[b]	0.17[c]
S	0.37	0.10[b]	0.03[c]	0.09[b]	0.02[c]	0.39[b]	0.06[c]	0.01[b]	0[c]	0.00[b]	0[c]
C/H ratio (wt/wt)	7.24	83.37[b]		116.30[b]		119.72[b]		32.23[b]		36.16[b]	
Mass ratio[d]			26.87		18.46		14.15		4.52		–
Calorific value (MJ kg^{-1})											
HHV[e]	9.71	6.38		7.53		8.47		0.76		1.13	
LHV[f]	7.59	4.27		8.47		6.35		–		–	
BET surface area (m^2 g^{-1})	–	19.49		34.85		65.18		70.70		81.21	

[a] MRM: municipal solid waste mixed with raw wood (MSW/RW) after Steam Mechanical Heat Treatment (SMHT) (blade type) (MSW:RW = 8:1).
[b] Based on mass of residue.
[c] Based on original mass of raw MRM.
[d] Mass ratio of residue to raw MRM.
[e] Higher heating value of dry basis.
[f] Lower heating value of dry basis.