Bioresource Technology 101 (2010) 5633–5637

Contents lists available at ScienceDirect

Bioresource Technology

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

Hydrogen-rich gas production by steam gasification of char from biomass fast pyrolysis in a fixed-bed reactor: Influence of temperature and steam on hydrogen yield and syngas composition

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ARTICLE INFO

Article history:
Received 6 September 2009
Received in revised form 7 February 2010
Accepted 8 February 2010
Available online 2 March 2010

Keywords:
Hydrogen-rich gas
Steam gasification
Biomass char
Biomass micron fuel (BMF)

ABSTRACT

Steam gasification experiments of biomass char were carried out in a fixed-bed reactor. The experiments were completed at bed temperature of 600–850 °C, a steam flow rate of 0–0.357 g/min/g of biomass char, and a reaction time of 15 min. The aim of this study is to determine the effects of bed temperature and steam flow rate on syngas yield and its compositions. The results showed that both high gasification temperature and introduction of proper steam led to higher yield of dry gas and higher carbon conversion efficiency. However, excessive steam reduced gas yield and carbon conversion efficiency. The maximum dry gas yield was obtained at the gasification temperature of 850 °C and steam flow rate of 0.165 g/min/g biomass char.

1. Introduction

With increasing demand for energy, biomass energy conversion and utilization attracts much attention. Thermo-chemical conversion is the most commonly biomass conversion method to upgrade biomass energy quality (Zhong and Wei, 2004). Fast pyrolysis liquefaction is a low-cost and promising thermo-chemical conversion process for biomass energy utilization (Zheng, 2008; Bridgwater et al., 2002). As a byproduct of biomass pyrolysis, biomass char can be used as material for combustion (Mary et al., 1996), activated carbon preparation (González et al., 2009) and gasification. Compared to other gasifying agents, pure steam gasification produces higher H_2/CO and hydrogen yield (Gil et al., 1999). Hydrogen can be used for hydrotreatment to reduce oxygen content of bio-oil (Courtney et al., 2009; Postelmans et al., 2009); with upgrading process, bio-oil can be directly used in engines and turbines.

Operation temperature for fast pyrolysis liquefaction varies from 400 to 600 °C (Beis et al., 2002; Montesinos et al., 2002). With the removal of moisture and volatile matter from biomass during pyrolysis, biomass char changes its properties, such as higher fixed carbon, lower volatile matter, higher carbon element and lower oxygen (Beis et al., 2002). Such changes make biomass char presents different steam gasification behavior from biomass.

Several studies have been reported on the gasification of biomass char from different kinds of biomass, e.g. grapefruit skin (Montesinos et al., 2002), Japanese cedar char (Keigo et al., 2009), sunflower shell (Haykiri-Acma et al., 2006), beechwood (Wolfgang and Michael, 2005), slashpine (Fermoso et al., 2009) and bagasse (Chaudhari et al., 2001, 2003). Our team has developed a process to produce a new kind of powdery biomass fuel, whose particle size is less than 250 μm, called biomass micron fuel (BMF) (Xiao et al., 2006). Despite the worldwide research efforts, studies on steam gasification of biomass char are fairly limited, thus the process of hydrogen-rich gas production by steam gasification of biomass char is still not fully understood, and the research on biomass char from fast pyrolysis liquefaction of BMF has not reported.

In this study, steam gasification characterization of biomass char, derived from fast pyrolysis of BMF at 500 °C, was investigated in a fixed-bed reactor. The purpose of this study is to determine the influence of temperature and the steam flow rate on the gas yields, gas composition and carbon conversion efficiency, thus lay the foundation for engineering application.

2. Methods

2.1. Materials

The feedstock material used in this study is biomass char, which was produced by fast pyrolysis liquefaction of pine sawdust in a fixed-bed reactor, at final pyrolysis temperature of 500 °C, particle size was below 0.25 mm, with heating rate of 30 °C min^{-1}. After

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doi:10.1016/j.biortech.2010.02.025

Table 1
Ultimate and proximate analysis of biomass char sample.[a]

Ultimate analysis		Proximate analysis	
C	70.68 wt.%	Volatile matter	23.95 wt.%
H	3.60 wt.%	Fixed carbon	63.72 wt.%
O[b]	23.11 wt.%	Ash	12.33 wt.%
N	2.40 wt.%	Low heating value	25172 kJ/kg
S	0.21 wt.%	Apparent density	130.5 kg/m^3

[a] Dry basis.
[b] By difference.

milling and sieving, the particle size distribution of biomass char was as follows: 38.9 wt.% below 0.125 mm, 24.2 wt.% 0.125–0.15 mm, 29.5 wt.% 0.15–0.1875 mm, 7.4 wt.% 0.1875–0.25 mm. The proximate and ultimate analyses of biomass char are shown in Table 1.

2.2. Apparatus and procedures

The apparatus used in this study mainly consisted of electric furnace heater, temperature controller cabinet, steam generator, steam flow meter, quartz tube reactor (1000 mm long and 50 mm i.d.), condenser, tar collector and filter, as shown in Fig. 1.

The steam gasification experiments were conducted at atmospheric pressure, the procedure of experiments is described below:

For each test 5.0 g biomass char was put into a porcelain boat, which was placed into the quartz tubular reactor. The temperature controller and electric furnace heater were then turned on to heat the reactor to desired temperature. Anoxic atmosphere was achieved by passing nitrogen gas (flow rate 1 mg/min) for 10 min, after that pure steam, whose flow rate keep constant during experiment (range from 0 to 1.787 g/min), was injected into reactor. Then porcelain boat and steam were fed into reactor zone simultaneously. The fluid products flowed out the reactor and passed through a water condenser. Condensable gas changed into bio-oil was captured by tar collector, while non-condensable gas was collected by gas-collecting bag for sampling after cleaning. After 15 min, the experiment stopped, the porcelain boat was removed and weighed to determine the amount of unconverted char by difference.

The tests mentioned above were performed at five different temperatures: 600 °C, 700 °C, 750 °C, 800 °C, 850 °C, while steam flow rate was varied from 0 to 0.357 g/min/g biomass char. In this study, each experiment was repeated at least three times to ensure data reliability. The data reported in this study are average value of three times, and data variability was within 5%.

2.3. Method of sampling and analysis

The product gas was analyzed by GC 9800T. Permanent gases (H_2, CH_4, O_2, N_2, CO, CO_2, C_2H_2, C_2H_4, and C_2H_6) were analyzed with TCD using 5A, porapakQ and TDX-01 columns. The carrier gas was argon in all analyses.

2.4. Methods of data processing

Low heat value (LHV) of dry gas, carbon conversion efficiency (X_c) are calculated by Eqs. (1) and (2). The stoichiometric yield of H_2 from biomass char is 124.67 mol H_2/kg biomass char calculated by Eqs. (3) and (4). Potential hydrogen yield (PHY) is defined as the sum of hydrogen yield from reactions of (4) and (5) (Turn et al., 1998).

$$\mathrm{LHV(MJ/Nm^3)} = (\mathrm{CO} \times 126.36 + \mathrm{H_2} \times 107.98 + \mathrm{CH_4} \times 358.18 + \mathrm{C_2H_2} \times 56.002 + \mathrm{C_2H_4} \times 59.036 + \mathrm{C_2H_6} \times 63.772)/1000 \tag{1}$$

$$X_c\% = \frac{12Y(\mathrm{CO}\% + \mathrm{CO_2}\% + \mathrm{CH_4}\% + 2 \times \mathrm{C_2H_2}\% + 2 \times \mathrm{C_2H_4}\% + 2 \times \mathrm{C_2H_6}\%)}{22.4 \times \mathrm{C}\%} \times 100\% \tag{2}$$

$$\mathrm{CH_{0.611}O_{0.245}} + 0.755\mathrm{H_2O} = 1.061\mathrm{H_2} + \mathrm{CO} \tag{3}$$

3. Results and discussion

In general, steam gasification reactions can be divided into two steps. One step is primary pyrolysis, which produces tar, char and volatiles by thermo-chemical decomposition of biomass char, followed by cracking and reforming of the volatiles, and the gasification of the char. The other step involves reactions of CO, H_2, CO_2, CH_4, hydrocarbon gases with steam and carbon in biomass char, thereby producing gaseous products. The final gas composition of the gasification process is the result of the combination of a series of complex and competing reactions (4)–(10), shown as follows:

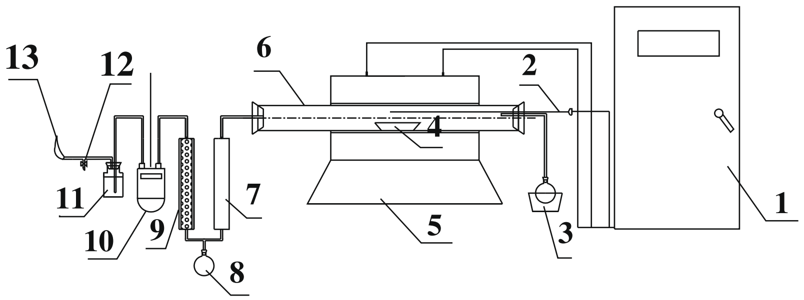

Fig. 1. Experimental apparatus of biomass char gasification. 1, temperature controller; 2, thermocouple; 3, steam generator; 4, porcelain boat; 5, electric furnace; 6, quartz tube reactor; 7, condenser; 8, tar collector; 9, filter; 10, flow meter; 11, water sealed bottle 12, to gas collector bag; and 13, exhaust gas burner