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Research article

Steam co-gasification of biomass and coal in decoupled reactors

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ABSTRACT

Steam co-gasification of pine sawdust and bituminous coal was conducted in a lab-scale external circulating radial-flow moving bed (ECRMB) gasification system. The system is composed of three decoupled reactors, i.e., a gas–solid countercurrent moving bed pyrolyzer, a radial-flow moving bed gasifier and a riser-type combustor. Calcined olivine was used as circulating heat carrier and in-situ tar destruction catalyst as well. The influences of biomass blending ratio (BR), pyrolyzer temperature, gasifier temperature and steam to carbon mass ratio (S/C) on the gasification performance were investigated. The results indicated that the gas and tar yields increased with the increase of BR. Synergetic effect based on gas composition was found during co-gasification. At the S/C range of 0 to 1.3, the gas yield and H_2 content in product gas increased but CO_2 decreased with the increase of S/C. Higher gasifier temperature promoted the gas yield, $H_2 + CO$ in product gas, carbon conversion and chemical efficiency of the process. A gas yield of 0.60 Nm^3/kg daf and a tar yield of 5.8 g/Nm^3 in the gas were obtained at the gasifier temperature of 850 °C, BR of 50% and S/C of 1.3. Pyrolyzer temperature at the range of 500 to 700 °C had no remarkable influence on the product gas composition.

1. Introduction

In the last decade, the method of reducing carbon dioxide emissions from fossil fuels is becoming a worldwide issue. Biomass received a lot of interest in recent years because carbon dioxide from biomass conversion is regarded as neutral [1]. Biomass can be an alternative for the fossil fuels since it is a renewable energy source with abundant source in some extent. Biomass gasification is one of the promising processes among all biomass conversion processes [2]. The product gas from biomass gasification can be used in many applications, for example generation of electric power, Fischer–Tropsch synthesis for liquid fuels and fuel cells [1]. The gasification process must be supplied by energy since the gasification reactions are endothermic. In the conventional gasification processes, air is used as gasification agent and the energy for the gasification reactions provided by partial combustion of the fuels. However, air gasification produces a gas with lower heating value due to dilution by nitrogen in the air. Product gas with higher heating value could be achieved using the pure oxygen as gasifying agent; but the production of pure oxygen increases the operational cost. Dual fluidized-bed system can also produce high-quality product gas which contains very small amount of nitrogen. In this gasification process, gasification reactor and combustion reactor are isolated and controlled separately. The energy for the endothermic gasification reactions is provided from the combustion reactor by circulating bed materials. In this case, the product gas achieved from the gasification reactor and the flue gas exited from combustion reactor are separated [3].

Specifically, when the combustion of the residual char does not provide enough energy to satisfy the endothermic gasification reactions in dual-bed biomass gasification systems, additional feedstock with higher carbon content is needed. Co-gasification of biomass with coal can be an alternative to pure biomass gasification since it has several advantages and may compensate their weakness with each other [4]. Co-gasification of biomass and coal has been received much attention in recent years. Saw et al. [5] and Kern et al. [6] investigated co-gasification of coal and biomass in dual fluidized bed. Saw et al. [5] found effective synergy during co-gasification of biomass and coal. Kern et al. [6] reported that increasing lignite ratios in the lignite–biomass blends enhanced the reduction of tars in the product gas with the catalytically active ash content from lignite. Synergistic effects were also reported by Miccio et al. [7] during co-gasification of coal and biomass in ICFB (internal circulating fluidized bed) gasification system. They stated that synergistic effect is exerted by the greater abundance of char. However, no synergetic effect during co-gasification was also reported by Aigner et al. [1] who investigated co-gasification of coal and wood in a 100 kW dual fluidized bed gasifier that gas composition and tar yield showed linear correlation with the changing coal to biomass ratio. Co-gasification biomass and coal can not only reduce air pollutants such as NO_x and SO_x [8–10] but also improve gasification reactivity [9,11] and the gasification efficiency [12]. Some components such as alkali and alkaline earth metals in the biomass act as catalysts and promoted the carbon gasification reactions during co-gasification [13,14].

Most of co-gasification investigations mainly focus on thermogravimetric analysis [15,16], fixed bed gasifier [17,18], drop tube furnace [19,20] and fluidized bed gasifier [12,22–24], however, in the reviewed literature there is limited study dedicated to the decoupled moving-bed

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co-gasification for biomass and coal, especially for the pyrolysis and gasification isolated system. In generally, gasification process involves a series of reaction such as fuel pyrolysis, tar cracking, char gasification and combustible matter combustion. In a conventional coupled gasification process such as the entrained flow gasification process these reactions take place in single reactor. In a decoupled gasification process, the reaction process is divided into several steps and is carried out in two or more reactors [25–27].

This paper presents results of the co-gasification of sawdust and bituminous coal in a decoupled gasification system, namely external circulating radial-flow moving bed (ECRMB) gasifier, at atmospheric pressure with the gasifying agent of steam. The influences of four reaction parameters, i.e., biomass ratio (BR), pyrolyzer temperature, gasifier temperature, and steam to carbon mass ratio (S/C), on the performance of the co-gasification were taken into account.

2. Experimental

2.1. Experimental apparatus

The ECRMB gasification system is a further development of the so-called ECCMB technology (external circulating concurrent moving bed) which was described by Wei [28], Tursun [29], and Zou [30]. Fig. 1 shows the principle of the ECRMB steam gasification process. The schematic of the lab-scale ECRMB gasification facility is shown in Fig. 2. The gasification system includes three isolated reactors, i.e., a gas–solid crosscurrent radial-flow moving-bed gasifier (3), a solid–solid cocurrent and gas–solid countercurrent moving-bed pyrolyzer (4) and a riser-type combustor (1). The pyrolyzer (40 mm i.d. and 330 mm high) operates between 500 °C and 700 °C where the solid fuels are pyrolyzed to produce volatiles and chars. In the gasifier, cracking and steam reforming of the volatiles take place at a relatively higher temperature. The combustion reactor (28 mm i.d and 1956 mm high) allows combustion of the residential chars and regenerates the deactivated bed materials/catalysts. Every reactor is made of stainless steel and electrically heated independently. As it is shown in Fig. 2, the radial-flow moving bed gasifier has an annular bed with a height of 220 mm, an i.d. of 24 mm, and an o.d. of 108 mm. This specific designed radial-flow moving bed gasifier provides longer residence time for steam reforming of the volatiles to yield a product gas with lower tar content. The gasifier also acts as a dust filter to produce a gas with less dust. The residual chars from the pyrolyzer along with the bed material are transported to the combustor by a screw conveyor (5) where the char and carbon deposit on the surface of catalysts burned off. The circulating rate of bed material can be adjusted by varying the rotation speed of the screw conveyor. The flue gas separated from bed materials in the cyclone (2) at the top of the gasifier before the bed material returned to gasifier. Energy balance has not been considered in the evaluation of the results since the gasification system is electrically heated, not only for startup, but also to compensate for heat losses to the surroundings.

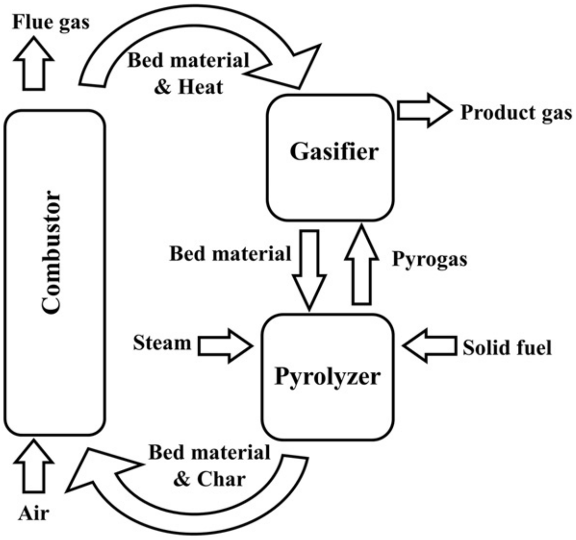

Fig. 1. The principle of the ECRMB steam gasification process.

2.2. Fuel feedstock and bed materials

The biomass feedstock used in this test is pine sawdust from Dalian City, Liaoning Province, China and the coal is bituminous coal from Changji City, Xinjiang Province, China. Their proximate and ultimate analyses are presented in Table 1. Before test, the fuel samples were sieved to 0.38–0.83 mm, and dried for 4 h at 105–110 °C. The BR is defined as the mass ratio of the sawdust feed rate to the total feed rate of sawdust and coal as follows:

$$\mathrm{BR}\ (\%) = \frac{\text{sawdust feed rate (g/h)}}{(\text{sawdust} + \text{coal})\ \text{feed rate (g/h)}} \times 100\%. \tag{1}$$

The olivine of particle size of 0.38–0.83 mm calcined at 900 °C for 4 h was used as bed materials and in-situ tar destruction catalyst. The olivine came from Yichang City, Hubei Province, China and the XRF (X-ray Fluorescence) analyses of the calcined olivine are listed in Table 2.

2.3. Procedure and product analysis

The reactors electrically heated up to desired temperature after about 5 kg of the calcined olivine as bed materials were loaded into the reaction system. The bed materials were fluidized by the preheated pressurized air (4.2–4.6 $\mathrm{Nm^3/h}$) in the riser-type combustor. The bed materials were circulated in the system continuously with the help of the screw conveyor between the bottom of the pyrolyzer and that of the combustor. Fuel particle feeds into pyrolyzer by two screw feeders (7) at a fixed feeding rate of 200 g/h. The S/C ratio could be controlled by changing of the steam flow rate of steam generator (6). Table 3 shows the operating parameters of the gasification system. The gaseous products are cooled in four sequential glycol-cooled (−20 °C) condenser and tar traps (10) to separate the condensable components. The liquids (tar and water) obtained are collected in the tar traps. The tar traps were washed with ethyl acetate after each experiment. The tar was recovered by evaporating the solvent at 45 °C in a rotary evaporator. Detailed information relating to tar sampling, analysis and composition for this test is available on our previous work [31]. The product gas is sampled when the system reached a steady state that kept for 2 h. The produced gas was collected in a gas bag (13) every 10 min and the main components (H_2, CO, CO_2, CH_4, C_2H_4 and C_3H_6) were off-line analyzed by a GC-7890II gas chromatograph coupled with a thermal conductivity detector (TCD) and a flame ionization detector (FID). Gas compositions reported in this paper are averaged values with respect to time on stream.

Chemical efficiency, carbon conversion and steam to carbon mass ratio (S/C) were determined by the following equations (Eqs. (2)–(4)):

$$\text{Chemical efficiency (\%)} = \frac{\text{LHV of product gas}\left(\mathrm{kJ/Nm^3}\right) \times \text{gas yield}\left(\mathrm{Nm^3/kg}\right)}{\text{LHV of fuel feedstock into system (kJ/kg)}} \times 100\% \tag{2}$$

$$\text{Carbon conversion (\%)} = \frac{\text{gasified carbon in the product gas (g)}}{\text{carbon of feedstock fed into system (g)}} \times 100\% \tag{3}$$