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Waste-gasification efficiency of a two-stage fluidized-bed gasification system

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ABSTRACT

This study employed a two-stage fluidized-bed gasifier as a gasification reactor and two additives (CaO and activated carbon) as the Stage-II bed material to investigate the effects of the operating temperature (700 °C, 800 °C, and 900 °C) on the syngas composition, total gas yield, and gas-heating value during simulated waste gasification. The results showed that when the operating temperature increased from 700 to 900 °C, the molar percentage of H_2 in the syngas produced by the two-stage gasification process increased from 19.4 to 29.7 mol% and that the total gas yield and gas-heating value also increased. When CaO was used as the additive, the molar percentage of CO_2 in the syngas decreased, and the molar percentage of H_2 increased. When activated carbon was used, the molar percentage of CH_4 in the syngas increased, and the total gas yield and gas-heating value increased. Overall, CaO had better effects on the production of H_2, whereas activated carbon clearly enhanced the total gas yield and gas-heating value.

1. Introduction

In Taiwan, over 6 million tons of municipal solid wastes are incinerated by 24 large incineration plants each year. The incineration rate of municipal solid waste reached 97% in 2014, excluding recycled waste. However, after recycling, most waste is organic material, which constitutes a type of resource (biomass). Replacing the current waste-treatment method with gasification would positively affect the sustainable development of the Earth's resources. During gasification, carbon materials, such as biomass and coal, undergo partial oxidization and pyrolysis at high temperatures, generating syngas. This syngas comprises moderate- and low-energy gases, such as H_2, CH_4, and CO, which can be used as fuel for steam boilers and internal-combustion engines.

Previous studies used both fixed-bed gasifiers and fluidized-bed gasifiers. Unlike fixed-bed gasifiers, fluidized-bed gasifiers are capable of nearly mass and heat-transfer efficiency (Tardos and Pfeffer, 1995) and are employed in a wide range of industrial applications, such as incineration, biomass gasification, and catalytic reactions (Lin et al., 2009; Foscolo et al., 2007; Hao et al., 2008). Fluidized-bed reactors consist of two types: circulating fluidized-bed reactors and bubbling fluidized-bed reactors. These systems are known for their easy, continuous operation, and they can handle a variety of feed materials. However, bubbling fluidized-bed gasifiers are widely used in academic research because of their low cost (Gonzalez et al., 2011; Jordan and Akay, 2013; Karatas et al., 2013; Lin and Chen, 2014; Miccio et al., 2009).

Multiple parameters influence fluidized-bed gasification, including the operating temperature, equivalence ratio (ER), steam/biomass (S/B) ratio, bed material particle size, bed material, biomass type, biomass particle size, and feed rate (Alauddin et al., 2010; Kumar et al., 2009; Lin et al., 2013). For gasification, the operating temperature is the most important parameter. Increasing the operating temperature can alter the syngas composition and the distributions of the tar and char products and can also increase the carbon-conversion efficiency. Luo et al. (2009) reported that the carbon-conversion efficiency increased from 61.96% to 92.59% and that the total gas yield also increased from 1.15 to 2.53 Nm^3/kg when the operation temperature was increased from 600 °C to 900 °C. By varying the operating temperature from 650 °C to 850 °C, Kumar et al.

Abbreviations: ER, equivalence ratio; GC-TCD, gas chromatograph with thermal conductivity detector; PP, polypropylene; S/B, steam/biomass.

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(2009) observed that the studied gasification system exhibited its maximum carbon-conversion efficiency (82%) and energy-conversion efficiency (96%) at 850 °C. Luo et al. (2009) found that increasing the operation temperature increased CH_4-steam reforming, the water–gas shift reaction, and the Boudouard reaction, resulting in the generation of more H_2 and CO. Increasing the operating temperature was also observed to increase the total gas yield (Andres et al., 2011; Wang et al., 2012; Yan et al., 2010).

In recent years, most studies concerning gasification have focused on altering the syngas composition or on improving the gasification efficiency. The most common methods involve using additives in the gasification process or improving the gasification process itself. According to previous studies, useful additives include calcium-based additives and activated carbon. For example, using CaO as an additive reduces the CO_2 in the syngas and increases the H_2 yield (Acharya et al., 2010; Chiang et al., 2011, 2012; Kobayashi et al., 2011), whereas activated carbon can adsorb tar and generate more gas via pyrolysis (Cho et al., 2013a,b; Li et al., 2010; Mun et al., 2014).

Two-stage gasification was developed to improve the gasification efficiency. Xiao et al. (2011) described two-stage gasification as connecting two pieces of gasification equipment in series. The gasification products generated by the Stage I gasifier, such as tar, are fed into the Stage II gasifier, where they react; thus, the initial product is gasified or pyrolyzed to generate more gas and reduce the overall production of tar. Soni et al. (2009) connected two fixed-bed gasifiers in series to achieve two-stage gasification. They reported that two-stage gasification increased the H_2-production rate (from 7.3% to 22.3%) and total gas yield (from 30.8% to 54.6%) and decreased the tar output (from 18.6% to 14.2%). Park et al. (2010) also used two fixed-bed gasifiers to test two-stage gasification and obtained similar results.

Currently, the two-stage gasification processes that have been developed exhibit good gasification efficiencies. However, most related studies investigated fixed-bed gasifiers (Sarker and Nielsen, 2015; Zeng et al., 2014; Guo et al., 2014). The fluidized-bed reactor is more advantageous than the fixed-bed one. Using two fluidized-bed reactors to create a two-state gasification system could result in better gasification efficiency, and a few previous studies have created such systems using bubbling fluidized-bed gasifiers. Therefore, in this study, two fluidized-bed reactors were combined to build a two-stage fluidized-bed gasifier, and the effects of operating temperature on the two-stage gasification process in this system were analyzed. Additionally, the effects of additives (CaO and activated carbon) were also addressed in Stage II. The syngas composition, total gas yield, and gas-heating value were calculated to determine the feasibility of this two-stage fluidized-bed system.

Table 1
Ultimate analysis, proximate analysis, and heating value analysis of artificial waste.

Species	Polypropylene (PP)	Wood chips	Vegetable capsule
Ultimate analysis (wt%)			
C	86.3	45.98	47.76
H	12.77	7.32	8.15
O	0.35	46.51	43.81
N	0.57	0.18	0.27
Proximate analysis (wt%)			
Moisture	0.01	7.27	5.0
Volatile matter	99.99	76.25	86.8
Fixed carbon	0	16.48	7.56
Ash	0	0	0.64
Lower heating value (MJ/kg)	44.27	15.83	17.91

2. Materials and methods

2.1. Artificial waste

The artificial waste used in this study consisted of polypropylene (PP) plastic pellets, wood chips, and plant capsules. The basic components of the experimental materials are listed in Table 1. The feed consisted of plant capsules (0.098 g), PP plastic pellets (0.022 g), and wood chips (0.163 g). The total weight of each piece of artificial waste was 0.283 g, and five pieces were fed in every 20 s.

2.2. Two-stage bubbling fluidized-bed gasifier

This study used a laboratory-scale, two-stage fluidized-bed gasifier. Fig. 1 depicts the equipment in detail. The furnace body was made of stainless steel (AISI-310) and had the following dimensions: thickness of 0.49 cm, height of 50 cm, outer diameter of 4.27 cm, and inner diameter of 3.29 cm. The Stage I furnace specifications were identical to those of the Stage II furnace. The pipe linking the two furnaces was also made of stainless steel with a thickness of 0.42 cm. A stainless-steel distributer was mounted at the bottom of the two furnace beds, and the open area constituted 15.2%. An electrical heating system was used to heat the furnace body, and the outer surface of the furnace body was covered with a heat-insulating fiber to minimize heat loss. Three sets of T-type thermocouples were used to monitor and record the temperature change inside the furnace body. A bivalved feed inlet was designed to prevent the gas generated in the furnace body from leaking during feeding and the outside air from entering the furnace body and influencing the experimental results.

2.3. Experimental process and procedure

This study focused on the effects of both the operating temperature and the use of additives on the two-stage gasification efficiency. A two-stage fluidized-bed gasifier was used for the experiments. The Stage I and Stage II operating temperatures were controlled at 700 °C, 800 °C, and 900 °C; the ER was fixed at 0.3; and the additives were CaO and activated carbon. The effects of both the operating temperature and the additives on the gasification efficiency of the two-stage fluidized-bed gasifier were evaluated based on the obtained data. The experimental conditions are listed in Table 2.

The minimum fluidization velocity was measured before the experiments using the method described by Lin et al. (2002). The minimum fluidization velocity was 0.10 m/s, and the gas flow was 1.3 times the minimum fluidization velocity. The pure N_2 and O_2 gases were adjusted using a mass flow meter and directed into Stage I of the two-stage fluidized-bed gasifier. The Stage I bed material used was silica sand, which had a mean particle size of 545 μm and a density of 2600 kg/m^3. The silica sand was composed of 97.8% SiO_2, 2% Al_2O_3, and 0.07% Fe_2O_3. The Stage II unit utilized either CaO or activated carbon as an additive. The particle sizes were 545 μm and 775 μm, respectively, and the weights were 25 g and 15 g, respectively. The bed height was fixed at 1 H/D (height/diameter), and the CaO purity exceeded 96%. For activated carbon, the specific surface was 429.14 m^2/g, the mean pore diameter was 6.13 nm, and the total pore volume was 0.66 cm^3/g. The specific surface of CaO was 0.52 m^2/g.

The syngas flowed through the glass fiber filter unit during the sampling, and most of the particles were trapped on GF/A-grade filter paper. The filtered gas flowed through the impinger in the

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