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Research paper

Syngas production via biomass self-moisture chemical looping gasification

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ABSTRACT

Fresh biomass self-moisture gasification (BSMG) is a promising route for biomass utilization. Unlike conventional biomass steam gasification (BSG), BSMG used the moisture content in biomass as the gasifying agent. In this work, the performance of biomass self-moisture chemical looping gasification (BSM-CLG) was compared with dry biomass chemical looping gasification (DB-CLG) and biomass steam chemical looping (BS-CLG) gasification. The data analyzed was the gas cumulative compositions, the hydrogen-to-carbon monoxide ratio (H_2/CO), the lower heating value (LHV) and the gas yield. Results showed that the moisture content increased the gas yield from 0.9927 $Nm^3\ kg^{-1}$ to 1.1646 $Nm^3\ kg^{-1}$, while the steam increased the H_2/CO ratio from 0.6398 mol mol^{-1} to 0.7436 mol mol^{-1} in the process. The interaction between OC and biomass moisture increased the biomass reactivity. The differing gasification reactivity was due to different water diffusion between the methods of biomass gasification. The diffusion of moisture content and steam had opposite directions, and the different diffusion led to the moisture content impacted the initial gasification stage, but the steam influenced the biomass molecular structure rearrangement.

1. Introduction

Biomass gasification is an advanced technology to produce useful convenient gaseous fuels with low cost and high efficiency [1,2]. Fresh biomass typically contains moisture from 8% to 60% [3]. In a traditional biomass gasification process, the fresh biomass feedstock should be dried to reduce the high moisture content before gasification [4]. In the gasifier, experimental studies reported that the high temperature steam can be used as a gasifying agent for maximizing the gas product yield by reformation [5,6]. However, both the biomass feedstock drying and the steam production consume much energy and complicate the process. If the moisture content could be used as the gasifying agent instead of the steam, it would reduce the energy consumption and cost of the process by eliminating the drying step.

Biomass gasification is a thermochemical partial oxidation process [7]. For conventional steam gasification, researchers used either enriched air or pure oxygen to improve the hydrogen yield [8] and the process efficiency [9]. Nevertheless, biomass gasification still needs a large capital investment for the oxygen rich air or pure oxygen production equipment. Chemical looping gasification (CLG), which is based on the chemical looping combustion (CLC) [10–12], is an innovative gasification technique for using lattice oxygen from oxygen carrier (OC) instead of molecular oxygen [13]. The significant economic advantages of CLG are economic by using OC to replace air separation unit [14]. It requires a relatively low temperature when compared with other reactors [15], and the reduction and oxidation process are combined into a single step via the circulation of the OC particles [16]. The biomass gasification and the OC regeneration can be conducted in different reactors simultaneously and auto-thermally (Fig. 1) [17,18]. In addition, for the iron-based OC, the hydrogen yield can be increased via the steam-iron process [19,20]. Consequently, the hydrogen-to-carbon monoxide (H_2/CO) ratio of the syngas can be improved [21]. Previous studies have promoted reforming reactions on iron-based biomass CLG process which used steam as the gasifying agent [13,14], but said the processes still consumed a large amount of energy. Considering that biomass moisture content and the steam have a similar role, biomass self-moisture chemical looping gasification (BSM-CLG) process was investigated to understand the effects of the moisture content and the OC.

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Nomenclature

CLG	Chemical looping gasification
CLC	Chemical looping combustion
OC	Oxygen carrier
FR	Fuel reactor
AR	Air reactor
LHV	Lower heating value, MJ Nm^{-3}
DBP	Dry biomass pyrolysis
BSMG	Biomass self-moisture gasification
BSG	Biomass steam gasification
DB-CLG	Dry biomass chemical looping gasification
BSM-CLG	Biomass self-moisture chemical looping gasification
BS-CLG	Biomass steam chemical looping gasification
H_2/CO ratio	Hydrogen-to-carbon monoxide ratio, mol mol^{-1}
Ω	The OC to fuel ratio, mol mol^{-1}
$\dot{n}_{in}$	The total inlet gas molar flow rate, mol
$x_{N_2,in/out}$	The volume fractions of nitrogen entering/exiting the fuel reactor, %
x_i	The volume fraction of gas species i ($i = H_2,\ CO,\ CO_2,\ CH_4$), %
Y_{gas}	The gas yield of the reactor, $Nm^3\ kg^{-1}$
$n_{CO_2/CO/CH_4/H_2}$	The mole of CO_2, CO, CH_4 and H_2, mol
$m_{biomass}$	The mass of the biomass, kg
R_{OC}	The oxygen transport capacity of the natural hematite, %
n_{OC}	The mole of the natural hematite, mol
$\varphi_{fuel,C}/\varphi_{fuel,H}$	The stoichiometric mole of lattice oxygen needed for complete conversion of one mole of fuel to CO_2/H_2O, %
n_c/n_H	The mole of the carbon/hydrogen in the fuel, mol

In this study, the experiments of dry biomass pyrolysis (DBP), biomass self-moisture gasification (BSMG) and biomass steam gasification (BSG) were compared on a fixed bed reactor. The variable studies were the product gas distribution, the hydrogen-to-carbon monoxide (H_2/CO) ratio, the lower heat value (LHV) and the gas yield. The dry biomass chemical looping gasification (DB-CLG) process was studied under different OC to fuel ratios. Then, biomass self-moisture chemical looping gasification (BSM-CLG) and biomass steam chemical looping gasification (BS-CLG) were compared based on the H_2/CO ratio, LHV and the gas yield. The interaction between the OC and the moisture content (or steam) were compared based on the experimental results. Water diffusion was also discussed.

2. Materials and methods

2.1. Material preparation

Pine sawdust obtained from Jiangsu (China) was used as the sample. The particles were crushed and sieved to the 0.1 mm - 0.2 mm range, then dried at 105 °C for 12 h in the oven. Afterwards, the dry particles were mixed with deionized water to use as the fresh biomass sample. Table 1 shows the proximate and ultimate analyses of the dry particles.

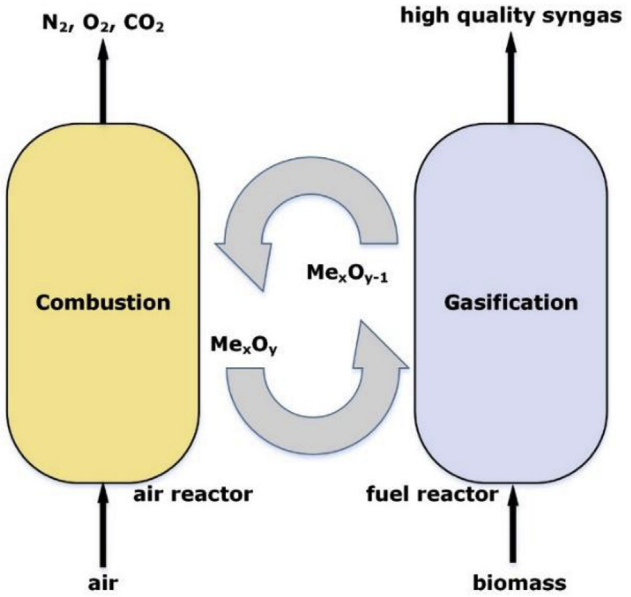

Fig. 1. Schematic of the biomass chemical looping gasification (CLG) process.

Natural hematite is one of the most promising iron-based OC, and it has been confirmed in our previous publications [22,23]. The particles used as the OC in this study were from Brazil. They were calcined in a muffle oven at 950 °C for 2 h. After that, they were crushed and sieved to the size range from 0.1 mm to 0.3 mm. They were mainly composed of 89.15 wt.% Fe_2O_3, 6.43 wt.%SiO_2 and 3.15 wt.% Al_2O_3 based on XRF (X-ray Fluorescence, ARL-9800, Switzerland) analysis.

2.2. Experimental setup and procedure

The gasification experiments were conducted in a fixed bed reactor. The reactor was a quartz glass tube (i.d. = 20 mm, length = 320 mm) with a porous distributor plate located 40 mm from the bottom, and it was heated in an electric furnace and the reaction temperature was monitored by a thermocouple in the tube. The schematic diagram of the reactor system is shown in Fig. 2. The flow rate of 99.99% purity N_2 was measured by a MFC (mass flow controller). The steam generator was an intelligent control water pump for generating steam through a 200 °C pre-heating furnace.

For each experiment of the process, the N_2 gas of 1200 mL min^{-1} was introduced into the reactor. The reactor was heated under this atmosphere to reach at 800 °C. Once the temperature was reached, a micro quartz glass tube ($\varphi 10 \times 40$) was used as a feeding unit to add the pre-mixed biomass and OC particles (or just the biomass, 0.2 g dried) through the top of the reactor. Also, the steam vapor of 0.5 mL h^{-1} was introduced to the reactor if the condition was needed. The reaction time was 10 min and the outlet gas was introduced to an ice-water cooler and a silica gel dryer successively. These units removed the fly ash and steam from the exhaust gas, which was then fed to a gas analyzer. The gas analyzer used in this study was a multi-component gas analyzer. The CO, CO_2, and CH_4 channels were Non-Dispersive Infra-Red (NDIR) detector. The O_2 channel was electrochemical oxygen detector. The H_2 channel was Thermal Conductivity Detector (TCD). The detectable range of each gas (CO, CO_2, CH_4, and H_2) is 0–100% (±2% FS) except O_2 (0–21%, ±0.2%). The brand of the device is MRU Co. Ltd, Germany, and the device is imported by Beijing York Instrument Co. Each experiment was repeated three times to ensure the accuracy of the data.