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Full Length Article

Co-gasification of coal and biomass in a fixed bed reactor with separate and mixed bed configurations

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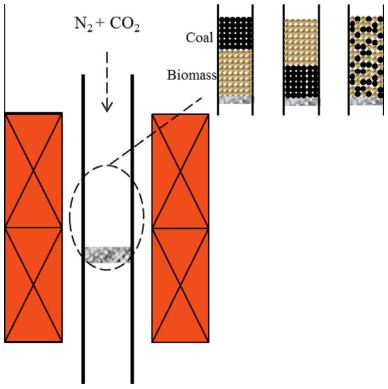
HIGHLIGHTS

- Co-gasification of coal and biomass was conducted in a fixed bed reactor.
- Two separate and a mixed-bed configurations were designed for comparative study.
- The mixed-bed configuration produced a well-dispersed bio-ash among coal char grains.
- A stronger synergy effect was observed in the mixed bed configuration rather than in the separate configuration.
- The bio-char bed exhibited better tar cracking performance than the coal char bed.

GRAPHICAL ABSTRACT



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ABSTRACT

This study inspects the occurrence of synergy in the co-gasification of coal and biomass in a fixed bed reactor. Two separate and a pre-mixed bed configurations with a congruent sample mass are designed for comparative study. The intimate contact between bio-ash and coal char grains is a prerequisite for the occurrence of the synergy effect in the co-gasification of coal and biomass. The separate bed configurations generally form either a coal-char/bio-ash or a bio-ash/coal-ash interface, whereas the pre-mixed bed configuration produces well-dispersed bio-ashes that come into close contact with coal char grains. As a result, a stronger synergy effect occurs in the mixed bed configuration rather than in the separate configuration. A novel method is explored to collect and determine the heavy tar and water yields generated during the initial pyrolysis step. Results show that bio-char bed has better tar cracking performance than coal char bed.

1. Introduction

Co-gasification of coal and biomass in existing coal-based systems is a promising approach to provide both environmental and economic benefits, including considerable reduction in CO_2 emission, less waste disposal problems, and low fuel cost. However, the use of biomass when co-gasified with coal may simultaneously exist technical risk in terms of deterioration of the system performance due to its inferior chemical and physical properties such as high moisture and volatile contents, low calorific value and bulk density, and fibrous structure. Therefore, proper choices of biomass/coal blends and system design and operation are essential.

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Previous studies on co-gasification have been carried out through different types of reactors such as thermogravimetric analyses (TGA) [1–4], fixed-bed reactor [5–9], and fluidized-bed reactor [10,11]. Much attention of these studies has been focused on whether there is any possible interaction or synergy between co-processed materials. If synergy occurs in coal/biomass blends, it is expected that an attractive possibility of improving the overall efficiency of the co-processing system is available, which can be in turn to mitigating the aforementioned technical risk. However, there is a contradiction on whether synergies occur even when studies have been conducted with the same type of facilities. For example, Fermoso et al. [6] and Howaniec et al. [5] reported that an improvement in hydrogen production and cold gas efficiency was achieved during the co-gasification of coal and biomass in a fixed bed reactor. However, Collot et al. [12] found some hints of synergy in the volatile yield in a fixed-bed reactor, but they were too small to constitute clear evidence of synergy. Contradictions on the existence of synergy between coal and biomass suggest that further systematic researches on this issue are needed.

Some scholars working on the topic of synergy have proposed the use of weighted average performance parameters as the criteria for evaluating synergy, i.e., a nonlinear increase in gas yield, char reactivity, or a nonlinear decrease in tar yield [2–4,13]. Three or more gasification tests on individual biomass, coal, and their blends with varying blending ratios should generally be conducted at the same setting temperature and a fixed gas flow rate. The synergy effect is then estimated from the deviation of weighted average and experimental parameters. However, the non-comparability of the weighted average and experimental performance parameters in some cases is an issue that has always been overlooked. For example, nonidentity in both the total and individual initial masses of coal and biomass may be linked to differences in both the external and internal diffusion effects of individual and co-gasification tests. A previous study revealed that the sample mass dependence of char reactivity could be misdiagnosed as synergy or inhibition as a result of the diffusion effect during the co-gasification of coal and biomass [14]. Furthermore, additional operational variables in terms of the gas-to-fuel ratio could not be avoided even by using a fixed gas flow rate.

Taken tar yield as a topic of the research, quantitative measurement of tar in the product gas is a great challenge. Some uncertainty always exists in this measurement, because tar is not well defined in literature. For example, it can refer to a sum of components with boiling points higher than 105 °C [15], or it may include all condensable organics with a molecular weight larger than benzene [16]. A large variety of sampling and analysis methods have been developed to determine the concentration of tar in the product gas, which makes uncertainty in tar definition and the comparison of data among researchers. Most tar measurements are based on cold solvent trapping (CST) in impinger trains with various organic solvents [16–19]. This type of sampling has drawbacks such as the long period for sampling, which provides limited information about transient gasifier conditions [18]. In addition, this methodology generally obtains a mixture of tar, solvents, and water. Evaporation or distillation must be taken for tar determination.

This study investigates the co-gasification of Chinese bituminous coal with forestry waste and the agricultural residue in CO_2 in a fixed bed mode. One mixed and two separate bed configurations with congruent mass are designed for comparative study. The study focuses on CO production, by which synergy effects between the co-processed fuels can be evaluated. A novel method to collect and determine the heavy tar and water yields during the initial pyrolysis step is also explored.

2. Experimental

2.1. Materials and analyses

The bituminous coal used in this study was collected from the Ningdong mine in the Ningxia Hui Autonomous Region, China. This coal sample is denoted by NBC hereafter. Chinese redwood (CR) and soybean stalk (SS) were selected as biomass samples. The former is a woody waste, while the latter is an agricultural residue. Both coal and biomass samples were ground and sieved into particle sizes of 0.25–0.71 mm. All the samples were used for experimental tests in an air-dried base.

2.2. Apparatus and procedures

The gasification tests for coal and biomass were performed in a fixed bed reactor. The schematic construction of the reactor is shown in Fig. 1. A quartz tube (400 mm high and 14 mm i.d.) was set vertically inside an electric furnace. The quartz filter was fixed in the quartz tube and located at the central heating zone of the furnace. The sample was previously placed in a tubular hopper (60 mm high and 14 mm i.d.) connected to the reaction tube by a manually controlled valve. The valve allowed only purge or reactant gas to pass through but completely stopped the sample particles when it was closed. The reactor was pre-heated to 850 °C. After keeping the said temperature constant for 5 min, the valve was opened, and the sample particles were dropped into the reactor tube. The gasification of individual coal, biomass, or their separate and mixed bed configurations was conducted isothermally at 850 °C in a mixed CO_2–N_2 stream (50 vol%). The total gas flowrate was always 200 mL/min.

A total of 1.0 g of NBC coal and 0.5 g of CR or SS were used for their individual gasification tests. For the study of the co-gasification of coal and biomass, three sets of bed configurations were designed: (1) 1.0 g of NBC was located above 0.5 g of the CR or SS bed in the tubular hopper, as shown in inset (a) of Fig. 1. This bed configuration is denoted by NBC/CR or NBC/SS. (2) 0.5 g of CR or SS was situated above 1.0 g of the NBC bed in the tubular hopper, as exhibited in inset (b) of Fig. 1 and represented by CR/NBC or SS/NBC. (3) 1.0 g of NBC was previously mixed with 0.5 g of CR or SS and then packed into the tubular hopper, as displayed in inset (c) of Fig. 1 and denoted by NBC-CR or NBC-SS. Preliminary tests were done to check the configurations when the samples were dropped from the tubular hopper into the reactor tube with mixed gas. In the present study, the tubular hopper and the reactor tube had the same inner diameter. It was confirmed that the samples dropped into the reactor tube kept their original configurations well as in the tubular hopper. All experiments were repeated 2–3 times and mean results were used to determine the synergy effect among different configurations.

Certain efforts were made to collect the tar and water produced in the initial pyrolysis/gasification step. The outlet of the reactor tube was series-connected with two dry condenser tubes and a chemical trap. The first condenser tube was an L-shaped quartz tube packed with quartz wool to stop the heavy tars. The second one was a straight Pyrex glass tube stored with polypropylene wool to adsorb light tars. The chemical trap was a U-glass tube in which 20 g of anhydrous $CaCl_2$ was placed to adsorb water. All condenser and trapping tubes were weighed before the experiments. The total yield of heavy and light tars was determined through the weight deviation of the first and second trapping tubes before and after gasification. The yield of water was evaluated from the weight deviation of the U-glass tube before and after gasification.