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Experimental study of torrefied pine as a gasification fuel using a bubbling fluidized bed gasifier

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ABSTRACT

Torrefied biomass has higher C/O ratio, resulting in improved heating value and reduced hygroscopic nature of the biomass, thus enabling longer storage times. In the southeastern United States, pine is has been identified as a potential feedstock for energy production. The objective of this study was to understand the performance of torrefied pine as a gasification fuel in a bench-scale bubbling fluidized bed gasifier. The gasification of torrefied pine was carried out at 790, 935 and 1000 °C and three equivalence ratios (ERs: 0.20, 0.25 and 0.30). The effect of process variables were studied based on i) products yield, ii) syngas composition iii) syngas energy content, and iv) contaminants. The mean concentration of CO increased with an increase in temperature, but was not statistically significant. On the other hand, H_2 concentration increased whereas CH_4 concentration decreased significantly with an increase in temperature from 790 to 935 °C. Further, with an increase in ER from 0.20 to 0.30, only CO_2 concentrations increased in the syngas. Results from torrefied pine were compared with raw pine gasification, and it was observed that torrefied pine gasification led to much higher char yield (more than twice) than pine; however, it produced less than half as much tar.

1. Introduction

The energy production from coal has drastically decreased with recent increase in natural gas production [1]. Along with increase in natural gas production, the improved emission standards have forced several coal power plants in the United States to use it. One alternative to its usage is to explore coal-biomass co-feeding scenarios that can help meet the emissions standard. In the southeastern U.S., the abundant forest resources provide the opportunity for co-feeding biomass with coal to help meet the emission goals [2–4]. However, several issues such as low energy density, high moisture content, low bulk density, higher transportation cost and low grindability associated with the raw biomass impede coal-biomass co-feeding [5–7]. Therefore, biomass pretreatment has been suggested to improve its properties and enable co-feeding in existing coal plants [8,9]. Torrefaction is one such pretreatment method. During this process hemicellulose is decomposed and increases grindability of biomass, improves energy and carbon content, and bulk density while reducing the hygroscopic nature, and thus making biomass handling easier [8–13]. One of the key benefits of this process is increase in biomass energy and carbon content closer to that of coal. This makes torrefied biomass an excellent choice for co-feeding with coal for power generation purposes.

A handful of studies have been performed on understanding the characteristics of torrefied biomass and its effect on syngas composition from gasification [14–19]. Some studies have conducted bench-scale studies to understand effect of densification along with torrefaction [16], while others have performed simulations [15] to understand performance of torrefied biomass. A few pilot scale studies have also been reported [14,17]. However, only a few of these studies have reported the contaminants released along with the primary syngas composition [14]. Couple of studies with torrefied biomass have been conducted using downdraft gasifiers [14,16]. The torrefaction or pretreatment of biomass affects the

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syngas production and composition. Kuo et al. [15] studied performance of torrefied bamboo using thermodynamic simulation and observed that torrefied bamboo produced lower hydrogen concentration and higher CO production. While Strandberg et al. [18] observed a reduction in methane production from torrefied saw dust when compared with raw saw dust in a pilot-scale entrained flow gasifier. Gasification of torrefied biomass in a downdraft gasifier [14,17] produced syngas with comparable syngas composition and energy content with raw biomass samples. However, Dudyński et al. [14] reported unstable temperature inside gasifier during torrefied biomass gasification. Sarkar et al. [16] suggested that when torrefaction was accompanied by densification, the syngas composition and carbon conversion increased. A study on torrefied Miscanthus x giganteus by Xue et al. [19] on a TGA suggested that torrefied biomass favored gasification at higher temperatures (above 850 °C).

It is clear based on the information available in the open literature that there is no study on torrefied biomass in a fluidized bed gasifier. If a large scale application is desired then it is important to understand the performance of torrefied biomass as a feedstock in a fluidized bed gasifier. The availability of pine in the Southeast and growing interest in torrefaction as a pretreatment process encouraged a comprehensive study of torrefied pine as a gasification fuel in a bubbling fluidized bed gasifier. The objective of this study was to experimentally investigate the performance of torrefied pine at three temperatures and equivalence ratios (ERs) based on the syngas composition (CO, CO_2, CH_4, H_2, C_2H_2, C_2H_4), syngas energy, cold gas efficiency and the contaminants (HCl, HF, NH_3, HCN, SO_2 COS and tar) produced when gasified using a bench-scale bubbling fluidized bed with sand as the bed material. A comparison was made between torrefied and raw pine gasification to better understand the effect of torrefaction on the performance of pine.

2. Materials and methodology

2.1. Materials

Southern pine was used for this gasification. Torrefied pine was obtained in the pelletized form whereas raw pine biomass (same biomass that was used for torrefaction) was received in chips from New Biomass Energy, LLC (Quintman, Mississippi). The pellets were ground and sieved through a 850 μm sieve before feeding into the gasifier. In the case of raw pine chips, they were first air-dried, ground, and also sieved through the same screen prior to gasification. The elemental analysis of biomass was performed using CHNS/O analyzer (Perkin Elmer, model 2400, Waltham, MA) and the higher heating value was obtained using bomb calorimeter (IKA Bomb Calorimeter, Model C-200, Wilmington, NC). The ash content, volatile matter and moisture content were performed according to ASTM D1102, BS EN 15148:2009, and ASTM E871, respectively. Structural carbohydrates and lignin were measured using an NREL (National Renewable Energy Laboratory) Laboratory Analytical Procedure (LAP) entitled "Determination of structural carbohydrates and lignin in biomass" [20].

2.2. Experimental setup

The experiments were carried out using a bench-scale bubbling fluidized bed gasification rig. A detailed description of this set up has been presented elsewhere [21]. Briefly, the set-up consisted of a hopper, an auger feeder, a fluidized bed gasifier, a high temperature filter unit (HTF), a pair of condensers, an electrostatic precipitator and a tar analysis impinger train. The bubbling fluidized bed gasifier had a diameter of two inches (0.0508 m) and a freeboard with diameter of four inches (0.1016 m). The overall height of the gasifier was 30 inches (0.762 m), while the freeboard was 6 inches (0.1524 m) high. The biomass was stored in the hopper and fed into the gasifier with the help of the auger feeder. Oxygen and nitrogen were used for gasification as the oxidizing and the fluidizing agent, respectively. The flow rate of the nitrogen supplied for fluidization was kept constant at 15 l/min and the corresponding superficial velocity was 0.12 m/s with Reynolds number of 1.11 at NTP. The flow rate of oxygen supplied was varied to achieve the target ER. ER was defined as the ratio of the actual amount of oxygen supplied to the gasifier to the amount of oxygen required for complete combustion of a given quantity of biomass [21].

2.3. Data sampling and analysis

Char and liquid condensate yields were gravimetrically calculated and the char was further analyzed using Perkin Elmer elemental analyzer for elemental composition. Tar collection method has been described in details in published document [21]. This tar collected was later analyzed using an Agilent GC-FID. The GC inlet and FID detector temperature were both maintained at 250 °C and the oven ramped at 5 °C/min from 40 °C to 250 °C. Gas components (CO, CO_2, CH_4, H_2, C_2H_2, and C_2H_4) and contaminants (HCl, HF, NH_3, HCN, SO_2 COS) were collected as discussed in details by Abdoulmoumine et al. [21]. The cold gas efficiency was calculated from syngas composition as shown in Eq. (1). It is defined as the ratio of the sum of the heating values (LHV) of the primary syngas components to that of the LHV (which was calculated from HHV) of the biomass. This efficiency showed how much energy in the biomass was converted to useful syngas components.

$$\text{Cold gas efficiency} = 100 \times \frac{\sum \text{Heating value of syngas component i} \times \text{volumetric flow rate of syngas i}}{\text{LHV of biomass} \times \text{biomass feed rate}} \quad (1)$$

2.4. Experimental design and statistical analysis

Several studies [14,16,21] have reported gasification with an ER ranging from 0.2 to 0.4 and a temperature range of 600–900 °C. In this study, the experiments were carried out at an ER of 0.25 at 790, 935, and 1000 °C and ER of 0.20, 0.25, and 0.30 at 935 °C to study the effect of the temperature and the ER on the gasification products, respectively. A limited number of raw pine gasification experiments were performed at feed rate of approximately 9 g/min to compare the results with the torrefied pine under similar conditions (ER 0.25, temperature 935 °C and feed rate ~9 g/min). The data presented in Section 3 are the average of three runs for every ER and temperature unless otherwise noted. Statistical analysis was carried out using 1-