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Oxygen-blown gasification of pine charcoal in a top-lit downdraft moving-hearth gasifier

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HIGHLIGHTS

- We describe a novel oxygen-blown top-lit downdraft moving-hearth gasifier.
- We study the effect of process variables on syngas quality and gasification rates.
- We compare simulated and experimental results.
- We find out the hearth loads and turndown ratio of this type of gasifier.

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ABSTRACT

The design of an efficient biomass gasifier is essential for the development and practical realization of biomass-to-fuels processes. The study of pine charcoal steam/oxygen gasification in a top-lit downdraft moving-hearth gasifier is presented in this paper. A thermodynamic analysis of the charcoal (C)–H_2O–O_2 system was conducted and the composition of the product gas, its lower heating value and the gasifier reduction zone temperature were predicted based on a number of assumptions. A series of the gasifier operations where oxygen flow rate and $[H_2O]/[O_2]$ molar ratio were process variables was conducted. It was found that in the range of O_2 flow rates tested (1–5 g/min), higher flow rates of oxygen resulted in higher concentrations of H_2 and CO as well as higher charcoal gasification rates. Likewise, increasing the $[H_2O]/[O_2]$ ratio resulted in higher H_2/CO ratio in the product gas as well as higher charcoal gasification rate. The minimum and maximum values of the gasifier hearth loads were estimated. The experimental results obtained underscored the importance of maintaining efficient heat transfer within the gasifier and reducing heat loses to the surroundings.

1. Introduction

There has been a renewed interest in utilizing biomass for the production of fuels and chemicals due to high oil prices and concerns over negative environmental impact of fossil fuel use. Biomass can be converted to fuels via biochemical and thermochemical processes. Thermochemical biomass conversion processes include, among others:

- gasification – with production of synthesis gas (or producer gas) which can be further converted to liquid fuels, chemicals and power [1–3],
- pyrolysis – to derive pyrolysis oil (or bio-oil) which can be further converted to fuels and chemicals [4–6], and
- hydrothermal liquefaction where biomass is treated with water at high temperature and pressure to produce oily products [7–9].

Gasification of carbonaceous feedstocks, particularly, coal is a well-established century old technology [10]. However, gasification of biomass is relatively new. Commercial gasifiers fall into three categories – fixed bed, fluidized bed and entrained bed. Each gasifier type has its own advantages and disadvantages with regard to the nature of available biomass feedstock. Fixed bed gasifiers are further divided into downdraft, updraft and cross flow gasifiers [11]. One challenge with fixed bed gasifiers is the movement of fuel bed across various zones, i.e., drying, pyrolysis, reduction and combustion zones. Bridging and channeling could occur in the feed bed reactors which is primarily due to fibrous, hygroscopic and non-uniform nature of most biomass feedstock [12,13]. These issues can be somewhat mitigated by continuous agitation of the bed materials. Likewise, ash removal can present a challenge especially in stratified downdraft gasifier resulting in a large pressure drop (if ash is not removed by a rotating grate) [14].

Here, we present the experimental data obtained for a semi-continuous, top-lit downdraft gasifier. The gasifier had a simple design and did not require mechanical agitation in order to affect continuous movement of the biomass feed. The most obvious

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disadvantage of the moving-hearth design is the semi-continuous nature of the system where fresh biomass feed must be fed to the gasifier after completion of the previous charge/load consumption (when the hearth reaches the grate). This is not an issue if two identical gasifiers were to operate in tandem.

2. Experimental

2.1. Gasifier design and operation

The gasifier was fabricated using a seamless aluminum tube having an ID of 10.2 cm and OD of 11.4 cm, and an overall length of 82.8 cm. The gasifier outer shell was shielded from inside using a ceramic composite made up of clay (Sybil's cone 6 stoneware clay) and silicon carbide (SiC powder, mesh size 35, Unasil 35, Universal Photonics, Hicksville, NY). The clay was mixed in 3:1 volume ratio with SiC. Addition of SiC to clay increases material's resistance to thermal shock. The clay-SiC paste was molded into a cylindrical shape inside the aluminum tube, dried at 120 °C overnight, and then temperature was ramped at a rate of 2.5 °C/min till the temperature reached 1200 °C, and kept at that temperature for 1 h before letting it cool down. The cylindrical insulating cast was wrapped with a ceramic insulation tape and snugly fit into the aluminum tube. With the insulator in place, the internal diameter of the gasifier was 7.6 cm. The outer shell temperature of the gasifier did not exceed 200 °C during gasification runs. Fig. 1 shows a schematic diagram of the tandem biomass gasification system concept.

The gasifiers operate in a top-lit downdraft mode. Oxygen and water enter from the top and producer gas exits from the bottom. The oxygen flow was metered by a rotameter. Saturated steam was generated using an electric water boiler (MBA-6 Sussman Electric Boilers, Long Island City, NY) and dispensed via a needle valve in the requisite amount into the gasifier. The exit gas from the gasifier entered a condenser operating at 0 °C for separating out water and tarry gasification products. The effluent gas was then passed through an activated charcoal (Fisherbrand™ Activated Carbon Charcoal, 6–14 mesh, Fisher Scientific, USA) bed before passing through a rotameter. The overall process flow diagram is shown in Fig. 2. The exit gas was periodically sampled using Tedlar sampling bags and its composition was determined using a Varian 450 gas chromatograph (Varian Inc., Palo Alto, CA) equipped with a thermal conductivity detector (TCD) and a flame ionization detector (FID); and PLOT alumina/KCL, Molecular sieve 13X and Haysep Q columns. Argon was used as the carrier gas.

The start-up procedure of the gasifier consisted of filling the unit with pre-determined amount of charcoal and then placing hot amber charcoal pieces at the top while O_2 flowed into the gasifier. Once the top layer of charcoal was visually observed to be even glowing red hot, the gasifier was sealed off and steam flow established.

2.2. Feedstock preparation and characterization

The feedstock used for the gasification experiments was charcoal made from pine wood pellets. The fresh pine wood pellets were obtained from Green Circle Bioenergy Inc. (Cottondale, Florida). These pellets were approximately 2.5 cm in length and 0.8 cm in diameter. The set-up for making charcoal consisted of a cylindrical riser sleeve filled with pine wood pellets. A nozzle for air/oxygen flow was placed below the riser sleeve. Initially, a red hot charcoal was placed on the top of the pine pellets with oxygen flowing up from the bottom. Cinder blocks were placed on the top leaving a small opening to allow for the pyrolysis vapors to escape. The flow was then switched to air so that only pyrolysis vapors were seen escaping without ignition. The pine wood pellets were stirred from time to time so as to allow homogenous devolatilization of the pellets. The charcoal was removed when the pellets appeared completely charred. The smoldering charcoal was placed in a metal bucket and covered with a lid (cutting off the air supply), thus stopping further oxidation.

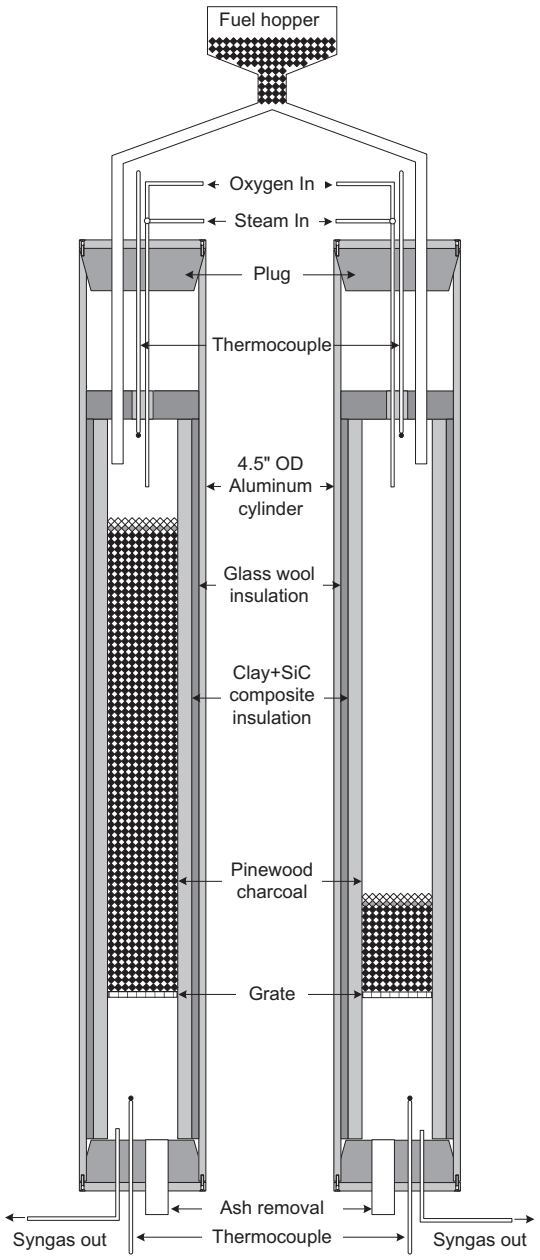

Fig. 1. Schematic diagram of depicting tandem top-lit downdraft gasification system.

Proximate analysis of the pine wood and pine charcoal was conducted using a Perkin Elmer Diamond thermogravimetric analyzer (TGA). Helium was used as the carrier gas and sample temperature was increased from 50 to 950 °C at a rate of 10 °C/min. Percentages of moisture, volatiles and fixed carbon were calculated from the TGA runs. Percentage of ash in the feed was determined by placing a known quantity of pine wood (or pine charcoal) in a crucible and heating it to 800 °C for three hours inside a furnace in the presence of air.