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Gasification performance of switchgrass pretreated with torrefaction and densification

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HIGHLIGHTS

- We evaluated effects of switchgrass torrefaction and densification on the syngas.
- The pretreatment and gasification temperature significantly effected performance.
- Combined torrefaction and densification had the highest gas yield and efficiencies.
- Increase in gasification temperature increased the gas yield and efficiencies.

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ABSTRACT

The purpose of this study was to investigate gasification performance of four switchgrass pretreatments (torrefaction at 230 and 270 °C, densification, and combined torrefaction and densification) and three gasification temperatures (700, 800 and 900 °C). Gasification was performed in a fixed-bed externally heated reactor with air as an oxidizing agent. Switchgrass pretreatment and gasification temperature had significant effects on gasification performance such as gas yields, syngas lower heating value (LHV), and carbon conversion and cold gas efficiencies. With an increase in the gasification temperature, yields of H_2 and CO, syngas LHV, and gasifier efficiencies increased whereas CH_4, CO_2 and N_2 yields decreased. Among all switchgrass pretreatments, gasification performance of switchgrass with combined torrefaction and densification was the best followed by that of densified, raw and torrefied switchgrass. Gasification of combined torrefied and densified switchgrass resulted in the highest yields of H_2 (0.03 kg/kg biomass) and CO (0.72 kg/kg biomass), highest syngas LHV (5.08 MJ m^{-3}), CCE (92.53%), and CGE (68.40%) at the gasification temperature of 900 °C.

1. Introduction

The increase in the world population to 7 billion and further projected increase to 10 billion has increased awareness about the need of more resources to supply energy, food and other consumable products [1]. Currently, a huge proportion of the demand for energy and chemicals are met by fossil fuels that are non-renewable, increase greenhouse gas (GHG) emissions and make many countries heavily dependent on import. The fossil fuels can be replaced with second generation biofuels, derived from lignocellulosic feedstocks, agricultural residues and their byproducts [2]. Biomass, an organic plant-based material, converts solar energy and carbon dioxide into chemical energy through photosynthesis. Since sunlight is a sustainable resource, biomass can be generated through photosynthesis on a sustainable basis, which makes the biomass a renewable resource that can be utilized worldwide.

Switchgrass (*Panicum virgatum* L.), a native North American perennial lignocellulosic grass grown in the central USA is one of the ideal biomass feedstocks due to its high crop yield (10–12 t/ha/annum) [3], adaptation to soil and climatic conditions and minimal requirement of fertilizers to grow the biomass [4,5]. However, certain properties of switchgrass [3] (similar to the properties of other biomass feedstocks) such as high moisture content, low bulk density, low calorific value, high volatile and oxygen contents, and its tenacious and fibrous nature create challenges to store the biomass for long hours, to transport and convert efficiently into fuels and other products [6,7]. Pretreatments such as torrefaction and densification have potential to improve the properties of biomass such as switchgrass making it a better feedstocks for conversion

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into fuels and chemicals [8]. Torrefaction, a thermochemical process, taking place at temperatures ranging between 200 and 300 °C in an inert atmosphere, produces a hydrophobic product which prevents the biomass from getting decomposed when exposed to the atmosphere [9]. The product obtained also has higher heating value (HHV) and a high energy density [10]. Densification converts loose biomass into pellets having less fines, high uniformity and high bulk density that can possibly solve challenges in storing and transporting biomass [11,12]. A combination of torrefaction and densification may further increase conversion efficiency, and reduce storage and transportation costs as this pretreatment leads to a more uniform hydrophobic product with high energy and bulk densities [6,13,14].

The second generation biofuels are produced through two distinct conversion processes namely the biochemical and thermochemical conversions. The biochemical conversion consists of enzymatic transformation of cellulose and hemicellulose to sugars and further fermentation into ethanol and higher alcohols [2,15], whereas, the thermochemical conversion uses heat and catalysts to convert biomass into intermediate products, syngas and bio-oil through gasification and pyrolysis, respectively [16]. The syngas (gasification intermediate) is composed of carbon monoxide, carbon dioxide, hydrogen, nitrogen (if air is used as oxidizing agent), and small quantities of hydrocarbons such as methane, ethane etc. The syngas can further be converted into useful fuels (gasoline and diesel), chemicals (methanol and ethanol) through catalytic and microbial processes [17]. The gasification can take place in a variety of reactors such as fixed bed (updraft, downdraft and cross draft, batch) and fluidized bed (bubbling and circulating) gasifiers [18]. Fixed bed gasifiers are advantageous over fluidized bed gasifiers especially for small scale applications as the design of fixed bed gasifiers is simple, less expensive and are suitable for biomass combustion, biomass gasification, small scale power generation and industrial heating applications [19]. Fluidized bed gasifiers (FBG) are more suitable for large scale applications because of their higher mass and heat transfer efficiencies but FBG are also more complex in design and operation as compared to fixed bed gasifiers [20]. This paper reports study on a fixed-bed gasifier.

The gasification performance of raw and pretreated biomass can be evaluated based on the concentration and yield of syngas, and energy and carbon conversion efficiencies. Gasification performances of several types of raw biomass feedstocks and gasifiers have been extensively reported in literature [21–30]. Limited studies have also been reported on gasification of pretreated biomass except switchgrass [7,31,32]. Bibens [7] investigated the downdraft gasification performance of pine chips torrefied at 250, 275 and 300 °C for 30 and 60 min and concluded that at a gasifier temperature of 800 °C and an equivalence ratio (ER) of 0.25, with an increase in the torrefaction temperature and time, the syngas HHV, and syngas yield and net energy output per unit of material increased. By fluidized-bed air gasification of raw and torrefied (at 250 and 300 °C) wood at a gasifier temperature of 950 °C, Prins et al. [31] observed that the overall exergetic efficiency of torrefied wood was lower than of raw wood because part of the biomass energy was lost in volatiles during torrefaction. With high-temperature air/steam gasification of densified wood pellets in an updraft gasifier using preheated air and steam, Lucas et al. [32] observed that an increase in the gasifier temperature from 350 to 900 °C increased the gas yield and HHV, and reduced production of tars, soot and char. However, to our knowledge, there is no literature available on gasification of switchgrass pretreated with torrefaction and densification.

The goal of this study was to investigate the effects of four pretreatment (torrefaction at 230 and 270 °C, pelletization, and combined torrefaction and pelletization) and three gasification temperature (700, 800 and 900 °C) on the gasification performance of switchgrass.

2. Materials and methods

2.1. Biomass feedstock

Kanlow Switchgrass (*P. Virgatum*) grown at the Plant and Soil Sciences department at Oklahoma State University was used as the biomass. Bales of Kanlow switchgrass were chopped using a Haybuster tub grinder (H1000, Duratech Industries International Inc., Jamestown, N.D) with a screen size of 25 mm. A portion of chopped switchgrass was further ground using a hammer mill (Bliss Industries, Ponca City, Oklahoma) with a mesh size of 4 mm. Chopped switchgrass was used for all torrefaction pretreatments and ground switchgrass was used for pelletization (densification) pretreatments at the Idaho National Laboratory (INL, Idaho Falls, Idaho).

2.2. Torrefaction

A moving-bed gravity-fed atmospheric pressure thermal treatment system was used to torrefy switchgrass (Fig. 1). It consisted of horizontal auger-driven sections to feed material into and out of a vertical, central reactor with diameter and height of 0.305 and 1.68 m, respectively. The details and schematic of the torrefaction unit can be found elsewhere [33]. The ground switchgrass was weighed and manually loaded into the feeder hopper. Biomass was then metered into the torrefaction reactor through a rotary airlock and a horizontal auger rotating at 0.4 RPM. The exterior of the reactor was heated using band heater and the biomass temperature was monitored at six different points along the reactor section. A stirrer was provided in the reactor to prevent bridging of particles. Biomass samples were torrefied for 30 min at temperatures of 230 and 270 °C. Torrefied biomass exited at the reactor bottom and was removed via a horizontal auger that cooled the material to about 50 °C before it exited through the twin knife-blade air locks. The residence time of the material in the torrefaction reactor can be controlled between 15 min and 1 h by adjusting the speed of the out-feed auger. An inert environment was maintained in the reactor by injecting clean nitrogen gas (heated to the desired torrefaction temperature of 230 and 270 °C) into the sides and bottom of the vertical thermal section. The inert gas, combined with process off-gas exited from the thermal unit at the upper end in a counter flow configuration. The gas was then passed through a heated cyclone separator to remove the particulates and then to a thermal oxidizer to burn the combustibles. After exiting the thermal oxidizer, the gas stream passed through an enlarged knockout vessel that provided velocity reduction and slight cooling to allow condensable constituents to drop out of the steam for separate collection. The gas was then reheated prior to recycling into the reactor. The cooled torrefied material collected was stored in air tight barrels.

2.3. Densification

A laboratory-scale flat-die pellet mill (model ECO-10, Colorado Mill Equipment) with a 10 HP, 460-volt, 3-phase motor was used for the pelletization (densification). This machine has been designed for research and development applications for testing the pelletability of variety of raw and pretreated biomass. The rated output of this pellet mill was 30–50 kg/h. The pellet mill was equipped with a hopper to hold the biomass and a screw feeder to uniformly feed biomass into the pellet mill. A flexible rectangular heater (Silicon Rubber Heater, Branom Instrument, WA)