Biomass and Bioenergy 110 (2018) 98–104

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

Research paper

Bubbling fluidized bed gasification of short rotation *Eucalyptus*: Effect of harvesting age and bark

Phillip Cross, Avanti Kulkarni, Hyungseok Nam, Sushil Adhikari*, Oladiran Fasina

Biosystems Engineering Department, Auburn University, Auburn, AL, 36849, United States

ARTICLE INFO

Keywords:
Eucalyptus
Bubbling fluidized bed
Gasification
Bark
Harvesting age
Bed height

ABSTRACT

The improvement of syngas production and reduction of tar contaminants from biomass gasification was achieved by altering feedstock age and the presence/absence of bark in combination with adjusting the amount of bed material within the bubbling fluidized bed reactor. *Eucalyptus benthamii* is a promising biomass source for the gasification process, and can be grown as a short rotation bioenergy crop allowing for selective growth cycles. Three *E. benthamii* samples harvested at two years with bark (2EWB), two years without bark (2EWoB), and seven years without bark (7EWoB) were used for this work. Upon gasification, the highest CH_4 gas concentration was obtained from 7EWoB sample, which led to the highest syngas heating value of 3.8 MJ m^{-3}. Alternatively, the highest H_2 gas yield was obtained from 2EWB sample. The presence of bark also significantly affected CO and CH_4 gas yields. Major tar compounds in the syngas were benzene, naphthalene, toluene and indene. Almost twice the amount of naphthalene and indene was obtained with older samples (7EWoB) compared to young samples (2EWoB and 2EWB). It was established that the presence of bark (2EWB) led to higher char yields and lower gas yields, which ultimately led to a lower syngas heating value (3.08 MJ m^{-3}). Utilizing different amounts of non-catalytic silicon sand as bed material during gasification of 2EWB allowed for improved syngas heating value by producing more CH_4. Higher amounts of bed material also lead to a higher conversion of char and improved syngas yields; however, tar yields also increased.

1. Introduction

Gasification of lignocellulosic biomass for the production of renewable fuels and chemicals is somewhat mature technology [1–3]. Gasification is a partial combustion of biomass, which produces valuable gases to be used as a direct fuel source or upgraded to more valuable liquid fuels and chemicals [4,5]. Using high temperatures (600 °C-1000 °C), low oxygen levels (0.20–0.45 of equivalence ratio, ER), gasification deconstructs and converts the main substituents of biomass (cellulose, hemicellulose and lignin) into gas product, known as syngas, solid char, liquid tar, and other contaminants (ammonia, hydrogen sulfide, and others) [1–3,6–8]. Pressure has also been studied for this technology [9]. Several reactor designs exist for biomass gasification [10,11]. Fluidized beds are of primary interest for this technology and mainly consist of circulating flow gasifiers [12] and bubbling fluidized bed gasifiers [13]. A major hurdle for gasification comes from the complexity of biomass leading to mixed reactions and the formation of aromatic contaminants that are costly to eliminate. These organic compounds with a molecular weight equal to or greater than benzene (78 g mol^{-1}) are classified as tar. The reduction of tar is the most important hurdle for the industrialization of gasification technology [2,3]. Lowering the level of tar can be somewhat accomplished by selecting appropriate biomass and reaction conditions. Carpenter et al. [4] studied gasification of different biomass (hardwood, softwood, herbaceous grasses and agricultural residues). Biomass type was shown to alter the abundance of aromatic tar compounds generated during gasification along with primary gas yield. In their study, the highest observed tar yield from wood was 270 g m^{-3} (0 °C, 101 kPa) while corn stover, switchgrass and wheat straw reached 370 g m^{-3} (0 °C, 101 kPa). Wood also showed a higher hydrogen mass yield of approximately 13% on average, and a higher total gas yield of 31% on average.

In the southeastern United States, *E. benthamii* is an emerging short rotation bioenergy crop. Plantations can produce a volume of 5120 m^3 km^{-2} of *E. benthamii* after 34 months, while that of *Pinus radiata* is 2970 m^3 km^{-2} at an equivalent age [14]. *E. benthamii*, grown in southern Florida by ArborGen (ArborGen, Inc., Ridgeville, SC), can produce 2700–3500 tonne km^{-2} year^{-1} on a 7-year rotation, and 3100–4000 tonne km^{-2} year^{-1} on a 3-year rotation [14]. Short rotation also provides the possibility of harvesting trees at a specific age to alter the chemical makeup, and thus potentially changing the product

* Corresponding author.
E-mail address: sushil.adhikari@auburn.edu (S. Adhikari).

https://doi.org/10.1016/j.biombioe.2018.01.014
Received 14 February 2017; Received in revised form 18 January 2018; Accepted 20 January 2018
0961-9534/

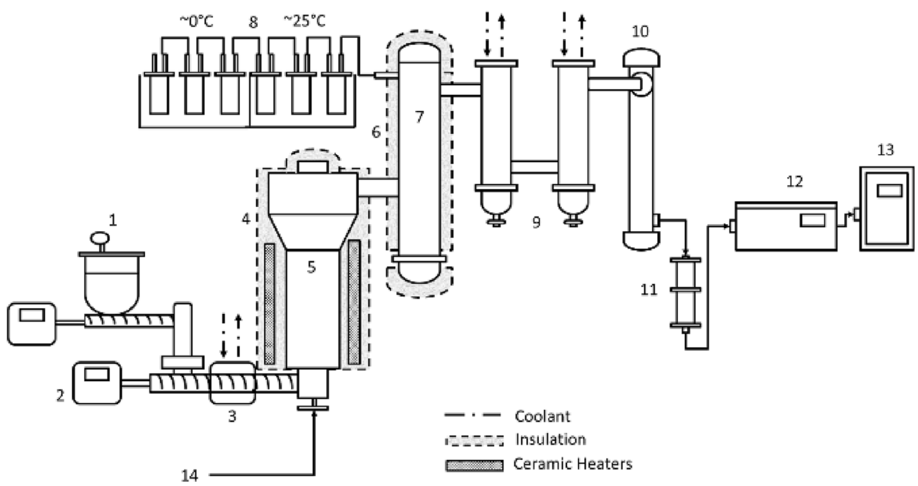

Fig. 1. Schematic diagram of gasification unit. 1: Biomass hopper; 2. Injection screw; 3. Heat exchanger; 4. Insulation and heaters; 5. Fluidized bed reactor; 6. Insulation and heaters; 7. High temperature filter; 8. Impinger train; 9. Condensers; 10. Electrostatic precipitator (ESP); 11. Charcoal filter; 12. FTIR gas analyzer; 13. NOVA gas analyzer; 14. O_2 and N_2 gas inlet.

slate of gasification. Rencoret et al. [15] studied effects of harvesting age on chemical compositions of *Eucalyptus globulus*. Samples harvested after 1 month, 18 months and 9 years were evaluated. The mass fraction of lignin varied from 16% with 1 month old trees to 25% with 9-year-old trees. Also, lignin composition of syringyl (S), guaiacol (G) and p-hydroxyphenyl (H) were changed as well. S/G ratio was 1.4 for the youngest samples (1 month) whereas 3.8 for the oldest (9 years). The amount of H type lignin fell from 9% to 2% with age. Indicating that lignin monomers are deposited at different times of the trees life, first H type lignin is deposited then G, and finally S. Additionally, there was a decrease in acetone extractives, water soluble material and ash with increasing age. Senelwa et al. [16] studied fuel characteristics of twelve different woody biomass at different ages; 3 years, 4 years and 5 years. This work also investigated differences in fuel characteristics of bark versus the inner wood including the heartwood and sapwood. It was found that the only differences between whole wood samples (heartwood, sapwood and bark) of different age were the basic density and the mass fraction of bark. Average wood basic density increased from 362 $kg\,m^{-3}$ at 3 years to 376 $kg\,m^{-3}$ at 5 years. The mass fraction of bark present in the different samples decreased from 14% at 3 years to 11% at 5 years, which affects the fuel properties of the sample due to the different chemical composition of bark compared to inner wood (sapwood and heartwood). Bark tends to have a high lignin mass fraction as well as alkali and alkaline earth metal salts, which affect the results of proximate analysis and higher heating value. Hanaoka et al. [17] determined that the light gas yield from Japanese red pine bark gasification was similar to the lignin gasification with respect to the CO, H_2 and CH_4 yields. Additionally, the total gas and tar yields from bark samples were lower than that of the whole Japanese oak due to a high lignin and low sugar content of bark.

In combination with feedstock selection, the amount of bed material is one parameter that can influence the formation of tar and syngas during bubbling fluidized bed gasification [18,19]. Mayerhofer et al. [19] studied the formation of tar and syngas at different heights of a bubbling fluidizing bed. The bed height to inner diameter of the reactor (H/D) ratio was varied at two points (3.25 and 5.84) showing different syngas samples. At higher H/D ratios the syngas yields increased, however, there was also an increase in the total tar yields. Wan Ab Karim Ghani et al. [18] studied the syngas production using palm kernel shells and coconut shells in a bubbling fluidized bed reactor by varying the H/D from 0.167 to 0.583. CO_2 yield increased at different ratios while the trends of other gases were dependent on the feedstock. Palm kernel shells have a proximate analysis more closely related to that of woody biomass and showed a decrease in H_2 yields while CO, CO_2 and CH_4 yields increased. Thus, the previous studies suggest that H/D ratio is an import parameter in the optimization of gasification performance with results dependent on feedstock and therefore further gasification study using short rotation biomass, *E. benthamii*, is of value to this technology.

The objectives of the current study were to investigate 1) gasification performance of short rotation *E. benthamii* biomass as energy crop in terms of product yields, 2) syngas composition as well as tar yield with regards to tree harvested age and the presence/absence of bark, and 3) the effect of alteration of fluidized bed H/D ratio on syngas for a non-catalytic bubbling fluidized bed bench-scale reactor with O_2 as oxidizing medium.

2. Experimental

2.1. Feedstock and characterization

Eucalyptus benthamii (*E. benthamii*) samples were obtained from ArborGen's plantation in South Florida and included 2-years old with bark (2EWB), 2-years old without bark (2EWoB), and 7-years old without bark (7EWoB). Additionally, *Pinus taeda* (loblolly pine) was used for comparison. Samples were air dried to have a moisture content less than 15% before being ground with a hammer mill (C.S. Bell Co., model 10HBLPK, Tiffin, OH, USA) and sieved with a screen size of 1.58 mm. Proximate, ultimate, and chemical analyses were performed to characterize biomass samples. A detailed description of the bubbling fluidized bed reactor equipment and methods can be found in a paper by Abdoulmoumine et al. [20] In addition to biomass analysis, elemental compositions of the inorganic ash were also conducted using ICP-OES, PerkinElmer Life Sciences 9300-DV system. Pyrolysis gas chromatography (Py/GC-MS) was used to study the lignin monomers released during mild pyrolysis. This method has been used to estimate S, G and H type lignin [15].

2.2. Gasification unit and operation

The bubbling fluidized bed gasifier used in this study is shown in Fig. 1. *E. benthamii* sample stored in the hopper was continuously fed using a screw feeder. An average biomass feed rate of 5.8 $g\,min^{-1}$ was used. Equivalence ratio (ER) was maintained at 0.22 by feeding a mixture of nitrogen and oxygen to the bottom of the reactor. Specific details of the reactor dimensions can be found in a paper by Abdoulmoumine et al. [20] Gasification was carried out at 935 °C with a static bed height of 6.4 cm (1.89 H/D) unless otherwise noted. Non-catalytic silicon sand with an average particle diameter of 0.03 cm was used as bed material. For comparison purpose, *P. taeda* was gasified at the same operating conditions. Bed height experiments used the same flow rate (15 L/min N_2) for all experiments and no attempt was made to adjust fluidization mechanics to offset the effects of altering bed height.

All solid, liquid and gas streams in and out of the reactor were