

The Effect of Air Flow Rate and Biomass Type on the Performance of an Updraft Biomass Gasifier

Arthur M. James,^a Wenqiao Yuan,^{a,*} Michael D. Boyette,^a and Donghai Wang^b

Airflow and the type of biomass are the two most important factors influencing the performance of a biomass gasifier. In this research, the effects of air flow rate (air-fuel equivalence ratios of 0.21, 0.25, and 0.29) and biomass type (woody biomass, agricultural residue, and perennial grass) on the performance of an updraft biomass gasifier were evaluated based on its tar and producer gas generation. It was found that increasing airflow increased the formation of tar species for all biomass types studied, but no significant differences in producer gas composition were found when the air-fuel equivalence ratio was changed. Thus, air-fuel equivalence ratios ranging from 0.21 to 0.25 were deemed appropriate for minimal tar generation. The results also showed that different biomass types generated producer gas with significantly different tar contents: woodchips yielded the most tar, followed by sorghum stover and prairie hay. The higher heating value of producer gas from various biomass types was also significantly different. Wood chip-derived producer gas had the greatest higher heating value, followed by prairie hay and sorghum stover. The carbon monoxide content in the produce gas of the three biomass types also exhibited significant differences with varying biomass type, similar to the higher heating value, but there were no significant differences in the H₂ content with varying biomass type or airflow.

Keywords: Gasification; Biomass; Producer gas; Updraft gasifier; Tar; Air-fuel equivalence ratio

Contact information: a: Department of Biological and Agricultural Engineering, North Carolina State University, Campus Box 7625, Raleigh, NC 27695 USA; b: Department of Biological and Agricultural Engineering, Kansas State University, 129 Seaton Hall, Manhattan, KS 66506 USA;

* Corresponding author: wyuan2@ncsu.edu

INTRODUCTION

Biomass gasification is an effective way to convert solid biomass into useful biofuels. Gasification is a theoretically complicated, often incompletely understood thermochemical process in which biomass materials experience incomplete combustion in a medium such as air, oxygen, or steam to produce a combustible gas called producer gas or synthesis gas. This gas is a mixture of hydrogen, carbon monoxide, carbon dioxide, water, nitrogen, and small amounts of methane and higher hydrocarbons (Lucas *et al.* 2004). The producer gas can be burned directly in furnaces, boilers, stoves, internal combustion engines, or micro-turbines for heat or power generation (Knoef 2005). It can also be further converted into a wide variety of useful, high-value petrochemicals or transportation fuels such as synthetic diesel (*via* the Fischer-Tropsch method), ethanol (*via* fermentation), and dimethyl ether and methanol (*via* catalytic reactions) (Hasan *et al.* 2010).

Gasification performance depends on the reactor design and the operational conditions. Gasifiers can be broadly categorized as fixed-bed or fluidized bed reactors.

Fixed-bed reactors are simple to build and operate and can perform carbon conversion using low gas velocities. However, tar formation is a major problem in fixed-bed reactors. On the other hand, fluidized bed reactors can operate with high carbon conversion, low tar content, and uniform producer gas yield, but they are complicated to build and operate (Reed and Das 1988; Hasan *et al.* 2010). There has been significant recent research to improve the operational performance of fixed bed gasifiers, with particular emphasis on the selection of optimal gasification parameters (Zainal *et al.* 2002; At Naw *et al.* 2013). However, the outputs are profoundly influenced by the properties of the feedstock and the nature of the process: producer gas composition and tar content can vary widely for different feedstocks (Hasan *et al.* 2010).

The objective of this study was to better understand the effects of biomass type and air flow rate on the gasification performance of an updraft biomass gasifier. Sorghum stover, prairie hay, and woodchips were studied because of their local availability and potential as energy feedstocks. Three levels of airflow were tested (air-fuel equivalence ratios of 0.21, 0.25, and 0.29). The air-fuel equivalence ratio was calculated by dividing the mass of air used to gasify the biomass by the mass of air required to completely burn the biomass. Gasification performance was evaluated based on the producer gas composition, higher heating value (HHV), and tar content.

EXPERIMENTAL SETUP

Biomass Gasification and Sampling System Setup

Experiments were carried out in a system composed of a biomass updraft gasifier, a water/tar condenser, and a gas burner, as depicted in Fig. 1. The updraft gasifier was a 0.5-m (internal diameter) by 0.96-m (height) steel reactor. Temperatures in the chamber were measured with a National Instruments® data acquisition system composed of type K thermocouples. A centrifugal blower (510 Lpm at 125 Pa) was used to supply air to the gasifier. The gasifier was a packed-bed updraft biomass gasifier operated at atmospheric pressure with a water seal on the top lid. After the producer gas was generated, it flowed from the reactor to an ambient-temperature condenser, a steel tank where water and heavy tars were condensed and removed. A 190.5-mm-diameter gas burner was located on top of the water/tar condenser and was used to burn the producer gas.

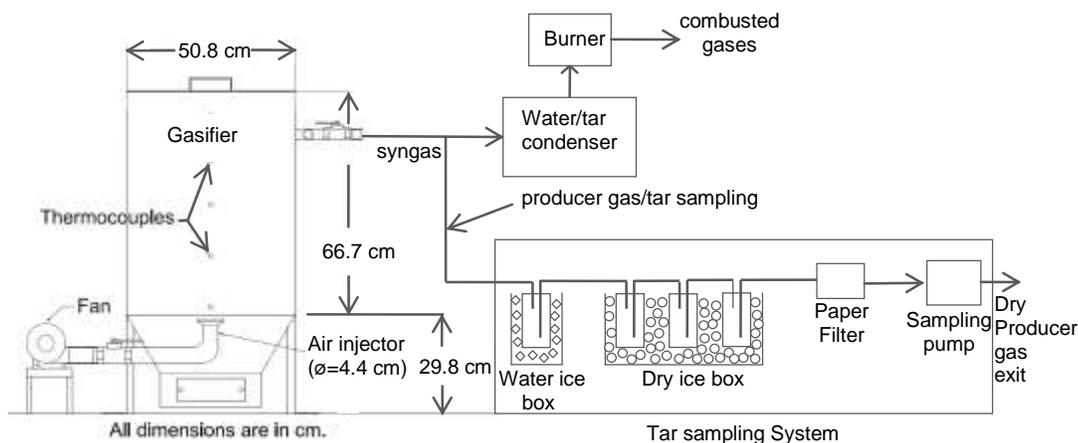


Fig. 1. Schematic of biomass gasification system and producer gas/tar sampling

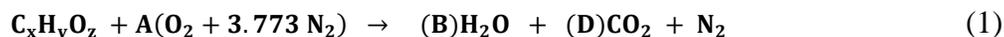
Tar and producer gas samples were collected from the gasification chamber. The tar sampling unit was composed of four 250-mL Erlenmeyer flasks connected in series in two steps (Fig. 1). One flask was immersed in water-ice mixture in an insulated box to condense moisture and heavy tars and the three other flasks were placed under dry ice (solid CO₂) to collect lighter tar species. Tar was sampled at 3.8 L/min for 15 min; the temperature of the gas in the sampling system was -49 °C at atmospheric pressure. After that, the flasks were dried in an oven at 105 °C for 24 h and weighed on a precision balance. A similar tar collection method was used in a previous study (Wang *et al.* 2010). At steady state, the producer gas was collected using a Tedlar® sampling bag. The producer gas composition was determined using an SRI 8610 Gas Chromatograph with a TCD detector (SRI, Torrance, CA) under room temperature (21 to 25 °C) and atmospheric pressure. Helium was used as the carrier gas, and the H₂, O₂, N₂, CH₄, CO, and CO₂ concentrations were measured.

Biomass Studied

Using biomass residues from industrial processes and grasses can increase the overall efficiency of biomass gasification (Milbrandt 2005). In this study, three feedstocks were utilized to test the effect of the biomass type on gasification performance, and each experiment was performed three times. Prairie hay is a grass with a number of advantages, including its wild growth and the fact that it does not need to be fertilized or irrigated. In the same way, sorghum stover, a byproduct from agricultural crops, has potential for biofuel production. Prairie hay and sorghum biomass collected from a local farm were ground using a tub grinder (Model H-100, Haybuster Big Bite, Jamestown, ND). Furthermore, wood chips from a local transfer station were used. The wood chips selected were byproducts from construction and gardening applications. Hemicellulose and cellulose analyses of the biomass were performed in an ANKOM 2000 Fiber analyzer (Macedon, NY). The acid detergent lignin method was used to determine the lignin content (ANKOM, method 8). The ash content was determined as the residue remaining after combustion at 450 °C overnight. An adiabatic bomb calorimeter (IKA-Calorimeter C 200, IKA-Werke GmbH and Co. KG, Staufen, Germany) was used to determine the higher heating values of the biomass feedstocks.

Methodology of Gasification Experiments

Three levels of air-fuel equivalence ratios (ER) were evaluated: 0.21, 0.25, and 0.29 with three replicates for each ER. At equivalence ratios close to 0.25, the producer gas from biomass gasification was found to have the highest energy potential (Knoef 2005). Several other studies have also found optimal gasification performance in this range (Lv *et al.* 2004; Sheth and Babu 2009; Ummadisingu *et al.* 2010). Equation 1 (Basu 2010) was used to calculate the mass of air needed for the complete combustion of the biomass. The mass of air required for gasification was calculated using the air flow and the reaction time of the gasification experiments. The air-fuel equivalence ratio was calculated using Eq. 2 (Basu 2010):



$$ER = \frac{M_g(\text{Actual air})}{M_c(\text{Stoichiometric air})}, \quad ER < 1.0 \text{ (gasification)} \quad (2)$$

In each experiment, the gasifier was loaded with one type of biomass for a single batch reaction (*e.g.*, 30 pounds (14 kg) of prairie hay or sorghum or 40 pounds (18 kg) of wood chips). All experiments were carried out for at least 60 min of stable gasification. The producer gas contents of hydrogen, carbon monoxide, and methane were used to calculate the heating value of the produced gas using Eq. 3 (Bejan 2006).

$$\Delta H^{\circ} = \sum(H_f^{\circ})_p - \sum(H_f^{\circ})_r \quad (3)$$

Statistical analysis was carried out to investigate the differences in tar content and producer gas composition. Tukey's HSD was used to analyze the differences among groups. Because different biomasses were used, tar content did not exhibit a linear relationship. As a result, the natural logarithm of the tar content was reported to correct the residuals for statistical analysis. A SAS®-GLM procedure was performed and adjusted for Tukey comparisons. Tests were performed for each variable analyzed. Values with significant differences are presented on the graphs with different letters (A, B, or C). Significant difference means that the *p*-value was lower than 0.05.

RESULTS AND DISCUSSION

Biomass Characteristics

Table 1 shows the biomass characteristics for all raw materials tested. All biomass types had similar heating values close to those of wood (20.2 MJ/kg) and crop residues (18.8 MJ/kg) (Rosillo-Calle *et al.* 2007). Wood chips had the highest lignin content (19.24%) and the lowest ash content (2.86%) of the three feedstocks.

Table 1. Biomass Characteristics

	C	H	O ^b	HHV ^c (MJ/kg)	Hemicellulose (wt.%)	Cellulose (wt.%)	Lignin (wt.%)	Ash (wt.%)	Moisture (wt.%)
Prairie Hay	43.3	5.5	49.4	18.17	29.78	30.01	2.06	8.41	10.0
Sorghum Biomass	43.0	5.9	49.3	18.18	27.99	41.53	4.37	7.18	8.56
Wood Chips	46.8	5.3	46.6	18.8	14.99	34.31	19.24	2.86	10.9

^bCalculated by difference, °21-25°C at atmospheric pressure.

Effects of Air Flow on Tar Content and Combustion Temperature

The results of prairie hay gasification at 0.21, 0.25, and 0.29 equivalence ratios are presented in Fig. 2. Prairie hay at an ER of 0.29 had the highest tar content, 3.1 g/m³. Increasing the ER increased the formation of tar species. Several researchers (Kinoshita *et al.* 1994; Chen *et al.* 2008) have reported that variation in the air available for gasification can affect tar yield during biomass gasification, increasing tar generation as the reaction air supplied increased. It is important to highlight the fact that prairie hay had a tar content of 1.67 g/m³ at an ER of 0.21, comparable to tar levels produced in downdraft gasifiers (Milne *et al.* 1998). The combustion zone temperature of prairie hay gasification decreased with increasing ER (Fig. 2B). The highest temperature (736 °C) corresponded to the lowest tar content (ER of 0.21). Comparing Figs. 2(A) and 2(B), it can be seen that there was a

negative correlation between tar content and combustion zone temperature. This study is in agreement with an earlier work (Chen *et al.* 2008), reporting that increases in the combustion zone temperature could increase the producer gas yield but decrease the formation of tar species.

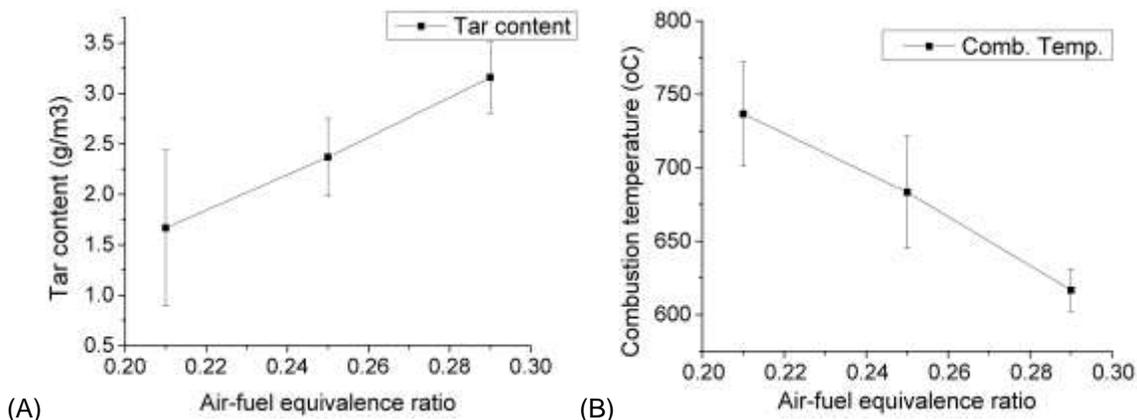


Fig. 2. (A) Tar content and (B) combustion zone temperature of prairie hay gasification at various ERs

The gasification of sorghum biomass presented comparable results to prairie hay gasification. The lowest tar content, 2.2 g/m³, was achieved at an ER of 0.21, and the highest tar content, 3.0 g/m³, was observed at an ER of 0.29, as shown in Fig. 3(A). In contrast with prairie hay gasification, the combustion zone temperature of sorghum stover was maximized at the moderate ER of 0.25 instead of at 0.21 ER as in prairie hay gasification, as shown in Fig. 3(B).

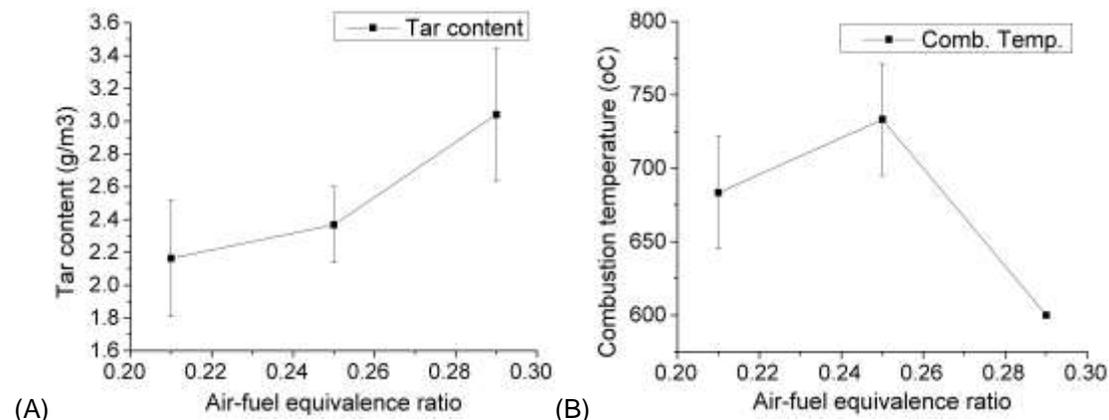


Fig. 3. (A) Tar content and (B) combustion temperature of sorghum stover gasification at various ERs

As presented in Fig. 4A, the producer gas from wood chip also exhibited increases in tar content when the ER increased, similar to the other two biomass types. Other researchers also found similar results. Increasing the equivalence ratio in biomass gasification had a negative effect on the tar content because of an increase in the formation of tar species (Kinoshita *et al.* 1994; Houben 2004). The combustion temperature decreased when the ER increased from 0.21 to 0.25, and then it started to increase as the ER further increased. A similar phenomenon was observed by Sheth and Babu (2009), who believed

that the initial reduction in combustion temperature could be attributed to the increase of inert nitrogen as a heat carrier in the combustion zone. It is important to note that the combustion temperature of wood chip gasification was the highest at ER 0.29, at which the tar content was also the highest. This trend was totally different from those of prairie hay and sorghum stover, which may be related to the significant differences in the bulk density of the biomass. Wood chips had significantly higher bulk density (roughly 40 lb (18 kg) per load) than prairie hay and sorghum stover (approximately 30 lb (14 kg) per load). Such a difference could cause differences in the airflow through the gasifier chamber, altering gasification.

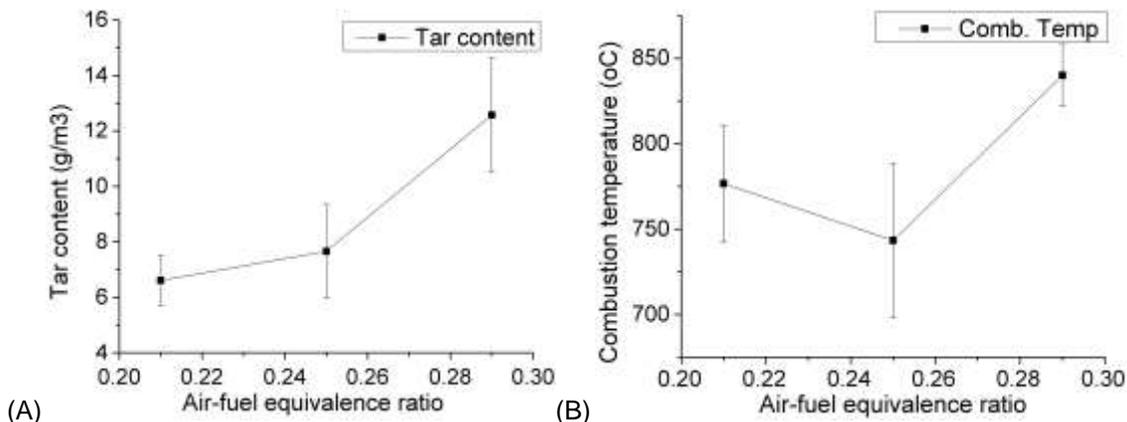


Fig. 4. (A) Tar content and (B) combustion temperature of woodchips gasification at various ERs

Effects of Air Flow on Producer Gas Composition and High Heating Value

The hydrogen and carbon monoxide contents were compared at different ERs for all biomass types. The results are shown in Table 2. No significant differences in hydrogen composition were found at different ER levels for any single biomass type.

Table 2. Average Higher Heating Value and Hydrogen and Carbon Monoxide Contents of Producer Gas

	Prairie Hay			Sorghum Stover			Wood Chips		
	0.21	0.25	0.29	0.21	0.25	0.29	0.21	0.25	0.29
Equiv. ratio	0.21	0.25	0.29	0.21	0.25	0.29	0.21	0.25	0.29
H ₂ vol.%	8.54	9.18	9.51	8.83	8.78	7.93	8.68	8.41	8.86
CO vol.%	17.09	16.86	16.19	15.20	15.05	13.12	20.44	22.42	21.26
CH ₄ vol.%	3.04	2.67	2.70	2.75	2.24	2.20	4.21	4.28	4.28
N ₂ vol.%	49.48	49.06	48.37	54.14	55.52	54.14	48.03	46.39	47.76
O ₂ vol.%	2.78	3.45	3.11	3.02	3.43	3.68	2.16	1.64	1.78
CO ₂ vol.%	19.05	18.76	20.10	16.06	14.98	18.93	16.47	16.84	16.06
HHV (MJ/m ³)	4.44	4.35	4.32	4.12	3.90	3.53	5.35	5.59	5.50

Similarly, the higher heating value and carbon monoxide content did not exhibit significant differences when an individual type of biomass was analyzed. Similar to results found by Turn *et al.* (1998), little differences in the hydrogen and carbon monoxide contents was observed when the air-fuel equivalence ratio was varied from 0.18 to 0.28.

Effects of Biomass Type on Tar Content and HHV

The overall tar formation from different biomass types was compared, as shown in Fig. 5. Prairie hay yielded lower overall tar content, 1.95 g/m^3 , than sorghum stover and wood chips. Gasification of wood chips formed the most tar, with an average tar content of 8.0 g/m^3 . The selected biomasses, categorized as agricultural residue (sorghum biomass), woody biomass (woodchips), and grass (prairie hay), were found to generate producer gas with significantly different tar contents. These differences in tar content could be due to the varying biomass characteristics. Wood chips had the highest lignin content (19.24%), followed by sorghum (4.37%) and prairie hay (2.06%). Lignin is an aromatic polymer that joins cellulose fibers to bind adjacent cells together. Lignin has been found to produce higher tar content than other biomass components (cellulose and hemicellulose) when gasified at various equivalence ratios and reaction temperatures (Hanaoka *et al.* 2005; Yu *et al.* 2014).

Figure 6 shows that the higher heating values of producer gas from prairie hay, sorghum biomass, and wood chip, and they are comparable to those reported in previous studies (Di Blasi *et al.* 1999; Sheth and Babu, 2009). Wood chip producer gas had the highest HHV (5.48 MJ/m^3), representing higher energetic potential compared to producer gas from sorghum stover (3.85 MJ/m^3) and producer gas from prairie hay (4.37 MJ/m^3). The heating value of the gas depends mostly on the quantities of hydrogen and carbon monoxide present in the gas mixture (Yang *et al.* 2006).

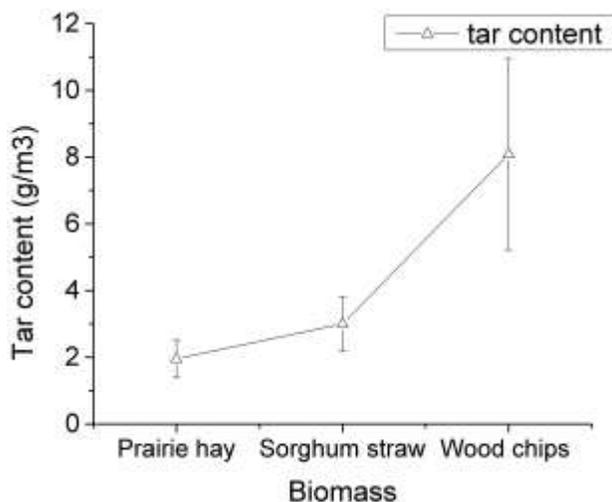


Fig. 5. Average tar content of producer gas from three biomass types

Effects of Biomass Type on Producer gas Composition

Carbon monoxide and hydrogen are the main sources of the heating power of the producer gas. These gases are the products of a large number of thermochemical reactions involving simple and complex molecules. Oxidation and reduction are some of the reactions taking place during the gasification process. Each is well-represented by several

single reactions (Knoef 2005). As shown in Fig. 6, the hydrogen content did not exhibit significant differences when the averages of all biomass types were compared. However, the carbon monoxide content of the producer gas from wood chips was found to be the highest (21.3%) among the three biomass types, followed by prairie hay (16.7%) and sorghum biomass (14.4%). This could be related to the carbon content of the biomass, which appeared linearly related to the carbon monoxide composition. The carbon monoxide content in the producer gas increased on the same order as the carbon content of the biomass types (Table 1). The R^2 value of the linear correlation between the CO content and the C content of the biomass was 0.92, indicating that the biomass carbon content significantly affected CO formation during the gasification process.

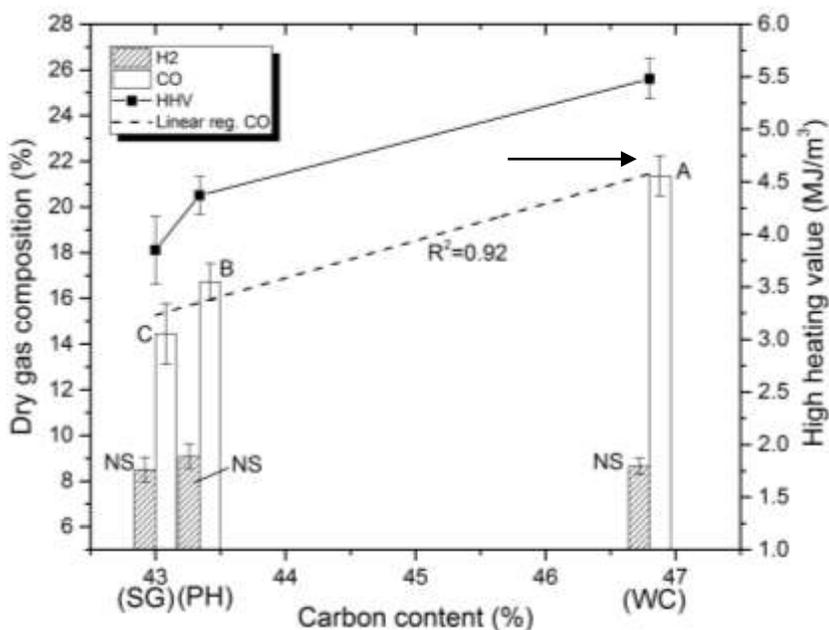


Fig. 6. Average contents of H₂, CO, and HHV in producer gas from the three biomass types. Different letters represent significant differences, and NS means no significant differences. SG (sorghum biomass), PH (Prairie hay), WC (wood chips).

CONCLUSIONS

1. Different biomass types resulted in different tar contents in the producer gas of biomass gasification. Gasification of wood chips yielded the most tar, followed by sorghum biomass and prairie hay. This difference was found to be strongly related to the lignin content in the biomass.
2. The higher heating value of the producer gas varied among the different biomass types. Producer gas from wood chips had the greatest higher heating value, followed by producer gas from prairie hay and sorghum biomass.
3. The hydrogen content in the producer gas was not statistically different among the different biomass types and air flow rates tested. However, the carbon monoxide content of the different biomass types showed significant differences: producer gas from wood chips contained the most CO, followed by producer gas from prairie hay

and sorghum stover. Furthermore, the CO content was linearly correlated with the carbon content of the biomass, therefore increasing the higher heating value.

4. The formation of tar species increased when the air-fuel equivalence ratio increased. However, no significant differences in the producer gas composition or higher heating value were observed after varying the air-fuel equivalence ratios because of the close proximity of the equivalence ratios tested.

ACKNOWLEDGEMENTS

This material was based upon work supported by the U.S. Department of Agriculture and Sun Grant (Award No. 2010-38502-21836 and Subaward No. AB-5-67630. KSU11) and the startup fund of North Carolina State University. The lead author was also partially supported by the scholarship program of IFARHU-SENACYT from the Government of Panama.

REFERENCES CITED

- Atnaw, S. M., Sulaiman S. A., and Yusup S. (2013). "Syngas production from downdraft gasification of oil palm fronds, *Energy* 61, 491-501. DOI:10.1016/j.energy.2013.09.039.
- Basu, P. (2010). *Biomass Gasification and Pyrolysis: Practical Design and Theory*, Academic Press, New York.
- Bejan, A. (2006). *Advanced Engineering Thermodynamics*, John Wiley & Sons, Hoboken, NJ.
- Chen, H. P., Li, B., Yang, H. P., Yang, G. L., and Zhang, S. H. (2008). "Experimental investigation of biomass gasification in a fluidized bed reactor," *Energy & Fuels* 22(5), 3493-3498. DOI: 10.1021/ef800180e
- Di Blasi, C., Signorelli, G., and Portoricco, G. (1999). "Countercurrent fixed-bed gasification of biomass at laboratory scale," *Industrial & Engineering Chemistry Research* 38(7), 2571-2581, DOI: 10.1021/ie980753i
- Hanaoka, T., Inoue, S., Uno, S., Ogi, T., and Minowa, T. (2005). "Effect of woody biomass components on air-steam gasification," *Biomass & Bioenergy* 28(1), 69-76, DOI: 10.1016/j.biombioe.2004.03.008.
- Hasan, J., Keshwani, D. R., Carter, S. F., and Treasure, T. H. (2010). "Thermochemical conversion of biomass to power and fuels," in: *Biomass to Renewable Energy Processes*, J. Cheng (ed.), CRC Press, Boca Raton, FL, pp. 437-489.
- Houben, M. (2004). *Analysis of Tar Removal in a Partial Oxidation Burner*, Technische Universiteit Eindhoven, The Netherlands.
- Kinoshita, C., Wang, Y., and Zhou, J. (1994). "Tar formation under different biomass gasification conditions," *Journal of Analytical and Applied Pyrolysis* 29(2), 169-181, DOI: 10.1016/0165-2370(94)00796-9
- Knoef, H. (2005). "Practical aspects of biomass gasification," in: *Handbook Biomass Gasification*, H. A. M. Knoef (ed.), BTG Biomass Technology Group, The Netherlands, chapter 3.

- Lucas, C., Szewczyk, D., Blasiak, W., and Mochida, S. (2004). "High-temperature air and steam gasification of densified biofuels," *Biomass & Bioenergy* 27(6), 563-575, DOI: 10.1016/j.biombioe.2003.08.015
- Lu P. M., Xiong Z. H., Chang J., Wu C. Z., Chen Y., and Zhu J. X. (2004). "An experimental study on biomass air-steam gasification in a fluidized bed," *Bioresour. Technol.* 95(1), 95-101, DOI:10.1016/j.biortech.2004.02.003.
- Milbrandt, A. (2005). "A geographic perspective on the current biomass resource availability in the United States," United States Department of Energy.
- Milne, T. A., Abatzoglou, N., and Evans, R. J. (1998). "Biomass gasifier 'tars': Their nature, formation, and conversion," National Renewable Energy Laboratory, Golden, CO.
- Reed, T. B., and Das, A. (1988). *Handbook of Biomass Downdraft Gasifier Engine Systems*, Biomass Energy Foundation, Normal, IL.
- Rosillo-Calle, F., De Groot, P., Hemstock, S. L., and Woods, J. (2007). *The Biomass Assessment Handbook: Bioenergy for a Sustainable Environment*, Earthscan, UK.
- Sheth, P. N., and Babu B. V. (2009). "Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier," *Bioresour. Technol.* 100(12), 3127-3133. DOI:10.1016/j.biortech.2009.01.024
- Turn, S., Kinoshita, C., Zhang, Z., Ishimura, D., and Zhou, J. (1998). "An experimental investigation of hydrogen production from biomass gasification," *International Journal of Hydrogen Energy* 23(8), 641-648. DOI: 10.1016/S0360-3199(97)00118-3
- Ummadisingu, A., Pratik, S., and Babu, B. V. (2010). "Experimental studies on gasification of pine wood shavings in a downdraft biomass gasifier," *Proceedings of the AIChE Annual Meeting*, 1-11.
- Wang, D., Yuan, W., and Ji, W. (2010). "Use of biomass hydrothermal conversion char as the Ni catalyst support in benzene and gasification tar removal," *Transactions of the ASABE* 53(3), 795-800. DOI: 10.13031/2013.30053
- Yang, W., Ponzio, A., Lucas, C., and Blasiak, W. (2006). "Performance analysis of a fixed-bed biomass gasifier using high-temperature air," *Fuel Processing Technology* 87(3), 235-245. DOI: 10.1016/j.fuproc.2005.08.004
- Zainal, Z. A., Rifau, A., and Quadir, G. A., and Seetharamu, K. N. (2002). "Experimental investigation of a downdraft biomass gasifier," *Biomass Bioenergy* 23(4), 283-289. DOI:10.1016/S0961-9534(02)00059-4

Article submitted: February 19, 2015; Peer review completed: April 5, 2014; Revisions received and accepted: April 24, 2015; Published: April 28, 2015.

DOI: 10.15376/biores.10.2.3615-3624