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Single-fuel steam gasification of switchgrass and coal in a bubbling fluidized bed: A comprehensive parametric reference for co-gasification study

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ABSTRACT

Recent regulatory sharp curbs on coal power plants have compelled industries to adopt alternative sources of fuels. Biomass/fossil fuel co-gasification could be a pathway through more sustainable energy production technologies. As a basis for co-gasification study, the characteristics of single-fuel switchgrass and coal steam gasification in an atmospheric pilot scale bubbling fluidized bed reactor were studied. Increasing the steam-to-fuel ratio at 860 °C caused a moderate increase in the H_2 and CO_2 concentrations and decreases in the CO and CH_4 concentrations, due to more steam-CH_4 reforming and water–gasification reaction of CO. With increasing reactor temperature, the H_2 concentration increased, whereas the CO, CH_4, and CO_2 concentrations fell slightly. Fall switchgrass gasification resulted in higher carbon, hydrogen and cold gas efficiencies than spring harvest gasification, possibly due to higher potassium concentration and hence, greater reactivity of the fall switchgrass. The equilibrium model was unable to predict the syngas composition properly. Adding an extra methanator stoichiometric reactor to produce methane based on the empirical CH_4 concentration, and removing part of the carbon, hydrogen and steam before introducing the feed and gas agent streams to the reactor based on experimental carbon, hydrogen, and steam efficiencies, the kinetically modified model predicted the syngas composition accurately.

1. Introduction

The combined average temperature over global land and ocean surfaces for January 2014 was the warmest since 2007 and the fourth warmest on record, 0.65 °C above the 20th century average [1]. The increasing GHG (greenhouse gas) concentrations and concern over the effect on climate [2–4] encourage indeed demand the development of new advanced energy cycles. Canada's total GHG (greenhouse gas) emissions in 2011 were 702 Mt (megatonnes) of carbon dioxide equivalent (CO_2 eq.), 19% (111 Mt) above the 1990 emissions of 591 Mt [5].

As part of a solution, renewable energy technologies currently supply ~18.5% of the world's primary energy supply, with bioenergy the largest contributor. In 2011, total biofuels supply was ~1311 Mtoe, accounting for 10% of the world's total primary energy supply and ~54% of its renewable energy supply [6]. Among bioenergy technologies, thermochemical conversion of solid fuels via gasification into synthesis gas (syngas) is a promising and diversified option. A main advantage compared to combustion is its downstream products diversity [7]. Although energy utilization from renewable sources will grow, fossil fuels are expected to remain the main source of energy and emissions for decades. Coal power plants are still contributing to about 42% of net electricity generation in the Unites States, and are projected to keep their lead until 2040 [8,9].

Panicum virgatum, commonly known as switchgrass, is a perennial warm-season bunchgrass native to North America.

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Switchgrass has potential as an energy crop for Eastern Canada [14] and for the US, where it was selected as a model herbaceous crop for the Oak Ridge National Laboratory's Biofuel Feedstock Development Program [15,16]. It shows promise due to its high productivity, appropriateness for marginal land quality, low water and nutritional requirements, environmental benefits, and flexibility for multipurpose uses [10]. Switchgrass ash is rich in AAEM (alkali and alkaline earth metals) and has potential to catalyze and enhance carbon gasification reactions [13,17,18,69]. A published review article [11] on the conversion of switchgrass to value-added products revealed that study of large scale gasification of switchgrass is rare.

In this paper therefore, switchgrass and coal were gasified separately in an atmospheric pilot-scale BFB (bubbling fluidized bed) reactor with pure steam as the agent to investigate the effects of different critical parameters on gasification performance. On the basis of this paper, the switchgrass/coal co-gasification study is developed and presented elsewhere [13]. To test the reliability of equilibrium modeling, a computer simulation was also presented and the product gas composition was predicted. This work provides reference data for a comprehensive study on co-gasification of biomass and fossil fuels with and without integrated CO_2 capture [12,13,17,18,68].

2. Materials and methods

2.1. Fuel characterization

Spring and fall harvest switchgrass from Ontario, Canada (Nott farm) and thermal coal from Vancouver Island, Canada (Quinsam mine) were tested in this study. The ASTM D346 and D346M-11 standard method were followed for feedstock sampling.

Table 1 presents the ultimate, proximate and elemental ash analyses of the parent fuels. As expected, the coal contained much higher carbon (80.3 wt%) and therefore heating value (28.4 MJ/kg) than the biomass. Fuel minerals act as in-situ catalysts to augment carbon thermochemical conversion [19]. Switchgrass ash is rich in potassium, 10.8 wt% for spring harvest switchgrass (SP-SG) and 21.8 wt% for fall harvest switchgrass (F-SG). The fall harvest variety was therefore expected to have higher reactivity, as it contained the highest potassium in its ash. More details on the morphology, surface area and thermogravimetric analyses of switchgrass can be found elsewhere [17,18,20]. The Quinsam mine coal is a thermal coal, with low crucible swelling index (0.5), suitable for fluidization applications. The amounts of undetermined species of the ash analyses were less than 3 wt% for all samples. Therefore, the "undetermined" in Table 1 is predominantly oxygen.

Table 1
Ultimate, proximate and ash analysis of fresh feedstocks for pilot-scale experiments.

Sample	Quinsam mine coal (Vancouver Island)	Spring switchgrass (Ontario) (SP-SG)	Fall switchgrass (Ontario) (F-SG)
Ultimate analysis (wt%), daf[a]			
Carbon, C	80.3	49.7	47.7
Hydrogen, H	5.5	6.2	5.9
Nitrogen, N	0.9	0.9	1.0
Sulfur, S	0.7	0.1	0.1
Oxygen, O (diff[b])	12.6	43.1	45.3
Proximate analysis (wt%)			
Moisture	4.25	9.26	11.63
Ash (db[a])	12.90	3.07	3.80
Volatile (db)	38.01	79.50	79.47
Fixed Carbon (db)	49.09	17.43	16.73
Higher heating value (db) (MJ/kg)	28.40	19.38	19.23
Crucible Swelling Number	0.5	n.a.	n.a.
Ash analysis (wt%)			
Si	16.87	20.14	14.60
Al	13.39	0.22	0.06
Ti	1.43	0.02	0.01
Fe	4.69	0.38	0.19
Ca	13.36	9.40	7.28
Mg	0.24	3.26	2.80
Na	0.16	0.09	0.02
K	0.06	**10.76**	**21.83**
P	0.24	2.2	3.13
S	2.30	2.15	1.35
Ba	0.01	0.02	0.01
Sr	0.07	0.01	0.01
Mn	0.05	0.05	0.03
Cr	0.00	0.01	0.01
Cu	0.03	0.01	0.01
Ni	0.02	0.00	0.01
V	0.05	0.01	0.00
Zn	0.01	0.02	0.03
Hg	0.00	0.04	0.02
Undetermined[c]	46.96	51.21	48.6

Both spring and fall switchgrass were rich in potassium (bold numbers).
[a] daf = dry and ash free, db = dry basis;
[b] Calculated by difference;
[c] Predominantly oxygen, since the inorganic elements are present as oxides (e.g., Al_2O_3, SiO_2, K_2O).

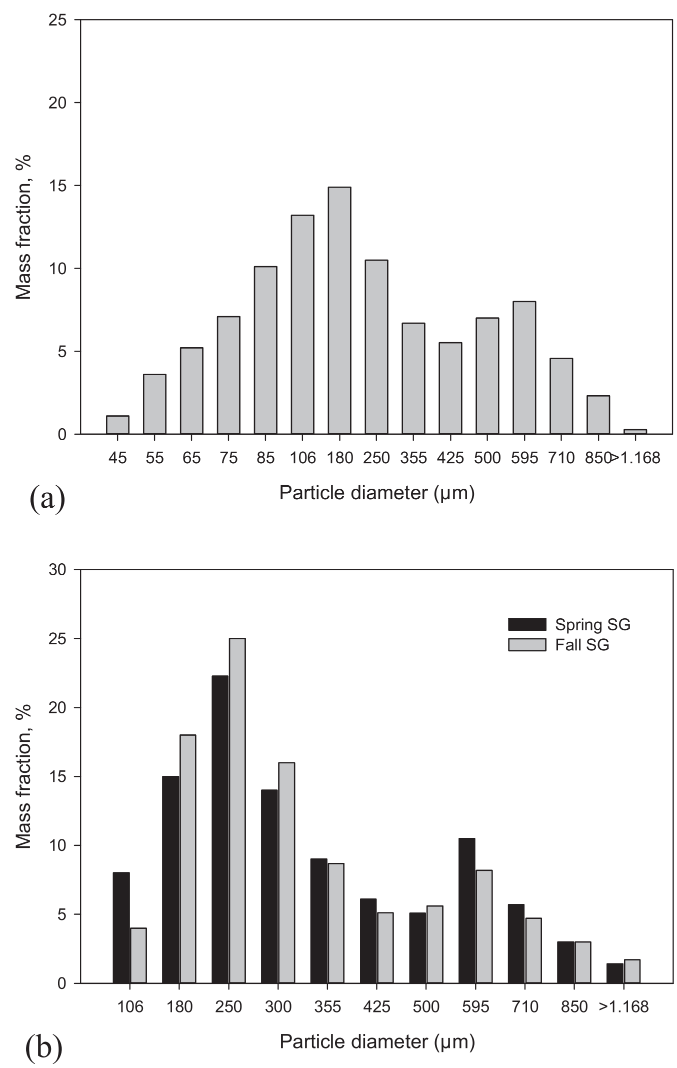

Fig. 1. Particle size distributions of (a) coal (b) spring and fall switchgrasses.