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An experimental study of combustion and emissions of biomass pellets in a prototype pellet furnace

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HIGHLIGHTS

- We studied combustion and emission of biomass pellets in a prototype pellet furnace.
- Performance and emissions of grass pellet is compared to that of wood pellets.
- We used scanning electron microscopy (SEM) for ash analysis.
- No ash sintering or agglomeration was observed.
- Grass pellet is successfully combusted.

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ABSTRACT

This study presents combustion and emission results obtained using a prototype pellet furnace with 7–32 kW capacity (designed for burning high ash content pellet fuels) for four biomass pellets: one grass pellet and three wood pellets. Fuel property, gas emissions and furnace efficiency are compared. In regard to fuel properties, proximate analysis, ultimate analysis and heating values are determined and emissions of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), nitrogen oxides (NOx) and sulfur dioxide (SO_2) are measured and compared. Scanning electron microscopy (SEM) was used for ash analysis. No ash agglomeration was observed and ash discharge was in the form of powder instead of lumped particles, which are usually observed for high ash biomass fuel. The results suggest that grass pellets can successfully be combusted with similar performance and emissions to that of other wood pellets if burned in appropriate combustion installations.

1. Introduction

Increasing environmental and energy dependency concerns have been the motivation for a rise in the use of biomass fuels as a substitute to fossil fuels [1]. Biomass is already seen as viable option to mitigate greenhouse gas (GHG) emissions [2,3]. In Canada, bioenergy provides six percent of primary energy, the second most important source of renewable energy following hydroelectricity [4]. A major application is the combustion of waste materials from the forest products and pulp and paper industries to generate electricity, steam, and heat. Wood, with fuel characteristics of low ash and low sulfur content allows a direct comparison with fossil fuel and provides good heating performance at a cost that is typically lower than that of heating oil [5]. The market for wood pellets in Canada has steadily increased in recent years. Wood pellets are made typically from waste sawdust or ground wood chips, resulting in a densified or compacted product which benefits from an increased energy density while also reducing the costs and problems associated with waste disposal experienced by many wood processing operations. Since the start of the pellet fuel market, the emphasis has always been on the use of wood which creates a low moisture, low ash product, however, the introduction of agro-forestry driven residues has the potential to play a significant role in the densified biomass market as demonstrated by Kristensen and Kristensen [6] and Dias et al. [7]. In a recent study, Verma et al. [8] reported that agro-pellets such as reed canary grass and straw pellets produced very low level of CO emissions.

Canada has significant agricultural resources and according to Wood and Layzell [9] could supply sufficient biomass to meet 20% of Canada's energy consumption. The use of agricultural biomass such as hay or dedicated energy crops such as switch grass are now considered as viable options for the production of pellets

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Nomenclature

ASTM	American Society for Testing and Materials
ASTM E870-82 (2006)	test methods that cover the proximate and ultimate analysis and the determination of the gross calorific value of wood fuels
C	carbon
cm	centimeter
CO_{2max}	the amount of carbon dioxide in the combustion gases if the combustion process is carried out with excess air factor of one
C_p	specific heat of flue gas
C_{pCO}	specific heat of carbon monoxide
C_{pCO2}	specific heat of carbon dioxide
C_{pN2}	specific heat of nitrogen
C_{pO2}	specific heat of oxygen
°C	degree Celsius
H	hydrogen
h_f	enthalpy of water at ambient temperature
h_g	enthalpy of steam at the temperature T_g
HHV	higher heating value
HHV_C	higher heating value of carbon
HHV_F	higher heating value of fuel
kg	kilogram
kg/h	kilogram per hour
kJ	kilo joule
kV	kilo volt
kW	kilowatt
m	meter
mm	millimeter
m_{CO}	mass of carbon monoxide
m_{CO2}	mass of carbon dioxide
m_{N2}	mass of nitrogen
m_{O2}	mass of oxygen
m_{dry}	mass of dry flue gas
MJ/kg	mega joule per kilogram
$m_{moisture}$	sum of water vapor produced from hydrogen in the fuel and moisture present in the fuel and air
N	nitrogen
nm	nanometer
O	oxygen
O_{2meas}	measured concentration of O_2 in combustion gases expressed in (% vol)
ppm	parts per million
rpm	revolution per minute
S	sulfur
SEM	scanning electronic microscopy
T_a	ambient air temperature
T_g	flue gas temperature

due to their low cost and higher GHG mitigation ability [10]. There is, however, some challenges associated with agro fuels in small scale applications. These arise from high particulate matters (PMs) and gaseous emissions, lower efficiencies, ash related problems including high ash contents and ash sintering and fouling [6,7,11–13].

Currently there are few companies manufacturing stoves specifically designed to burn grass pellets, but some wood pellet and corn stoves have been adapted and used to burn grass pellets [14]. A recent study in Cornell University [15] found that even the best performing pellet burning equipment (multi-fuel stoves and boilers designed for pellets and grains) must be serviced on regular intervals (usually everyday) if using grass pellets. Gonzalez et al. [16] investigated combustion of different biomass residue pellets (tomato, olive stone and cardoon) for domestic heating and compared them with forest pellets. The efficiencies of the three residues were found similar to that of forest pellet with a maximum fuel mass flow and minimum draft. Although they reported high efficiency, the emission of CO was very high, as high as 5000 ppm or more in some cases. Olsson [17] investigated wheat straw and peat pellet combustion. The results indicated that wheat straw and peat pellets are fuels with relatively low emissions during combustion. However, wood pellets burned efficiently with even lower emissions than straw and peat pellets during flaming burning. Slagging tendencies of wood pellet ash during combustion were investigated [13]. The results showed that the slagging properties were relatively sensitive to the variations in total ash content and ash forming elements of the fuel. It is therefore recommended that ash rich fuels like bark and logging residues should not be used in the existing residential pellet burners. The results also indicated that the Si-content in the fuel correlated well to the sintering tendencies in the burners. Andreasen and Larsen [18] presented straw pellet combustion and compared it with the wood pellet. Five types of straw and wood pellets made with different binders and antislag agents were tested as fuel in five different types of boilers in test firings at 50% and 100% nominal boiler output. The tests proved that the wood pellets could be used in all the boilers tested without any operational problems. There were many other studies that dealt with biomass pellet gasification, combustion and emissions including different types of grass pellets [19–24]. The CO_2 emissions with grass pellet combustion reduced by 90% as compared to coal combustion [20] and the energy balance of grass pellets was found distinctly superior to other biofuels production route such as corn ethanol and biodiesel [22]. Spring harvested reed canary grass showed improved combustion and less ash agglomeration due to reduced concentration of elements that are undesirable in combustion, and the initial ash deformation temperature was increased [23,24]. Previous works of the authors [25,26] demonstrated the feasibility of biomass/biosolids use in commercial wood/wood pellet stoves. An experimental study of combustion and emissions of biomass briquettes in a domestic wood stove is presented [25] and it is shown that hay and switch grass briquettes can successfully be combusted in domestic wood stoves with similar performance and emissions to that of other woody briquettes. This study has investigated the potential of burning switch grass pellets in a prototype furnace developed and patented by LST energy [27] and compares their performance, emissions and ash agglomeration to commercially available wood pellets in Canadian market.

2. Materials and methods

2.1. Pellets

Four pellets: one grass pellet, two premium grade wood pellets and one industrial grade wood pellet were used in this study. The pellets are commercialized in Canada and designated here as grass pellet, grade 1 wood pellet, grade 2 wood pellet and grade 3 wood pellet. Grass pellet, and grade 1 and 2 wood pellets have a diameter of 1/4 in. (6.35 mm), but grade 3 wood pellet has a diameter of 5/16 in. (about 8 mm). The bulk density of grass pellet was 566 kg/m^3 and that of wood pellets were 648 kg/m^3 for grade 1, 636 kg/m^3 for grade 2 and 653 kg/m^3 for grade 3. Fig. 1 shows a photograph of different pellet fuels.