

Article

Corn Stover and Wheat Straw Combustion in a 176-kW Boiler Adapted for Round Bales

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Abstract: Combustion trials were conducted with corn stover (CS) and wheat straw (WS) round bales in a 176-kW boiler (model Farm 2000). Hot water (80 °C) stored in a 30,000-L water tank was transferred to a turkey barn through a plate exchanger. Gross calorific value measured in the laboratory was 17.0 and 18.9 MJ/kg DM (dry matter) for CS and WS, respectively. Twelve bales of CS (1974 kg DM total, moisture content of 13.6%) were burned over a 52-h period and produced 9.2% ash. Average emissions of CO, NO_x and SO₂ were 2725, 9.8 and 2.1 mg/m³, respectively. Thermal efficiency was 40.8%. For WS, six bales (940 kg DM total, MC of 15%) were burned over a 28-h period and produced 2.6% ash. Average emissions of CO, NO_x and SO₂ were 2210, 40.4 and 3.7 mg/m³, respectively. Thermal efficiency was 68.0%. A validation combustion trial performed a year later with 90 CS bales confirmed good heating performance and the potential to lower ash content (6.2% average).

Keywords: corn stover; wheat straw; round bale; combustion; flue gas emission; calorific value; ash content; energy balance

1. Introduction

In Canada, the five major cultivated grains are wheat, canola, corn, barley and soybeans, with a total yearly production of 65 Mt [1]. According to Lal [2], corn and soybeans have a straw/grain ratio

of 1, while it is 1.5 for wheat, barley and canola. Residual biomass production (straw and stover) is thus well above 70 Mt per year. It is estimated that 30% to 60% of this amount may be harvested sustainably without affecting the future productivity of cropped areas [3].

Meanwhile, the use of crop residues as a solid fuel for energy has been discussed and analyzed for several decades. In 1981, Lockeretz [4] compared costs and benefits of using crop residues for energy. The author suggested renewable energy policies to be developed in close coordination with soil conservation programs. The issue still needs to be addressed today, especially for corn stover (CS) as an intensive crop [5–7]. Considering 30% removal of stover and straw, a very large quantity of biomass (>20 Mt/yr) is still potentially available for various applications such as cellulosic feedstock for distillation, food processing, co-firing, combined heat and power generation, hot water and building heating. In contrast with fossil fuels, crop residues are generally more dispersed over a large territory, have a high moisture content, a low bulk density, and a low heating value [8]. In many cases, decentralized usage of crop residues can be profitable in remote areas where natural gas or woody biomass are costly and not produced locally [9].

The use of crop residues as a solid fuel for heating can be implemented with existing technology on a small scale, as long as exhaust air quality is well controlled. However, combustion of such biomasses can cause different problems like fouling, slagging, bed material agglomeration, and premature corrosion of the furnace metallic components [10]. The high level of alkalis (chloride, potassium) in crop residues may lead to aerosol formation, resulting in ash melting temperature drop, fouling and emission issues. An additive like clay may help to reduce the alkali release from straw and CS [11]. Another way to achieve this, and lower the moisture content as well, is to harvest CS in the spring after winter washing [12].

The combustion of round bales of CS, cotton stalks and soybean residues was done in 1981 by Sumner *et al.* [13] for the purpose of grain drying. They observed mitigated success with CS because of its relatively high bale density compared to cotton stalks (142 vs. 99 kg/m³) and incomplete combustion of the bale core. Today, many efficient straw burners with power ranging from 35 to 5000 kW are commercially available, mainly manufactured in Europe.

A poultry (turkey) farm in Port Williams, Nova Scotia, Canada, recently converted a propane heating system to a biomass heating facility using round bales of straw [14]. As the farmer produces his own wheat and corn grain for feeding, a substantial amount of straw and stover is available. The combustion equipment was originally designed and recommended for cereal straw-type bales. The objective of this research was to evaluate the potential use of CS bales in the same boiler without major modifications. The experimental approach was to evaluate flue gas emissions, residual ash, and the energy balance of wheat straw (WS) and CS combustion in the Farm 2000 boiler designed for burning round bales.

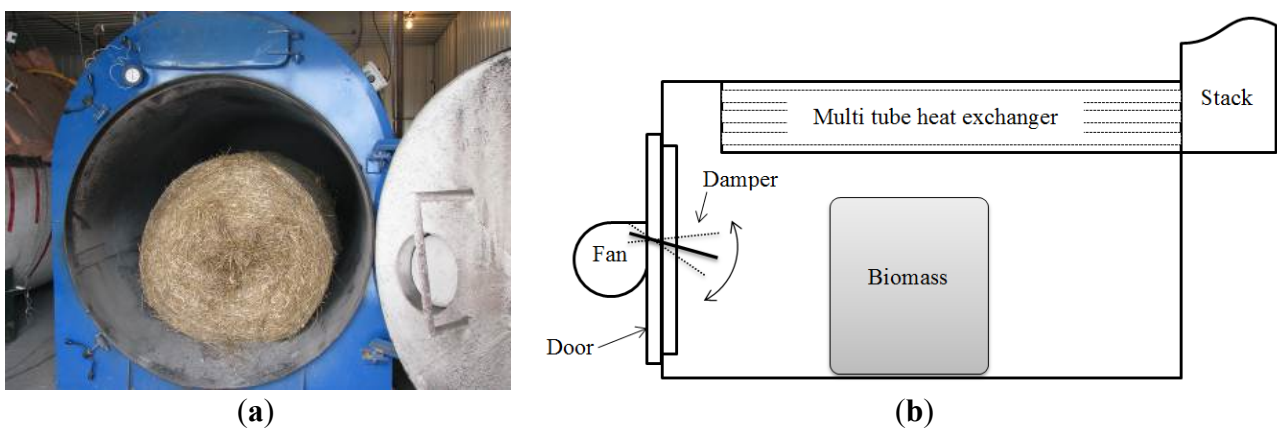
2. Material and Method

2.1. Biomass Boiler, Hydronics System and Barn Description

The heating system consists of a straw bale burner that transfers energy to hot water up to 80 °C which is used to maintain warm temperatures in a poultry barn. The boiler is a Farm 2000 model

BB254/2 (Teisen Products Ltd., Worcestershire, UK) that can hold up to two round bales of 1.52 m diameter and 1.22 m width (Figure 1a). The rated output power is 176 kW with two loads per day (four bales) according to the manufacturer. Bales are loaded with a tractor through a large frontal opening normally closed by a well-sealed door. Heat is transferred to a 3500-L water jacket by a multi tube heat exchanger. Flue gas is exhausted by a 362-mm diameter stack without any filtering system. The boiler includes a partially automated primary air controller. The fan and damper assembly is mounted on the front door (Figure 1b). Based on operator experience, the damper downward travel time and fan intensity are adjusted prior to combustion. For WS, the low speed fan setting and the damper downward movement were used during the first 20 min, and then the full fan speed was utilized until the end of bale combustion. For CS, the low speed and damper downward movement were set at 40 min, and then fan setting was adjusted at full speed until the end of bale combustion.

Figure 1. (a) The combustion chamber; and (b) a schematic of boiler's main components.



Hot water is stored in a 30,000-L water tank (2.45 m diameter, 6.5 m length) prior to being pumped through a 352-kW plate exchanger where heat is transferred to the barn. The tank is partially insulated with six-inch rockwool (R24) on the upper half plus a Flex foil (R4) jacket on all surfaces of the tank. Water is pumped to the storage tank with a centrifugal pump (rated 18 m³/h at 65 kPa head pressure). A similar pump delivers the water flow to the barn. All pipes are in steel except the underground high-density polyethylene (HDPE) pipes that link the boiler room to the barn network. A propane boiler is located in the barn for backup, for high heating demand periods and during biomass boiler maintenance.

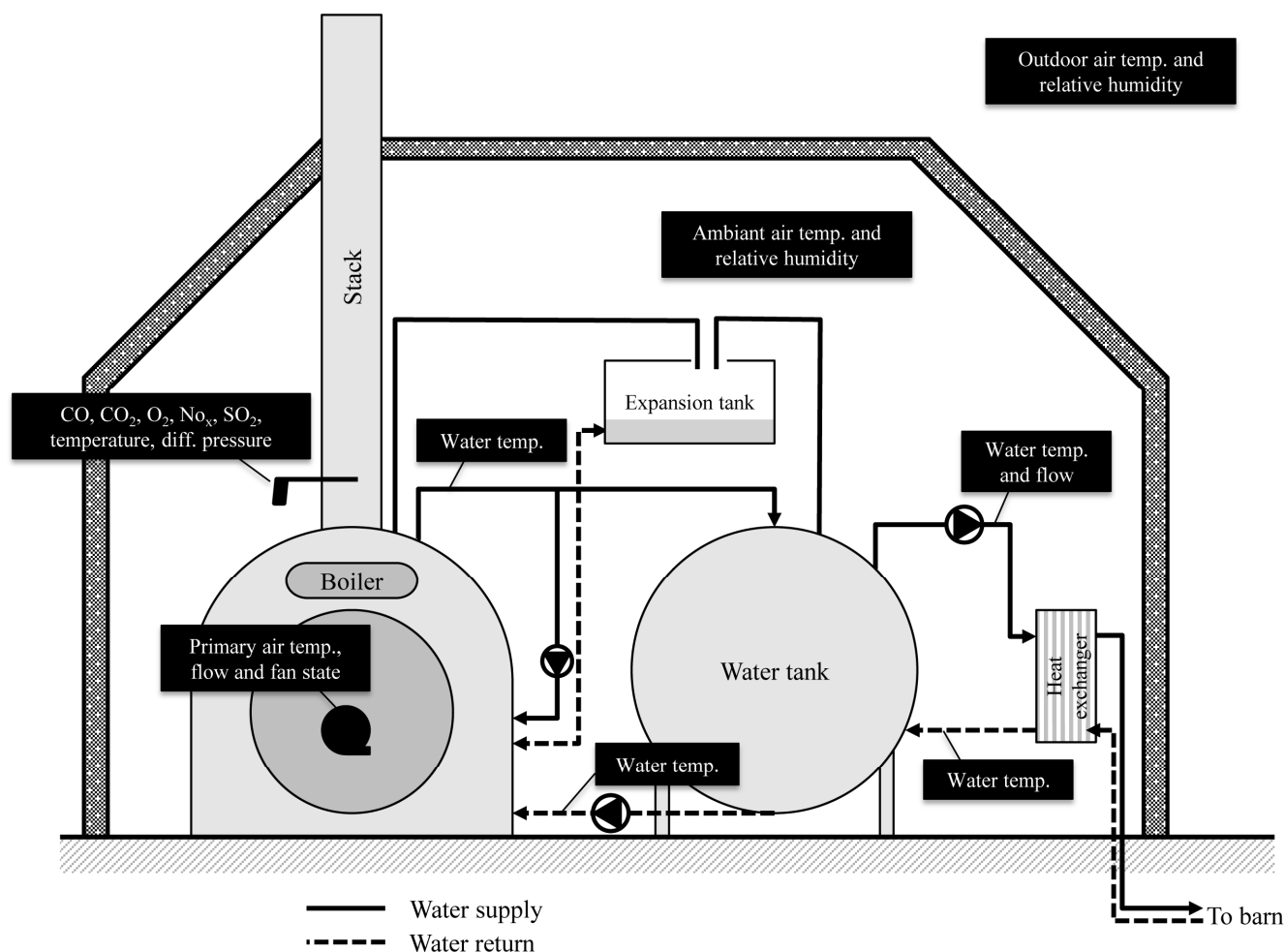
The barn has two floors of 91.4 m × 13.4 m for a total heated volume of 6541 m³. Each floor has six 22-kW heat exchangers, each mounted with an axial fan, to maintain the set point temperature according to flock growing stage, humidity control and ventilation rate. Normal air temperature is 36 °C at day one, gradually decreases down to 19 °C at day 50 of turkey bird life and is maintained constant thereafter. Air exchange rate is about 2500 m³/h at day one and gradually increases up to 40,000 m³/h at day 70 for each floor. For each 77-day growing cycle, the barn can hold up to 14,000 turkeys (7000 per floor).

2.2. Monitoring Devices

Standalone data acquisition devices (HOBO logger from ONSET Corp., Bourne, MA, USA) were installed in different locations in the boiler room to measure water and air temperature and pump states

(Figure 2). Water temperatures were taken with surface thermocouples at boiler exit (primary flow), boiler return, tank exit and tank return. Air temperatures were taken at the boiler intake (primary air) and inside and outside the boiler room. Relative humidity was also monitored inside and outside the boiler room. Primary air fan state and pump state were logged. Temperature, relative humidity and state were sampled every 5 min. Primary flow was monitored periodically using an ultrasonic flow meter (Hoskin Scientific, model DMTFH-12-A, Saint-Laurent, QC, Canada).

Figure 2. Schematic of the heating system (boiler room), probe location and description.



Flue gases were monitored with a portable combustion analyzer (Bacharach, model ECA 450, New Kensington, PA, USA). The gas sampling probe was located at the bottom of the stack and a temperature probe was mounted upstream in the boiler's primary air blower. Sampling rate was 5 min. Measured parameters were oxygen (O₂, %), carbon monoxide (CO, mg/m³), nitric oxide (NO, mg/m³), nitrogen dioxide (NO₂, mg/m³), sulfur dioxide (SO₂, mg/m³), flue gas temperature (°C), and differential pressure (mbar). From these parameters, calculations were performed by the analyzer for CO₂ (%), NO_x (mg/m³), combustion efficiency (%), and excess air ratio. The combustion efficiency is defined as the net calorific value (NCV) of the fuel minus the sum of heat losses in unburned components exiting the stack divided by NCV. The excess air ratio is the amount of air that exceeds the need for a stoichiometric combustion.

2.3. Biomass Characterization Prior to Combustion

WS bales were harvested on the same farm where the boiler is located in Port Williams, Nova Scotia, Canada. They were formed with a fixed chamber round baler (Claas ROLLANT 250 without chopper, Claas, Harsewinkel, Germany) in fall 2011 and stored under shelter. Meanwhile, CS bales were harvested in spring 2011 in Sainte-Hélène-de-Bagot (Québec, Canada) according to a procedure developed by Lizotte and Savoie [15]. Because of the high moisture content of CS at grain harvest in late fall, which is between 35% and 50% [12] and the slow natural drying at that time of the year, stover was collected in the following spring to facilitate dry storage without further treatment after baling. Indeed, six months after grain harvest, a Hiniker model 5610 flail cutter-windrower (Hiniker Company, Mankato, MN, USA) collected from 30% to 50% of the residual corn fiber that had dried down naturally to less than 15% moisture. The stover bales were formed with a variable chamber round baler (New Holland 648, New Holland, PA, USA), stored under shelter and transported by truck in January 2012 to Nova Scotia.

Prior to combustion, every bale of WS and CS was weighed, measured (diameter and length), and sampled for moisture content (MC) determination, ash, and energy content. A sample of at least 100 g was extracted from each bale with a core probe (31 mm diameter, 61 cm long). Samples were weighed in a paper bag and oven dried for 24 h at 103 °C for MC determination. Gross calorific value (GCV) and ash content were determined in the laboratory with a calorimeter (Parr 6100 Oxygen Bomb Calorimeter with 1108P Oxygen Combustion Bomb, Parr Instrument Company, Moline, IL, USA) to meet standard EN 14918:2009 [16]. Ash content was measured with an ash analyzer (LECO TGA701 Thermogravimetric Analyzer, LECO, St. Joseph, MI, USA), complying with standard ASTM D7582-10 [17].

2.4. Combustion Procedure

As the combustion rate depends on the heating needs and biomass properties, conservative assumptions were made to plan the experiment. According to the boiler operator, a single bale can provide heat for up to 4 h. Within the limited time scheduled to perform the experiment and a definite number of bales available, six bales of WS within a 24-h period followed by twelve bales of CS within a 48-h period were burnt. Prior to each biomass type trial, the combustion chamber and the tube heat exchanger were cleaned while ashes were removed using a tractor front-end loader. Each bale was loaded in the combustion chamber at a distance between 1.25 and 1.5 m from the door. Primary air fan settings were adjusted according to the operation manual. Only one bale at a time was loaded and burned except during the night when two bales were placed typically at 11 p.m. until the next morning. During combustion trials, process air and water conditions, pump state, and flue gases were monitored continuously to ensure proper energy balance calculations. At the end of a trial (six WS bales or twelve CS bales), ashes were removed and weighed using a high capacity floor scale (0.2 kg resolution).

2.5. Energy Balance Calculation

An energy balance was calculated for each bale load as described by Equation (1). The total energy available from the bale load (E_{Fuel}) was estimated from the NCV which is the GCV estimated

experimentally and corrected for moisture content and hydrogen, as explained in Section 3.1 below. Temperature data were collected every 5 min in the boiler (T_B), in the water tank (T_T), at the hot water outlet (T_O) and at the water return (T_R) from the heat exchanger. An average water flow (m' , in kg/s) was measured and a standard heat capacity was considered (c_p , 4.18 J/g/°C). The energy loss (E_{Loss}) was the sum of energy dissipated to the surroundings, the chimney stack and the ash box. These losses were not measured but estimated as a group from other terms. The change in stored energy in the boiler and in the tank was estimated as a function of mass of water (m_B and m_T , respectively) and temperature change during the combustion. The energy transfer was measured at each measurement interval (i), for the total number of intervals (n). The change in energy in the boiler and the tank need to be estimated simply between the first ($i = 1$) and the last ($i = n$) interval. The energy balance equation can be expressed as follows:

$$E_{Fuel} = E_{Loss} + m_B c_p (T_{Bn} - T_{B1}) + m_T c_p (T_{Tn} - T_{T1}) + \sum_{i=1}^{i=n} m' c_p (T_{Oi} - T_{Ri}) \Delta t_i \quad (1)$$

Energy loss can be estimated since all other terms are measured and calculated experimentally.

2.6. Combustion Validation Trials with CS

A second set of combustion trials was done between January and April 2013 with 90 CS bales that were harvested on the farm in Nova Scotia during spring 2012. CS bales for the 2013 validation trial were formed with a fixed chamber round baler (Claas ROLLANT 250 without chopper) which resulted in lower density than bales used in the previous 2012 trial (which were formed with the variable chamber baler). Between spring 2012 and winter 2013, CS bales were stored under shelter. The purpose of this second set of trials was to validate combustion rate, ash content and ash rate removal. All bales were measured and weighed at harvest; they were weighed again just before being burned. One bale out of five was sampled for moisture content. No energy balance was performed during these validation trials. Ashes were collected and weighed after each trial which comprised 30 bales.

3. Results and Discussion

3.1. Biomass Characteristics

Table 1 reports average properties of WS and CS bales used for the January 2012 combustion trials. For WS bales, average moisture content and bale mass were 14.6% and 183.2 kg, respectively. Bale diameter and width averaged 1.47 m and 1.20 m, respectively, while average density was 77.1 kg DM/m³. For the CS bales, moisture content and mass averaged at 13.6% and 190.2 kg, respectively. Diameter was 1.32 m and width was 1.15 m. Thus, CS bale density was 104.5 kg DM/m³ and 35% higher than WS bale density.

All samples were analyzed in the laboratory for GCV and ash content. NCV was determined using Equation (2) [18], where GCV units are MJ/kg fuel (dry basis—d.b.); w is moisture content in % (wet basis—w.b.); and h is concentration in hydrogen (5.5% d.b. as estimated in the literature for straw and stover [19]). This equation is a good estimate for any woody and herbaceous biomass fuel:

$$NCV = GCV \left(1 - \frac{w}{100}\right) - 2.444 \cdot \frac{w}{100} - 2.444 \cdot \frac{h}{100} \cdot 8.936 \left(1 - \frac{w}{100}\right) \left[\frac{MJ}{kg}, w.b.\right] \quad (2)$$

Table 1. Characteristics of wheat straw (WS) and corn stover (CS) bales measured in the laboratory.

Parameter	Unit	WS (six bales)				CS (twelve bales)			
		Ave.	S.D.	Min.	Max.	Ave.	S.D.	Min.	Max.
Moisture content	%	14.6	0.7	13.6	15.5	13.6	1.4	12.7	17.7
Bale mass	kg	183.2	13.7	166.6	198.6	190.2	12.4	163.4	206.8
	kg DM	156.5	11.9	144.0	170.7	164.5	12.5	134.5	180.4
Diameter	m	1.47	0.03	1.43	1.52	1.32	0.04	1.25	1.39
Width	m	1.20	0.00	1.20	1.20	1.15	0.02	1.12	1.18
Volume	m ³	2.04	0.09	1.91	2.16	1.58	0.11	1.40	1.76
Density	kg/m ³	90.2	8.7	79.6	103.8	120.8	6.7	112.0	131.8
	kg DM/m ³	77.1	7.6	68.8	89.2	104.5	6.3	96.1	114.2
Gross calorific value	MJ/kg d.b.	18.91	0.33	18.55	19.47	17.04	0.87	15.90	18.72
Net calorific value	MJ/kg w.b.	14.77	0.23	14.54	15.07	13.35	0.74	12.51	14.98
Total gross energy	MJ/bale	2955.9	188.7	2731.6	3167.5	2800.5	227.5	2422.1	3226.1
Total net energy	MJ/bale	2702.7	169.9	2503.4	2894.4	2540.1	216.6	2189.9	2957.9
Ash content	% d.b.	1.82	0.22	1.59	2.14	11.70	5.32	5.09	22.14

GCV (MJ/kg d.b.) averaged 18.91 for WS and 17.04 for CS (Table 1). NCV based on average moisture content were 14.77 and 13.35 MJ/kg w.b., respectively. Ash content obtained with the thermogravimetric analyzer (TGA) was 1.82% for WS and 11.70% for CS. Ash for WS had a small range (1.59% to 2.14%) compared to CS (5.09% to 22.14%). According to Van Loo and Koppejan [18], ash has a negative contribution to GCV. Analyses showed that the high ash content of CS resulted in a lower GCV compared to WS.

3.2. Combustion Trials

Six WS bales were burned from 15:40 on 23 January 2012 to 19:55 on 24 January 2012 (about 28 h; Table 2). Bales were placed one at a time in the furnace except during the night when two WS bales were placed together (bales number S3 and S21). The average combustion time per bale was 280 min with an average burning rate of 33.52 kg DM/h for WS.

The 12 CS bales burned over a period of 52 h from 20:00 on 24 January to 23:55 on 26 January. Average combustion time per bale was 9% shorter compared to WS (255 vs. 280 min) while CS bales were 5% heavier than WS bales (165 vs. 157 kg DM). The biomass burning rate was therefore 15% higher for CS than for WS (38.69 vs. 33.52 kg DM/h). The higher burning rate of CS was partly related to the average lower exterior temperature (0 vs. 5.4 °C) during CS trial and the lower net calorific value of CS (13.35 vs. 14.77 MJ/kg w.b.).

The quantity of ash removed from the boiler is shown in Table 3. It includes ash in the combustion chamber, in the heat exchanger and in the bottom stack. It does not include fly ash in the flue gas which was not monitored. Ash produced by the combustion of 48 WS bales for normal heating (between 13 January 2012 and 23 January 2012) was weighed and identified as the “pre-combustion

trial” (PCT). This PCT was followed by individual bale monitoring. Ash content of WS bales during the PCT was 1.70%; it was 2.55% on average during the six individual WS bale combustion. These ash levels were comparable to the level measured in the laboratory (1.82%). However, they were lower than those reported in the literature, which ranged from 2.69% to 13.5% d.b. with an average of 6% d.b. [19]. Ash production rates were 0.53 and 0.86 kg/h for the 48 and 6 WS bale trials, respectively. CS ash content after the 12-bale combustion trial averaged 9.17% d.b., which was lower than the TGA value (11.70% d.b.). Various ash levels for CS are reported in the literature: 4% for standing stalk, unwashed [20] and 5.9% for small stover bales harvested in the spring six months after grain harvest [21]. Higher values and variations observed for ash content of CS are probably linked to the harvesting method and soil contamination. Actually, the Hiniker mower-windrower tended to mix soil dust into the stover. The contamination depends on machinery operation, soil type and moisture, frost cover and distance of rotary parts from ground level. Ash production rate during the combustion of the 12 CS bales averaged 3.5 kg/h, *i.e.*, more than four times higher than ash production with WS bales. This implies that ash removal operations and multi tube exchanger cleaning will be more frequent with CS than with WS.

Table 2. Combustion trial loading sequence with burning duration and rate (2012 trials).

Bale ID	MC (%)	Mass (kg)	Mass (kg DM)	Start date and time	End date and time	Duration (min)	Burning rate (kg DM /h)	Ext. temp. (°C)
WS								
S1	14.4	193.2	165.4	01/23 15:40	01/23 18:55	195	50.88	0.1
S2	14.0	198.6	170.7	01/23 19:00	01/23 23:15	255	40.17	2.0
S3	13.6	166.6	144.0	01/23 23:15	01/24 09:35	620	29.93	5.5
S21	15.0	194.4	165.2	Dual burning with S3				
S4	15.1	174.0	147.8	01/24 09:40	01/24 13:45	245	36.19	11.2
S5	15.5	172.2	145.6	01/24 13:50	01/24 19:55	365	23.93	8.3
Ave.	14.6	183.2	156.5	-	-	280 ^a	33.52	5.4
Sum	-	1099.0	938.7	-	-	1680	-	-
CS								
C6	13.1	198.2	172.3	01/24 20:00	01/24 23:30	210	49.22	5.8
C7	13.7	168.6	145.5	01/24 23:35	01/25 06:25	410	21.30	3.4
C8	12.8	190.0	165.7	01/25 06:30	01/25 10:55	265	37.52	3.3
C9	13.8	191.6	165.2	01/25 11:00	01/25 14:55	235	42.18	4.1
C10	12.9	195.2	170.0	01/25 15:00	01/25 18:20	200	50.99	1.7
C11	12.8	206.8	180.4	01/25 18:25	01/25 22:40	255	42.44	−0.4
C12	13.9	199.0	171.3	01/25 22:45	01/26 03:55	310	33.15	−0.5
C13	13.8	190.4	165.2	01/26 04:00	01/26 07:45	225	43.79	−3.3
C14	12.8	191.6	166.1	01/26 07:50	01/26 11:40	230	43.61	−1.7
C15	12.7	197.4	172.4	01/26 11:45	01/26 15:35	230	44.97	0.0
C16	12.9	190.4	165.9	01/26 15:40	01/26 20:40	300	33.18	−6.0
C17	17.7	163.4	134.5	01/26 20:45	01/26 23:55	190	42.46	−6.4
Ave.	13.6	190.2	164.5	-	-	255	38.69	0.0
Sum	-	2282.6	1974.4	-	-	3060	-	-

^a: Average per bale.

Table 3. Ash content from pre-combustion trial (PCT) WS and individually monitored WS and CS bales during January 2012 combustion trials.

Biomass	Bales burned	Mass burned	Accumulation period	Ash and unburned content		Ash production rate
-	-	kg DM	h	kg	% d.b.	kg/h
PCT WS	48	7517	240	127.6	1.70	0.53
WS	6	938.7	28	24.0	2.55	0.86
CS	12	1974.4	52	181.0	9.17	3.48

3.3. Flue Gas Emissions

Table 4 reports gas emissions during the 2012 combustion trials of some individually monitored bales, including supplementary WS bales S22 and S23.

Table 4. Flue gas emission measurements for WS and CS bale combustion.

Bale ID	Stack Temp. (°C)	Intake Temp. (°C)	Mass air flow (kg/s)	Eff. (%)	Excess air ratio (%)	O ₂ (%)	CO ₂ (%)	CO (mg/m ³)		NO _x (mg/m ³)		SO ₂ (mg/m ³)	
-	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.	Ave.	Max.	Ave.	Max.	Ave.	Max.
WS													
S1	275.0	27.1	0.30	68.9	181	13.7	7.4	3533	7148	108.8	179.0	7.9	76.3
S2	249.3	30.8	0.27	70.2	110	15.1	10.0	1644	4622	58.3	121.4	1.8	6.9
S3–S21	181.6	34.3	0.26	70.8	135	17.0	9.5	2357	8999	11.3	91.4	8.0	24.3
S22	181.8	22.8	0.24	67.4	178	16.8	7.5	1719	3604	6.1	17.3	0.7	3.0
S23	206.0	26.2	0.28	63.1	220	17.3	6.4	1799	4366	17.4	36.5	0.1	1.4
Ave.	218.7	28.2	0.30	68.1	165	16.0	8.2	2210	-	40.4	-	3.7	-
CS													
C7	139.0	34.9	0.21	69.6	235	18.5	6.7	1724	7604	2.3	12.5	4.7	10.4
C8	195.9	24.0	0.27	68.5	241	16.6	6.7	3132	7782	10.2	29.3	2.6	33.1
C9	200.5	24.0	0.28	69.0	203	15.4	7.0	3564	7915	3.2	11.3	1.1	13.0
C14	212.4	19.1	0.28	67.6	219	15.5	6.5	3592	8571	16.8	36.2	3.6	95.0
C15	194.9	28.5	0.25	68.5	227	16.4	6.3	3238	8005	10.6	31.3	1.2	19.0
C16	195.1	23.0	0.23	67.9	166	16.4	8.0	1774	6023	6.7	17.3	0.8	4.6
C17	213.8	25.9	0.27	63.9	218	17.0	6.6	2053	6939	19.1	44.7	0.7	11.2
Ave.	193.1	25.6	0.26	67.8	215	16.6	6.8	2725	-	9.8	-	2.1	-

Concentrations reported are at pressure, temperature and O₂ levels within the stack (not normalized at O₂ reference). Average stack temperatures were 219 and 193 °C for WS and CS, respectively. Average primary air mass flow was 0.30 and 0.26 kg/s, respectively. Combustion efficiency was calculated by the analyzer based on measured parameters. Similar combustion efficiencies of about 68% were obtained for WS and CS. Excess air ratio was higher for CS, averaging at 215% compared to 165% for WS. Average oxygen levels were around 16% for both biomasses, which is higher than normally observed in literature (between 5% and 8% for a continuously fed grate furnace [18]). Since the combustion process is a batch type and fuel-air contact was not homogenous, higher excess

of air for CS did not reduce CO level compared to WS (2725 vs. 2210 mg/m³). Average NO_x and SO₂ were 40.4 and 3.7 mg/m³ for WS and 9.8 and 2.1 mg/m³ for CS, respectively. The combustion of CS in a bale boiler has demonstrated higher levels of CO, but lower levels of SO₂ and NO_x, when compared to continuous combustion of CS pellets in a pellet boiler where CO, SO₂ and NO_x were 54, 100 and 252 mg/m³, respectively [22]. However, there is no Canadian legislation regarding in-stack emission limits for CO, NO_x, and SO₂, but only for surrounding air quality. Beauchemin and Tampier [23] reported that German legislation for small 50–100 kW straw furnaces built before 2008 limits CO emissions to less than 2000 mg/m³; the limitation is reduced as furnace output power increases. The NO_x concentration is limited to 200 mg/m³ for wood furnace under 2 MW (at 11% vol. O₂). The Farm 2000 boiler would meet the German requirement for NO_x but not for CO. A more efficient combustion could be obtained by adding an oxygen sensor within the stack to vary primary air flow.

Figures 3 and 4 show typical flue gas emissions for WS and CS. Oxygen level in exhaust gases was lower for the first 2 h and then increased to normal concentration (around 20%) when less biomass was available for combustion according to primary air input. CO levels are relatively stable for the first 2 h and then decrease (for a single bale batch). Higher concentrations of NO_x were generally observed when O₂ was lower, particularly for WS (about 20 to 100 mg/m³ of NO_x) and stover (10 to 30 mg/m³ of NO_x).

Figure 3. Typical flue gas emission concentrations for WS (bale S1 shown).

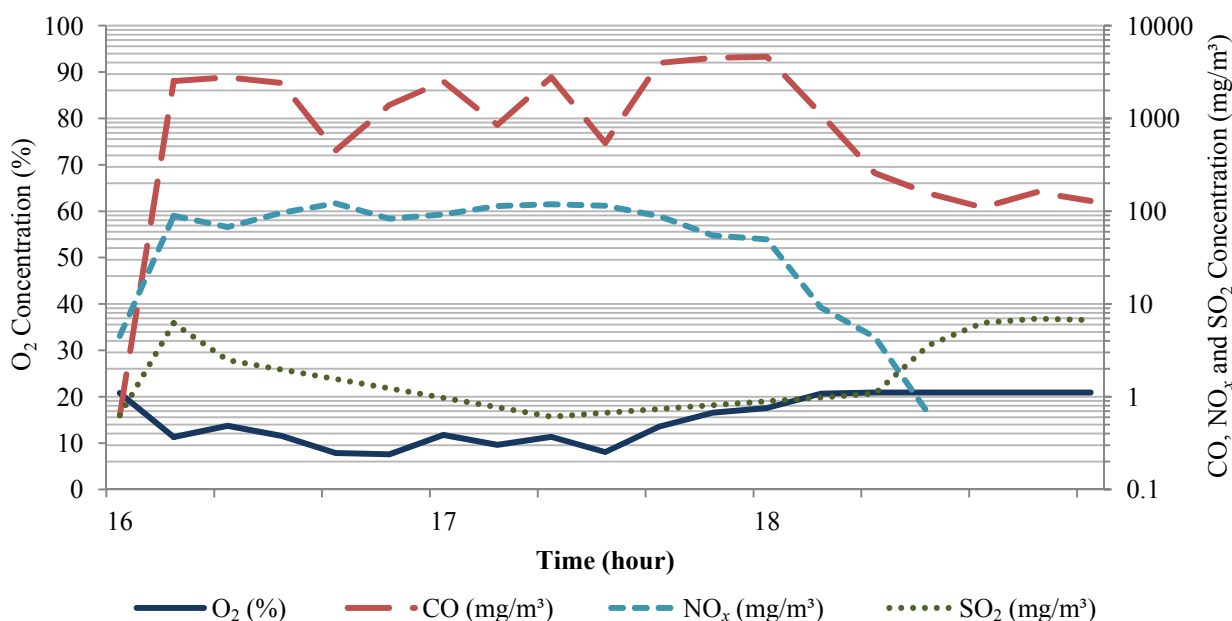
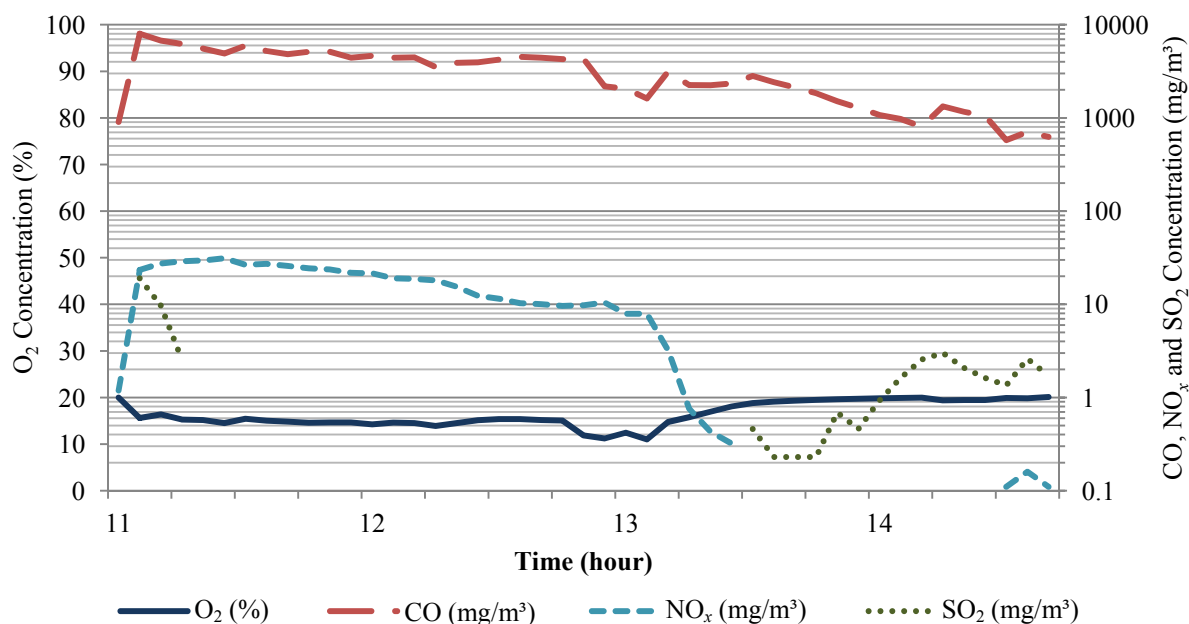


Figure 4. Typical flue gas emission concentrations for CS (bale C14 shown).

3.4. Energy Balance

Table 5 shows energy balance for each trial. Losses were calculated by difference as described in Equation 1. Thermal efficiency is the ratio of accumulated and output energies over total fuel energy (biomass NCV). For WS, total bale energy content was 16,216 MJ. About 9500 MJ (59%) were transferred from the hot water tank to the barn's plate heat exchanger and 1400 MJ were accumulated at the end of the trial. Total losses (by difference) were 5190 MJ for an overall thermal efficiency of 68%. With an operation period of 1680 min (28 h), the average output power of the boiler was 108 kW. For CS, total bale energy content was 30,481 MJ. Energy transferred to the heat exchanger was 13,332 MJ (about 44% of total NCV) while energy accumulated in the tank was −960 MJ (less energy than initially available). Total losses were calculated at 18,036 MJ with a thermal efficiency of 40.8%. The average output power was only 68 kW based on a 3060 min (52 h) trial duration. In all cases, there was no significant energy accumulation in the boiler water jacket itself. The thermal efficiency differences between CS and WS can partially be explained by the bale characteristics and the boiler design. As the CS bales were denser, less biomass area was in contact with the primary airflow to make them burn properly compared to lower density WS bales. According to the gas analyzer data, excess air ratio was higher for CS (215% vs. 165%) which may lower the combustion temperature in the combustion chamber (193 °C for CS vs. 219 °C for WS, see Table 4), and affects simultaneously the boiler's thermal efficiency, operational reliability and environmental performance (emissions from the unit) [24]. The Industrial Boiler Owners indicates that boiler efficiency can be increased by 1% for each 15% reduction in excess air [25]. It has also been demonstrated in the literature that biomass fuels with high ash content will produce more fly ash that may deposit on the surface of boiler tubes, which decrease the efficiency of heat transfer in the boiler [26]. A soot layer of 0.8 mm thick can reduce heat transfer by as much as 12% [27]. For biomass fuels with high ash content it is best to have an automatic heat exchanger cleaning system to maintain boiler efficiency.

Table 5. Energy balance for WS and CS 2012 combustion trials.

Biomass type	Biomass	Boiler	Tank		Total losses	Thermal
	NCV (MJ)	Accumulated (MJ)	Output (MJ)	Accumulated (MJ)	(By difference) (MJ)	Efficiency (%)
WS	16,216	117.7	9,509	1,400	5,190	68.0
CS	30,481	72.8	13,332	−960	18,036	40.8

3.5. Combustion Validation Trials Results

Table 6 reports data for three 30-bale validation combustion trials in 2013 with CS. Most of the time, combustion was conducted with a single bale at a time. However, two bales at a time were put in the boiler in some cases, especially during the night. Average bale mass was 175.4 kg (153.5 kg DM) and moisture content was 12.5%. With an average diameter and width of 1.4 m and 1.22 m, respectively, the dry matter density of CS bales in 2013 was 82.7 kg DM/m³, 21% lower than density of CS bales in 2012 (104.5 kg DM/m³). The first validation trial was conducted over a nine-day period where the average combustion period per bale was 412 min and average combustion rate was 27.1 kg DM/h. Trial 2 in 2013 was done over an effective period of 14 days. The average combustion time per bale was higher than trial 1 with 624 min/bale. Thus, the average combustion rate was lower at 19.0 kg DM/h. For the third trial, 12 days were necessary to burn the last 30 bales. The average interval between two bale loadings was longer (671 min) but the combustion rate was about the same as trial 2 (19.5 kg DM/h). These differences may be explained by the lower heating need during trial 3 (higher outdoor temperature) and longer overnight periods without loading.

Table 6. Average data for 30-bale CS combustion validation (2013 trials).

Trial	MC	Bale mass		Start date	End date	Duration	Burning rate	Ext. temp.
	%	kg	kg DM			min/bale	kg DM/h	°C
1	13.3	182.4	158.1	2013-01-30	2013-02-08	412	23.0	−4.7
2 ^a	12.4	176.4	154.5	2013-02-17	2013-03-23	624	14.8	−2.3
3	11.7	167.5	147.9	2013-04-12	2013-04-23	537	16.5	6.1
Ave.	12.5	175.4	153.5	-	-	524	17.6	−0.3

^a: Trial 2 was interrupted from 26 February until 17 March for mechanical maintenance (broken pump).

Compared to the 2012 trial, bales in 2013 were lighter (153.5 vs. 164.5 kg DM), had a lower density (82.7 vs. 104.4 kg DM/m³), and had a slightly lower moisture content (12.5 vs. 13.6%). Average combustion time per bale in 2013 was more than double and burning rate was half the value obtained in 2012. Even if average outdoor temperature was similar (0 vs. −0.3 °C), energy consumption was lower than in the 2012 trial. According to the farmer, more birds were placed in the barn, thus generating more of their own heat. Also, ventilation was improved, which keeps the barn drier, and less heat was required.

Table 7 reports total mass burned and ash produced in 2013. The average dry matter burned during each trial was 4605 kg over an average period of 262 h of continuous operation. Ash collected in 2013 represented 7.90%, 5.75% and 4.93% d.b. of total mass burned for trial 1, 2 and 3, respectively. The average 2013 CS ash content was lower (6.19%) than the 2012 CS ash content (9.17%); it was

still higher than 2012 WS ash content (1.7% and 2.55% for PCT and individual bale trial, respectively). The average ash production rate with CS in 2013 was three times lower than in the CS 2012 trial (1.09 vs. 3.48 kg/h) but only twice more than WS (0.56 kg/h weighted average). Burning CS will require more maintenance than WS. However, with good production management practices (*i.e.*, barn ventilation, flock size, clean stover harvest), biomass consumption can be lowered as well as boiler maintenance.

Table 7. Ash content and production rate for CS (2013 trials).

Trial	Bales burned	Total mass burned	Accumulation period	Ash content		Ash production rate
		kg DM	h	kg	% d.b.	kg/h
1	30	4,743.2	206.2	374.6	7.90	1.82
2	30	4,634.0	312.2	266.4	5.75	0.85
3	30	4,437.9	268.3	219.0	4.93	0.82
Ave.	30	4,605.0	262.2	286.7	6.19	1.09
Sum	90	13,815.0	786.7	860.0	-	-

4. Conclusions

Combustion trials of WS and CS bales in two consecutive years in a Farm 2000 commercial boiler showed differences between biomass characteristics, energy balance, ash content and flue gas emissions. Both biomasses were relatively dry (14.6% and 13.6%), but CS bales harvested in 2011 with a variable chamber baler were 35% denser than WS bales harvested with a fixed chamber baler (104.5 vs. 77.1 kg DM/m³). CS bales harvested in 2012 with a fixed chamber baler had an average density of 82.7 kg DM/m³ which resulted in a more complete combustion with less ash and unburned residues. The heating system's overall thermal efficiency was 68% with WS and 41% with high density CS in the first year. Ash content of CS was considerably higher than ash in WS in 2012 (9.2% for CS vs. 1.7% for a pre-combustion trial of WS and 2.55% for individual WS bale combustion trials in 2012). The lower density CS bales in the second year produced one third less ash and unburned residue (6.2%) than in the previous year with high density CS bales. The highest CO levels were observed with CS in the first year (average of 2725 mg/m³ with a peak at 8571 mg/m³) while NO_x emissions were higher for WS (40.4 vs. 9.8 mg/m³). The limited insulation, heat losses in the flue gas, the high ash content of the biomasses and the basic combustion process controller (mainly for oxygen input) contributed to reduce overall system efficiency. Thus, the Farm 2000 has good potential for heat production using baled CS as a complementary energy source to WS if special attention is focused on harvesting methods to reduce ash content and to maintain low-to-medium bale density. These trials also highlighted the importance of using combustion technologies that are adapted to solid fuels in order to achieve lower emissions and higher thermal efficiency.

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Conflicts of Interest

The authors declare no conflict of interest.

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