CLEAN ENERGY TECHNOLOGIES

DRAFT REPORT

Combustion Testing of Switchgrass Pellets on a 1 MW_{th} KMW Industrial Grate Furnace

CANMET Energy Technology Centre – Ottawa
Industrial Innovation Group

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Table of Contents

List of Figures

List of Tables

Introduction

The fall harvested switchgrass pellets evaluated in this study had an energy potential of 18.95 MJ/kg, which is slightly lower in calorific value than wood (Bunker "C" fuel oil is 40 MJ/kg.) As is the case for all solid fuels the physical form of the biomass fuel has a direct bearing on combustion performance. Excessively large particle sizes can give rise to reduced reactivity of the fuel, causing start-up problems and poor combustion performance. Bulk density can have considerable impact on combustion performance, as it influences the fuel residence time in the fire box, fuel velocity and gas flow rate. The fuel was sieved and 88% was larger than 6.3mm. The bulk density is 721 kg/m^3, which is denser than wood chips that are approximately 300 kg/m^3.

The objective of this trail was to perform a combustion test on fall harvested switchgrass pellets as a fuel source. The fuel was provided by REAP Canada to CETC-O for testing to determine the: gaseous emissions, combustion efficiency, total particulate matter emissions, volatile organic compounds and assessment of handling and operating switchgrass pellets as a fuel.

Experimental

The 1 MW(thermal) moving grate furnace installed at the CETC-O laboratories in Ottawa, shown in Figure 1, is typical (at a reduced scale) of the units sold by KMW Energy Inc. for wood chips and hog fuel in the sawmill and pulp and paper industries. It has a thick refractory lining to provide thermal inertia to help maintain steady combustion. Primary air is injected through the grate from below and secondary air to complete combustion is injected above the grate into the flame region. Ash is removed by an auger located below the ash grate. The test furnace is well instrumented with thermocouples. Stack gas sampling is carried out continuously from the stack. The flue gas sample is filtered, dried and passed through a bank of on-line analysers (for O_2, CO_2, CO, SO_2 and NOx). The information from this relatively large pilot plant (1MW$_{th}$ or up to 200 kg/h of dry fuel) collected allows designers and operators to accurately assess the performance of their fuels in large-scale units.

During operation, the test fuel is manually loaded into a hopper equipped with an inclined screw which feeds the fuel to a metering stoker bin. A stoker screw (capable of handling 60 mm nominal particle size) meters the fuel into the combustion chamber. The (1.8 m long by 0.75 m wide) combustion chamber features a reciprocating grate driven by a hydraulic system. Primary (under-fire) and secondary (over-fire) air is provided by two separate fans controlled by variable speed drives. During tests, once the test fuel is in the combustion chamber, adjustments are made to the primary and secondary air, stoker feed rate and grate cycling in order to optimize combustion. At the end of the grate, ash is collected into an ash pit. Automatic removal of the ash is accomplished by an auger which deposits the ash into an external bin. From the furnace the hot flue gas generated from the combustion is drawn through a low-pressure steam boiler by an induced draft fan. It should be noted that for these tests the pilot plant was not equipped with dust and particulate control devices such as cyclones, fabric filters or electrostatic precipitators. The particulate levels are therefore the most that would be generated under actual combustion conditions – any secondary particulate control system would reduce the reported levels. The furnace and boiler are controlled by an automated system which allows for individual setting of fuel feed and furnace parameters.

Particulate Collection

The emissions data that this report provides will allow pollution control suppliers to design a control device that will meet the removal requirements of an end user. The amount of particulate produced will identify the efficiency that can be achieved using different technologies. Table 1 provides a range of typical particulate removal efficiencies that can be achieved with various technologies.

Table 1: Particulate control removal technologies

	Control Efficiency
Mechanical Collectors	65 - 95%
Wet Scrubber	>90%
ESPs & Fabric Filters	93 - 99.8%
Electrified Gravel Bed Filters	~95%

(Cooper and Alley, 2002)

Sampling Procedures

Flue gas samples were collected using, Method 31 - Volatile Organic Sampling Train (VOST) onto a pair of sorbent resin cartridges. With this method, a vacuum pump continuously extracts a sample of flue gas through a heated (130°C) glass-lined probe. The sample first flows through a coiled water-cooled condenser which reduces the sample temperature to 20°C. Next is the first cartridge, which contains Tenax, and is followed by an impinger which collects any liquid condensate. The sample then flows through a second straight water-cooled condenser and the second cartridge, which contains Tenax and charcoal. Before exiting the VOST and moving to the control console, the sample is dried using silica gel. The control console contains the dry gas meter, the vacuum pump and flow meter for controlling the flow through the system. It should be noted that for VOCs isokinetic sampling is not required since the compounds are in a gaseous from at the point of sample collection. Once the samples are collected, the cartridges are sent for analysis by an external laboratory. PSC Analytical performed the analysis on the cartridges using Method 5041A - Analysis for Desorption of Sorbent Cartridges from Volatile Organic Sampling Train (VOST) in conjunction with analysis by GC/MS.

Particulate samples were collected isokinetically from the stack after the induced draft fan. Total particulate sampling was performed in accordance with EPA Method 5, which dictates that the sample port must be between eight and ten diameters length from the last obstruction. The probe and filter are heated and the dry flue gas volume is measured. The flow in the stack was turbulent, so it was assumed that the velocity profile was flat and limited stratification of the particulates would occur.

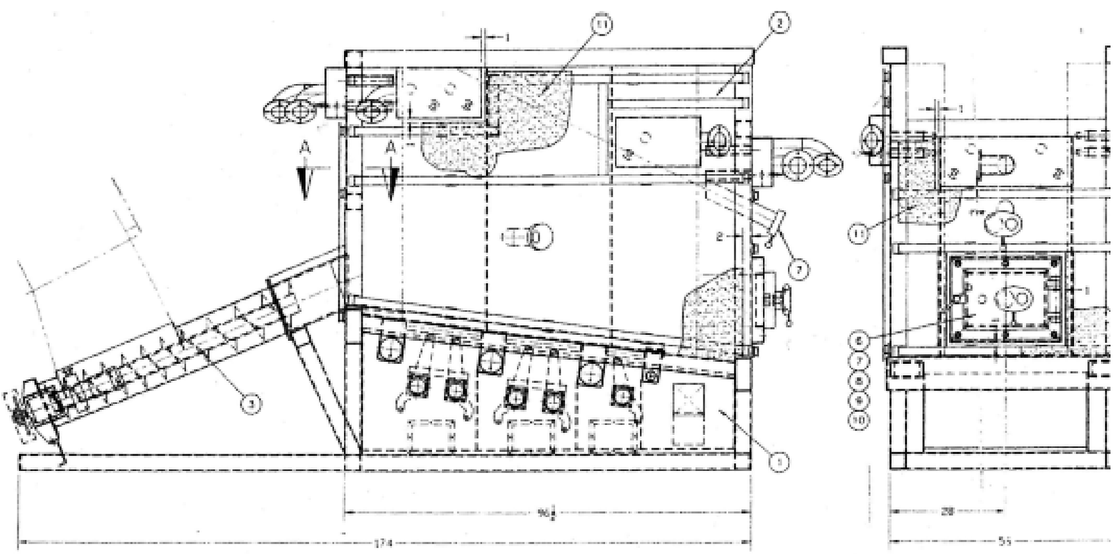

Figure 1: Schematic of the industrial grate furnace at CETC-O

Results and Discussion

On June 20, 2007 CETC-O staff operated the grate furnace for the test on switchgrass pellets. The grate furnace was preheated with natural gas until the chamber temperature exceeded 400^{o}C. A preliminary test was performed to identify potential operating conditions for the combustion test. The pellets were feed into the chamber at those settings and temperatures increased to over 900^{o}C. Steady state conditions were achieved and the analytical testing was completed. Figure 2 shows the combustion chamber during testing.

Figure 2: Combustion in bed burning pellets

The switchgrass pellets arrived on site at CETC-O in bags, which were used to fill barrels as shown in Figure 3. The barrels were weighed to determine the feed rate, which averaged 101 kg/hr. There were no material handling issues and the fuel moved from the hopper through the metering bin and into the combustion chamber without any problems (shown in Figure 4). The pellets were approximately 6.4 mm in diameter and a few cm in length. The bulk density of the material was measured to be 721 kg/m^3, which is denser than wood chips.

Figure 3: Barreled fuel

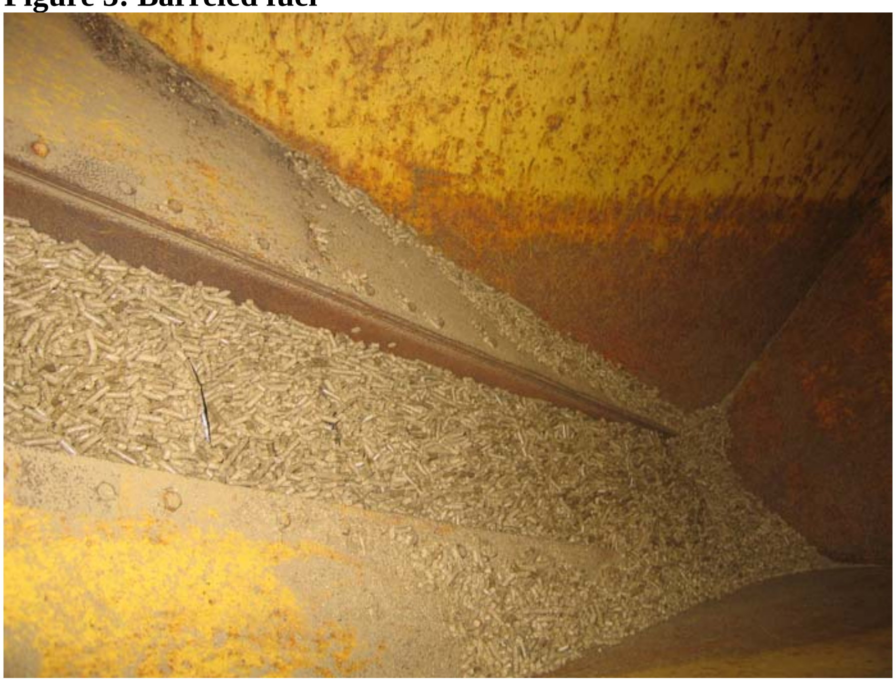

Figure 4 Fuel being fed in hopper

A fuel sample was taken during testing and analyzed in the characterization lab at CETC-O. The results are presented in Table 2. The as received moisture was 7.8 wt%, which is in the range of other biomass fuels where pretreated wood pellets are at 5 wt% to green wood at 55wt%. The calorific value is 18.95 MJ/kg on a dry basis, which is on par to most biomass, which is typically 18 MJ/kg. The ash content is 3.9 wt% which is higher than wood < 1wt%, and in the range of other herbaceous biomass. This fuel is very volatile at 80 wt% volatiles and 16 wt% fixed carbon. Highly volatile fuels require more volume in the combustion chamber and more over fire air to complete the combustion of the fuel. The major metals analysis of the fuel shows that when ashed in a muffle furnace at constant temperature, the fuel has, typical potassium and phosphorous content for herbaceous fuels compared to wood, which would be 2-4% for potassium and <1% for phosphorous. Alkali metals, like these, are indicators of clinkering, as they can reduce the ash melting temperature.

Table 2: Fuel Analysis

Proximate Analysis (WT%)		
	As Analyzed	Dry @ 105°C
Moisture (ASTM D 5142)	7.85	
Ash (ASTM D 5142)	3.57	3.87
Volatiles (ISO 562)	74.09	80.40
Fixed Carbon (by diff)	14.49	15.73
Ultimate analysis (WT%)		
Carbon (ASTM D 5373)	44.42	48.20
Hydrogen(ASTM D 5373)	5.63	6.11
Nitrogen(ASTM D 5373)	0.39	0.42
Sulphur (ASTM D 4239)	0.07	0.08
Oxygen (by Diff)	38.07	41.32
Calorific Analysis (ISO 1928)		
Cal/g	4171	4526
MJ/Kg	17.46	18.95
BTU/LB	7508	8147
Major and Minor Metals		
SiO2	64.48	wt%
Al2O3	2.13	wt%
Fe2O3	1.02	wt%
TiO2	0.08	wt%
P2O5	4.045	wt%
CaO	7.34	wt%
MgO	3.42	wt%
SO3	2.81	wt%
Na2O	0.26	wt%
K2O	7.13	wt%
Barium	346	ppm
Strontium	171	ppm
Vanadium	<50	ppm
Nickel	<50	ppm
Manganese	987	ppm
Chromium	<50	ppm
Copper	91	ppm
Zinc	1993	ppm
Loss on Fusion	6.92	wt%
Sum	99.99	wt%
Halogens		
Total Chlorine by Pyrohydrolysis	760	ug/g
Total Fluorine by Pyrohydrolysis	<14	ug/g

A bottom ash sample was taken from the chamber bed after testing and analyzed by the characterization lab. This data will vary from the analysis in Table 2 because of the higher and fluctuating temperatures in a large combustor compared to a muffle furnace.

Table 3: Ash Analysis

Carbon Content in Ash (wt%)	
Carbon (AS1)	0.55
Major Metals in Ash	
SiO_2 (wt%)	54.51
Al_2O_3 (wt%)	3.35
Fe_2O_3 (wt%)	3.19
TiO_2 (wt%)	0.17
P_2O_5 (wt%)	2.140
CaO (wt%)	19.96
MgO (wt%)	5.72
SO_3 (wt%)	0.18
Na_2O (wt%)	0.51
K_2O (wt%)	7.15
Barium (ppm)	436
Strontium (ppm)	784
Vanadium (ppm)	<50
Nickel (ppm)	83
Manganese (ppm)	1230
Chromium (ppm)	147
Copper (ppm)	137
Zinc (ppm)	49
Loss on Fusion (wt%)	2.84
Sum (wt%)	99.99

The steady state conditions during the run are presented in Table 4. The oxygen varied and was on average 9.6%. The trend of the oxygen and carbon monoxide throughout the day and during the testing are shown in Figures 6 and 7 respectfully. The air staging in the chamber favoured the over-fire air throughout the run. The over-fire air was used to maintain the chamber temperature, decreasing carbon monoxide and VOC levels.

Table 4: Statistical summary of combustion parameters

Steady State Temperature and Pressure

	Average	Min	Max
Temperatures (*C)			
Furnace	1028	895	1127
Lower Chamber	958	830	1096
Top Chamber	1037	953	1128
Chamber Outlet	994	887	1170
Boiler Inlet	731	661	860
Boiler Outlet	211	205	216
Overfire Fan	31	28	32
Pressures ("WC)			
Underfire Press.	0.94	0.61	1.33
Overfire Press.	1.64	0.64	2.04
Boiler Inlet Press.	-0.10	-0.53	0.18
Boiler Outlet Press.	0.06	-0.09	0.17
Duct Press.	0.16	0.12	0.23
Chamber Outlet Press.	-0.21	-0.68	0.15

Continuous Emissions Monitoring	Average	
O2	9.6	%
CO2	14.2	%
CO	30.1	ppm
Nox	124.5	ppm
SO2	64.9	ppm

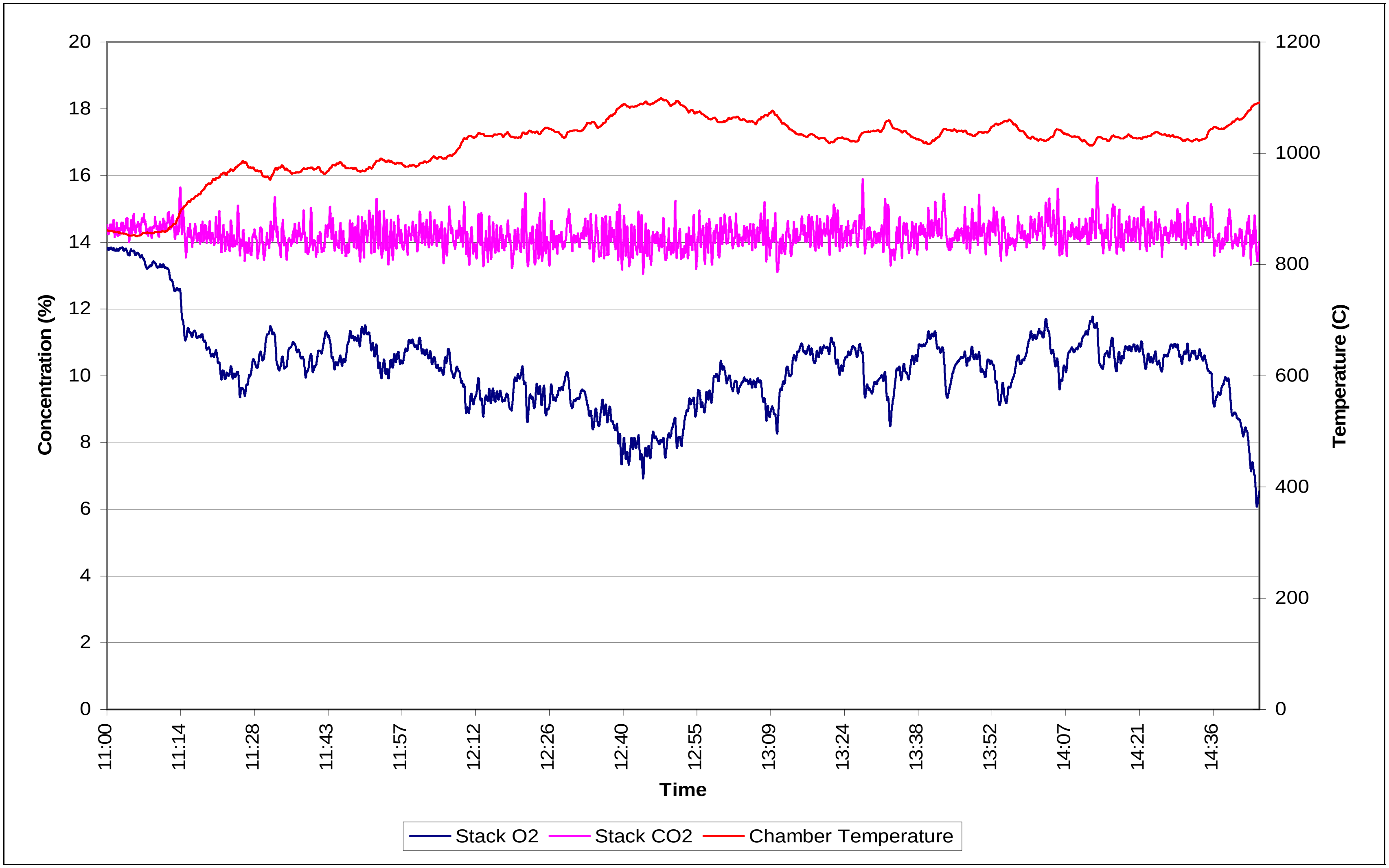

Figure 5: Summary of chamber temperature, oxygen and carbon dioxide normalized to 7% O_2 emissions during steady state

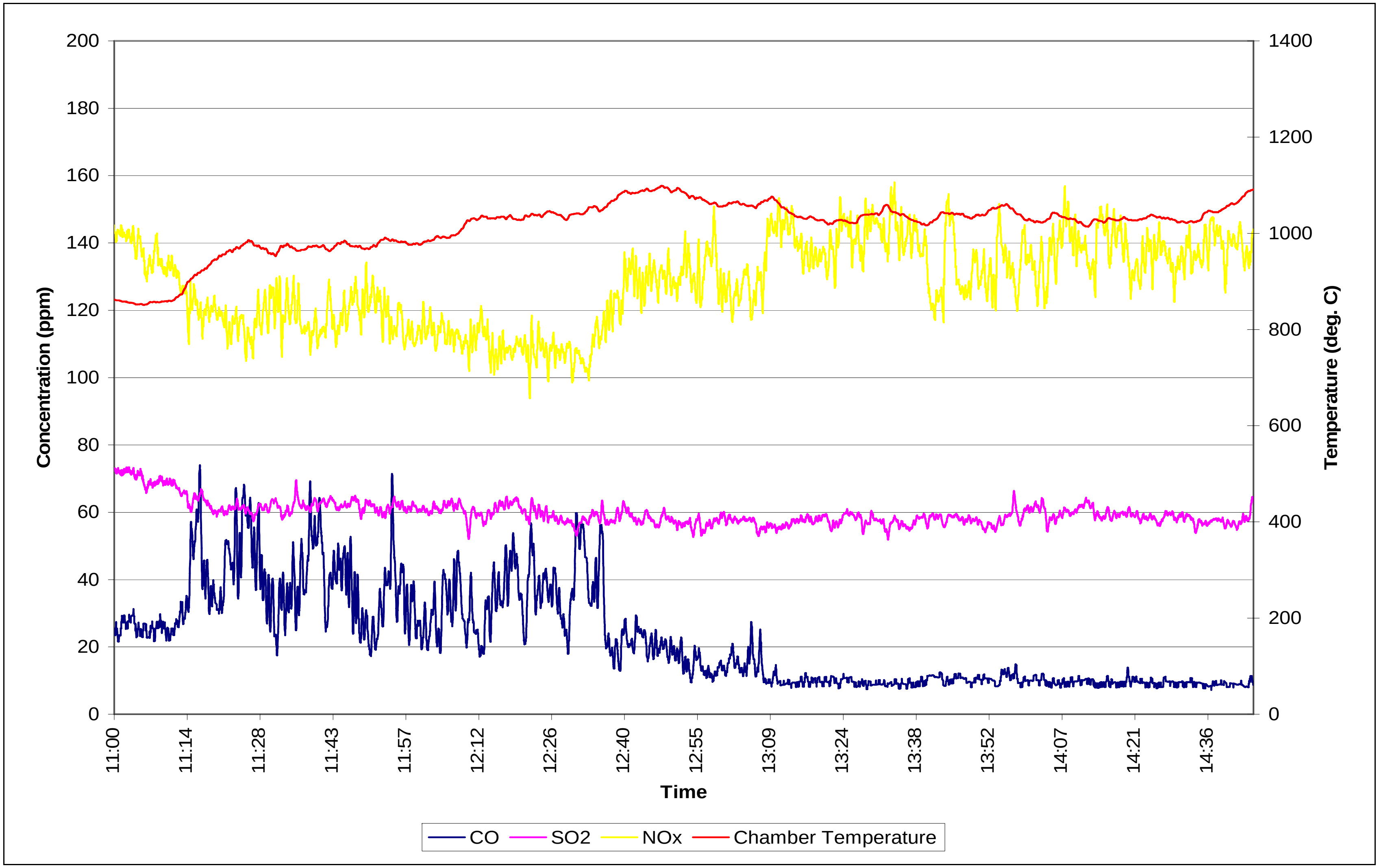

Figure 6: Summary of chamber temperature, sulphur dioxide, nitrous oxide and carbon monoxide emissions normalized to 7% O_2 during steady state

The total particulate testing was performed using EPA Method 5 and the results in Table 5 show that the concentration of particulate in the flue gas was 117mg/m3, when normalized to 7% oxygen. This measurement was taken from the stack and the flue gas had not gone through any control devices, such as a cyclone, ESP or bag house. The MOE limit for virgin wood is 90 mg/m3, which would require a removal device designed for this removal capacity.

Table 5: Total particulate matter results

Total amount of Particulate from M-5 Train (g)	Concentration of Particulate Dry Basis (mg/m^3)	Emission Rate of Particulate matter Dry Basis (mg/min)	Concentration Normalized to 7% O2 (mg/m3)
0.0887	*96*	*1259*	*117*

Table 6 provides a listing of all of the volatile organic compounds that were part of the analysis. The majority of compounds were not detected above the limit of the analysis equipment. Benzene, chlorobenzene and tolunene were measured in the highest concentrations at 30.8, 7.28 and 2.95 ug/m^3 respectively. The total VOCs measured was 55.8 ug/m^3.

Table 6: Volatile Organic Compounds in Flue Gas

Component	mg/m^3	Component	mg/m^3
Dichlorodifluoromethane (FREON 12)	0.59	Trichloroethylene	< 0.2
Chloromethane	2.36	Dibromomethane	< 0.2
Vinyl Chloride	< 0.2	Bromodichloromethane	< 0.2
Bromomethane	< 0.39	cis-1,3-Dichloropropene	< 0.2
Chloroethane	< 0.18	trans-1,3-Dichloropropene	< 0.14
Trichlorofluoromethane (FREON 11)	1.77	Dibromochloromethane	< 0.18
Acetone (2-Propanone)		Methyl Isobutyl Ketone	< 0.39
1,1-Dichloroethylene	< 0.2	Toluene	2.95
Iodomethane	< 0.39	Ethylene Dibromide	< 0.2
Carbon Disulfide	0.59	Tetrachloroethylene	< 0.39
Methylene Chloride(Dichloromethane)	< 0.39	Chlorobenzene	7.28
1,1-Dichloroethane	< 0.2	1,1,1,2-Tetrachloroethane	< 0.2
Vinyl Acetate	< 0.39	Ethylbenzene	0.20
trans-1,2-Dichloroethylene	< 0.2	m / p-Xylene	0.79
cis-1,2-Dichloroethylene	< 0.2	Styrene	< 0.2
Chloroform	0.59	o-Xylene	< 0.39
1,2-Dichloroethane	< 0.14	Bromoform	< 0.2
Methyl Ethyl Ketone (2-Butanone)	1.57	1,1,2,2-Tetrachloroethane	< 0.2
1,1,1-Trichloroethane	< 0.2	1,2,3-Trichloropropane	< 0.39
Carbon Tetrachloride	< 0.39	1,3-Dichlorobenzene	2.75
Benzene	30.8	1,4-Dichlorobenzene	1.18
1,1,2-Trichloroethane	< 0.39	1,2-Dichlorobenzene	2.36
1,2-Dichloropropane	< 0.2	**Total**	**55.80**

Conclusions and Recommendations

The fall harvested switchgrass pellets have a calorific value of 18.95 MJ/kg on a dry basis and can be combusted in a grate furnace. The fuel was handled and conveyed into the chamber without major problems. The steady state conditions were 9.6% O2 and approximately 1000^{o}C. The total particulate emissions were normalized to 7% O2 and were found to be 117 mg/m3, without having gone through any particulate control devices. The majority of volatile organic compounds were not detected. Benzene and cholorobenzene were measured in the largest concentrations at 30.8 and 7.28 ug/m3. The total VOCs measured was 55.8 ug/m3. The fuel size was consistent and the bulk density was 721 kg/m3 which is a desirable fuel property. Switchgrass pellets are an ideal biomass fuel because they could be transported economically, they had good combustion characteristics and low emissions. It should be noted that this fuel is highly volatile at 80wt% and therefore the combustor used should have sufficient volume and over-fire air capacity to complete the combustion of the fuel. Otherwise, much higher emissions from incomplete combustion, such as, volatile organic compounds, and carbon monoxide would be expected.