Biomass Gasification and Syngas Combustion for Greenhouse CO_2 Enrichment

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Greenhouse carbon dioxide (CO_2) enrichment from biomass residues was investigated using exhaust gas from the combustion of syngas produced by gasification. Near complete syngas combustion is essential to achieve CO_2 levels which increase plant yields while maintaining a safe environment for workers. Wood pellets were supplied to a downdraft gasifier to produce syngas fed to a steel swirl burner. The preliminary results were encouraging and represented a first step toward a successful development of this technology. The burner required an equivalence ratio (the actual air to fuel ratio relative to the stoichiometric air to fuel requirements) of 2.6 for near complete combustion. Concentrations of sulphur dioxide (SO_2) and ethylene (C_2H_4) emissions were either below critical concentrations or negligible. In 60% of the trials, carbon monoxide (CO) emissions were below ASHRAE standards for indoor air quality. However, the average nitrogen oxide (NOx) emission was 23.6 ppm, and it would need to be reduced below the 0.05 ppm to meet ASHRAE standards. Proposed improvements to the syngas burner design to lower NOx emissions and increase efficiency are: integration of a low swirl design, mesh catalysers, a higher quality refractory material, and a more efficient heat exchanger. Theoretically, combustion or gasification of biomass could provide more CO_2 for greenhouse enrichment than propane or natural gas per unit of energy.

Keywords: Biomass gasification; CO_2 enrichment; Greenhouse; Wood pellets; Syngas combustion; Exhaust gas emissions

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INTRODUCTION

In cool northern climates, the high thermal energy requirements have stimulated greenhouse operators to consider sustainable energy sources to reduce their dependence on fossil fuels for both economic and environmental reasons. Currently in Canada, biomass heating from widely available wood chips of residual forest biomass or wood pellets has shown a lot of promise for its ability to provide thermal energy for very large greenhouses at competitive costs (Biomass Magazine 2012; Canadian Bioenergy Association 2010; Chau *et al.* 2009). Biomass encompasses many sources of organic vegetal matter and their derivatives, such as wood residues, dedicated energy crops, agricultural residues, animal waste, or municipal waste (Basu 2010). Notably, solid woody biomass is recognised by the US Environmental Protection Agency (EPA) as a sustainable renewable for heating purposes (Dones 2003; Eriksson *et al.* 2007; Petersen Raymer 2006). Wood pellets are of particular interest since densification has shown to be a viable process to increase the energy content and fuel homogeneity while reducing shipping and storage costs (Mani *et al.* 2006).

CO_2 enrichment practices in controlled plant environments have been successfully applied since the early 1900s (Wittwer and Robb 1964; Mortensen 1987). Since the 1980s, in conjunction with maturing technologies and best practices, CO_2 enrichment has found steady commercial applications and wide adoption from the horticulture industry (Mortensen 1987). It is now accepted that increasing CO_2 concentrations in greenhouses between 700 to 1000 ppm can increase yields from 21 to 61% in dry mass (Wittwer and Robb 1964; Mortensen 1987; Willits and Peet 1989; Hanan 1998; Critten and Bailey 2002; Jaffrin *et al.* 2003; Tisserat *et al.* 2008; Sánchez-Guerrero *et al.* 2009). This practice is typically performed either from pure CO_2 in bulk, or from dedicated natural gas or propane burners, which are considered efficient and clean combustion systems (Hicklenton 1988). Current biomass heating system technologies do not permit CO_2 enrichment due to high emission levels (Hanan 1998), which can affect human health, and impair plant production.

Biomass gasification technology coupled with efficient combustion of syngas presents a promising avenue for both research and commercial applications (Quaak *et al.* 1999; McKendry 2002; Basu 2010). Gasification is a thermo-chemical reaction that differs from combustion by being heated under low oxygen levels (partial oxidation), thus converting the biomass into a gaseous fuel. This raw gas contains some impurities and is called producer gas, while it is referred as synthesis gas when cleaned into a mixture of CO and H_2. For the sake of this research, the term syngas is used in reference to producer gas. Gasification coupled with syngas combustion for heat and power can achieve high efficiency, and is recognised to make the thermo-chemical conversion of biomass cleaner and easier to control, compared to direct combustion of solid fuels (Reed and Das 1988; Quaak *et al.* 1999; Whitty *et al.* 2008).

Table 1. ASHRAE Standards for Indoor Environmental Quality (ASHRAE 2009)

Compound		**Concentration Limit**	
Carbon Dioxide	CO_2	3500	Ppm
Carbon Monoxide	CO	11	ppm (8 h)
		25	ppm (1 h)
Nitrogen Dioxide	NO_2	0.05	Ppm
		0.25	ppm (1 h)
Particulate		40	μg/m^3 (8 h)
		100	μg/m^3 (1 h)
Sulphur Dioxide	SO_2	0.019	Ppm
VOC[a]		1 - 5	mg/m^3
Acrolein	C_3H_4O	0.02	Ppm
Acetaldehyde	C_2H_4O	5.0	Ppm
Formaldehyde	CH_2O	0.1	Ppm

[a]: Limits for VOCs are usually presented per individual compound. The presented value for VOCs concentration limit is a suggested target from Health Canada (Health Canada, 2007) while limits for C_3H_4O, C_2H_4O, and CH_2O are from ASHRAE (2009).

Injection of exhaust gas from syngas combustion in a greenhouse requires compliance with air quality and workplace safety legislations (Table 1); however, this challenge has not yet been published in peer reviewed literature. This research paper summarizes the results from the last chapter of a Master's thesis on CO_2 enrichment from biomass gasification (Dion 2011). While the system was studied and developed as a whole, this article concentrates on syngas combustion since it directly affects the potential of CO_2 enrichment. The gasifier stage remains important to obtain quality syngas and is fully developed in the Thesis (Dion 2011).

Thermodynamics of Combustion and Gasification

The stoichiometric air or oxygen requirement depends on the chemical composition of the fuel, which can be obtained from its ultimate analysis (normally expressed by mass) (Glassman *et al.* 2008). The stoichiometric air to fuel ratio, $(A/F)_{stoich}$, is the theoretical mass of air required for complete combustion of a unit mass of a fuel (Glassman *et al.* 2008). Other applicable theoretical concepts of combustion such as air-fuel mixtures and flame characteristics are thoroughly explained in classical textbooks such as Glassman *et al.* (2008). Ideally, premix or partly premix flames would be most desirable to obtain the cleanest exhaust when burning syngas for CO_2 enrichment (De Nevers 2000).

Combustion reactions differ mainly from gasification in terms of the level of oxidation. The equivalence ratio (ER) is used to determine the actual oxygen (or air) to fuel ratio relative to the stoichiometric oxygen (or air) to fuel requirements, as explained in greater detail in Glassman *et al.* (2008). It must be noted that some authors report fuel to air ratios (F/A), rather than air to fuel (A/F), which influences the value of the ER (Glassman *et al.* 2008).

Emissions affected by syngas composition

Post-combustion concentrations of CO, NO_x, SO_x, and HCl are influenced by syngas composition. According to Whitty *et al.* (2008), syngas with high CO and H_2 content reduces the probability of CO emissions. One of the three primary NO_x formation mechanisms, "Prompt NO_x", occurs in fuel rich conditions, such as with high CH_4 content, when N_2 reacts with active hydrocarbons. The other two NO_x formation mechanisms are "Thermal NO_x" and "Fuel NO_x", as explained in Van Loo and Koppejan (2008). Sulphur content is typically between 0.01 to 2% in biomass fuels (Reed and Das 1988); thus the resulting SO_x emissions are generally considered minor (Van Loo and Koppejan 2008). Hydrogen chloride (HCl) is found in very low abundance in wood, unlike other biomass products such as *Miscanthus*, switchgrass, and straw (Van Loo and Koppejan 2008).

Emissions affected by the burner design

While the exhaust gas emissions are strongly affected by the syngas composition, the concentration levels at which they are emitted depends primarily on the burner design and the effectiveness of air-fuel mixing (Whitty *et al.* 2008). Incomplete combustion and improper air-fuel mixing will generate various types of volatile organic compounds (VOC) such as ethylene (De Nevers 2000), which causes early senescence in plants (Mortensen 1987), and needs to be kept below 0.05 ppm (Hanan 1998). "Thermal NO_x" is the most prominent NO_x formation mechanism, as explained in Van Loo and Koppejan

(2008). “Fuel NO_x” formation as demonstrated in Whitty *et al.* (2008) can be controlled using air staging or two-stage combustion. A compromise for the temperature of combustion between 1000°C and 1300°C is usually recommended to reduce both CO and NO_x emissions. Thermal NO_x and VOC can be reduced effectively with a proper combustion temperature, residence time, and oxygen mixing, which needs to be determined (Van Loo and Koppejan 2008).

Gasifier and syngas burner design

There are many conventional designs for gasification of biomass that influence the syngas composition and quality, as well described in Basu (2010).

Research has been conducted to evaluate various dedicated syngas burners to elucidate the complexity of combustion of gases under unsteady composition (Littlejohn *et al.* 2007; Li *et al.* 2009; Whitty *et al.* 2008; Wood *et al.* 2009). Typically, raw syngas used for heat and power is burned directly in a furnace or a boiler. The residence time depends on the combustion chamber dimension, while temperature is kept at optimal levels with refractory materials, ceramics, or high temperature metal alloys. Turbulence is promoted by various means of air-fuel mixture and injection to ensure adequate mixing (Reed and Das 1988). Injectors or ejectors are components of a venturi mixer and can ease the task of entraining gas flow, as explained by Lawn (2003). The degree of air to fuel premixing required in achieving near complete combustion needs to be determined.

The purpose of this research was thus to investigate the exhaust gas emissions from a rudimentary syngas swirl burner through an outlook of the flue gas compounds formation and the syngas burner design. Also, the experimental CO_2 enrichment potential of syngas combustion was compared with theoretical estimations. These results were used to identify which exhaust gas compounds exceed air quality standards when operating a small scale downdraft gasifier using the manufacturer’s optimal conditions, in order to find suitable components to be added or modified in the burner design for future experiments.

THEORETICAL ESTIMATES

For a complete combustion reaction, the mass of O_2 needed per kg of fuel was calculated as follows (Law 2006; Van Loo and Koppejan 2008),

$$m_{O_2}\left[\frac{\text{kg }O_2}{\text{kg fuel}}\right] = Y_C\frac{M_{O_2}}{M_C} + \frac{Y_H}{4}\frac{M_{O_2}}{M_H} + Y_S\frac{M_{O_2}}{M_S} - Y_O \qquad (1)$$

where,

$M_i\left[\frac{\text{kg of i}}{\text{kmole}}\right]$ is the molecular mass of element i (C, H, S or O);

$M_j\left[\frac{\text{kg of j}}{\text{kmole}}\right]$ is the molecular mass of compound j (CO_2 or O_2); and

$Y_i\left[\frac{\text{kg of i}}{\text{kg fuel}}\right]$ is the mass fraction of element i from ultimate analysis (C, H, S or O).

The stoichiometric dry air to fuel ratio, $(A/F)_{stoich}$), required was then computed as (Law 2006; Van Loo and Koppejan 2008),

$$(A/F)_{stoich}\left[\frac{\text{kg air}}{\text{kg fuel}}\right] = m_{O_2} + m_{N_2} = m_{O_2} + m_{O_2}\frac{X_{N_2}}{X_{O_2}}\frac{M_{N_2}}{M_{O_2}} \tag{2}$$

where X_j [%] is the volume fraction of compound j in air (O_2 or N_2). Subsequently, ER was determined from this ratio:

$$ER = {(A/F)_{actual}}\Big/{(A/F)_{stoich}} \tag{3}$$

Typically, the equivalence ratio for biomass gasification is ER = 0.25, but depending on the feedstock, it may vary between 0.20 and 0.45 (Erlich and Fransson 2011). When ER = 1, the system has stoichiometrically balanced combustion, whereas ER > 1 implies combustion with excess air.

Gasification efficiency is expressed as cold gas efficiency (η_{CG}), and represents the energy contained in syngas over the potential energy from the solid fuel using the lower heating value (LHV) of both fuels, the solid biomass consumption rate ($\dot{m}_{biomass}$), and the syngas flow rate output of a gasifier ($\dot{m}_{syngas}$) (Basu, 2010). It is calculated as follows:

$$\eta_{CG} = \frac{LHV_{syngas} \cdot \dot{m}_{syngas}}{LHV_{biomass} \cdot \dot{m}_{biomass}} \tag{4}$$

The maximal theoretical quantity of flue gas CO_2 that could be used for enrichment was estimated according to the carbon content of the solid biomass or syngas. Assuming complete combustion of either fuel, the mass of emitted CO_2 per kg of dry fuel was calculated as follows:

$$m_{CO_2}\left[\frac{\text{kg } CO_2}{\text{kg fuel}}\right] = \left(Y_C\frac{M_{CO_2}}{M_C}\right) \tag{5}$$

By using $\dot{m}_{biomass}$ or $\dot{m}_{syngas}$ in kg/hr, the CO_2 output useable for enrichment was estimated and then compared with other enrichment systems:

$$\dot{m}_{CO_2}\left[\frac{\text{kg } CO_2}{\text{hr}}\right] = m_{CO_2} \cdot \dot{m}_{\text{biomass or syngas}} \tag{6}$$

From the predetermined size of the existing heating unit, the potential enriched greenhouse surface area was found using the recommended CO_2 injection rate of 5.6 g/(m^2·hr) (Hanan 1998), and calculated as:

$$A\,[m^2] = {\dot{m}_{CO_2}}\Big/{\frac{0.0056\text{kg } CO_2}{m^2\cdot\text{hr}}} \tag{7}$$

The gasifier airflow intake was estimated using the following empirical relationship produced by All Power Labs (2010), and valid only for the GEK gasifier using wood pellets, Eq. 8.

$$Q_{\text{air in}}\left[\frac{m^3}{hr}\right] = 2.4207 \cdot (\text{Vacuum Pressure}[\text{inH}_2\text{O}])^{0.5227} \tag{8}$$

The syngas mass flow rate was estimated in Eq. 9 below by adding the air intake mass flow (extrapolated from Eq. 8, and using ρ_{air} = 1.205 kg/m^3) with the volatile fraction of the biomass consumption rate (estimated at 80%).

$$\dot{m}_{\text{syngas}}\left[\frac{\text{kg syngas}}{hr}\right] = Q_{\text{air in}}\left[\frac{m^3}{hr}\right] \cdot \rho_{\text{air}} + 80\% \cdot \dot{m}_{\text{biomass}}\left[\frac{kg}{hr}\right] \tag{9}$$

The volumetric flue gas fractions were obtained from Eq. 10 shown below (Law 2006; Van Loo and Koppejan 2008):

$$X_j = \frac{Y_j}{M_j}\Big/\sum_i \frac{Y_j}{M_j} \quad , \quad \text{where } \sum_i \frac{Y_j}{M_j} = \frac{Y_{CO_2}}{M_{CO_2}} + \frac{Y_{H_2O}}{M_{H_2O}} + \frac{Y_{O_2}}{M_{O_2}} + \frac{Y_{N_2}}{M_{N_2}} \tag{10}$$

EXPERIMENTAL

Characteristics of the Feedstock

Premium quality wood pellets were supplied by Energex Pellet Fuel Inc. (Lac-Mégantic, QC, Canada). They were fabricated from a mix of Canadian hardwood sawdust and contained less than 1% ash. Bulk density of the feedstock was approximately 700 kg/m^3 with a particle density of 1055 kg/m^3. Particle diameter was approximately 6.5 mm with an average length of 16 mm, varying between 8 and 24 mm. The moisture content of the sawdust wood pellets was 7%. The wood pellets elemental composition was obtained from the literature (Reed and Das 1988), from an ultimate analysis performed on similar hardwood sawdust pellets (Table 2).

Table 2. Ultimate Analysis from Sawdust Pellets (dry basis, mass percent) (Reed *et al.* 1988)

Material	C	H	N	S	O	Ash
Sawdust pellets	47.2	6.5	0.0	0.0	45.4	1

Experimental Setup

A downdraft gasifier was selected as a dedicated CO_2 production unit for greenhouse enrichment, since it operates with air flow moving along the biomass flow. The application range is from 10 kW up to 1 MW, and syngas production yields very low tar content (from 0.015 to 3.0 g/m^3) (Basu 2010), which makes it ideal for internal combustion engines. The Gasifier Experimenters Kit (GEK v3.5), developed by All Power Labs (Berkeley, CA, USA) based on the Imbert design, was shown to be reliable at producing syngas with low tar content in Reed and Das (1988), and was thus selected for lab-scale experiments (All Power Labs 2010). The GEK steel swirl burner was placed inside the combustion chamber of a forced-air furnace (Superior Bio-mass Furnace, Ja-Ran Enterprises Inc., Lexington, MI, USA), where syngas was allowed to burn (Fig. 1). The setup facilitated the flue gas flow of syngas combustion to be directed into the furnace chimney, where representative exhaust gas measurements were taken.

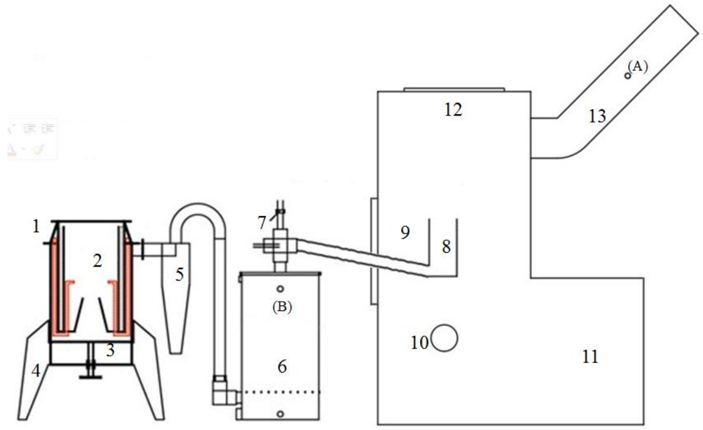

Fig. 1. Schematic of the gasifier coupled with the forced-air furnace. Compounds include: (1) three ports: Ignition, Air inlet, Instrumentation, (2) Reactor, (3) Ash grate, (4) Support legs, (5) Cyclone, (6) Packed bed filter, (7) Ejector venturi, (8) Swirl burner, (9) Furnace combustion chamber, (10) Furnace fuel inlet for direct combustion only, (11) Furnace blower for heat exchanger, (12) Air-air heat exchanger, (13) Chimney, (A): Exhaust gas sampling port, (B): Syngas sampling port (GEK schematic courtesy of All Power Labs (Berkeley, CA, USA))

The GEK functioned under negative pressure (suction operation), which was driven by the ejector venturi before the swirl burner. Compressed air was provided to the ejector by a compressor with a maximum capacity of 19.4 m^3/hr at 275 kPa and 15.3 m^3/hr at 620 kPa (manufacturer recommendations were 10 to 14 m^3/hr at about 620 to 830 kPa). A needle valve, connected before the ejector, allowed manual control of the compressed air flow and the negative pressure for the gasifier. Two water-filled U-tube manometers (one at the bottom of the reactor core and the second at the top of the packed-bed filter) provided a direct visual output of the gasifier operating conditions. The gasifier operating conditions were also monitored with 8 thermocouples and 4 differential gauge pressure transducers. All Power Labs identified the optimal vacuum condition for the bottom of the reactor core to obtain an ideal core temperature over 850^oC along with corresponding air intake flow rates when using wood pellets (Eq. 8). This ideal performance condition identified by the manufacturer was in accordance with the literature (Reed and Das 1988; Basu 2010) to produce the highest yield of producer gas with lowest tar content when the vacuum pressure was set close to 1.25 ± 0.75 kPa (5 ± 3 in H_2O).

The ejector venturi premixed the syngas with air controlled from the primary needle valve (Fig. 2). The mixture converged in a 19 mm steel pipe, which increased to 38 mm to enter tangentially at the bottom of the swirl burner. A secondary air inlet was controlled manually with the secondary needle valve to introduce additional excess air tangentially with a 13 mm steel pipe at the middle height of the swirl burner and in the opposite direction of the primary air-fuel inlet (Fig. 2). A propane gas inlet was connected at that same level to be used only at start-up. The swirl burner had a diameter of 127 mm with a height of 241 mm.

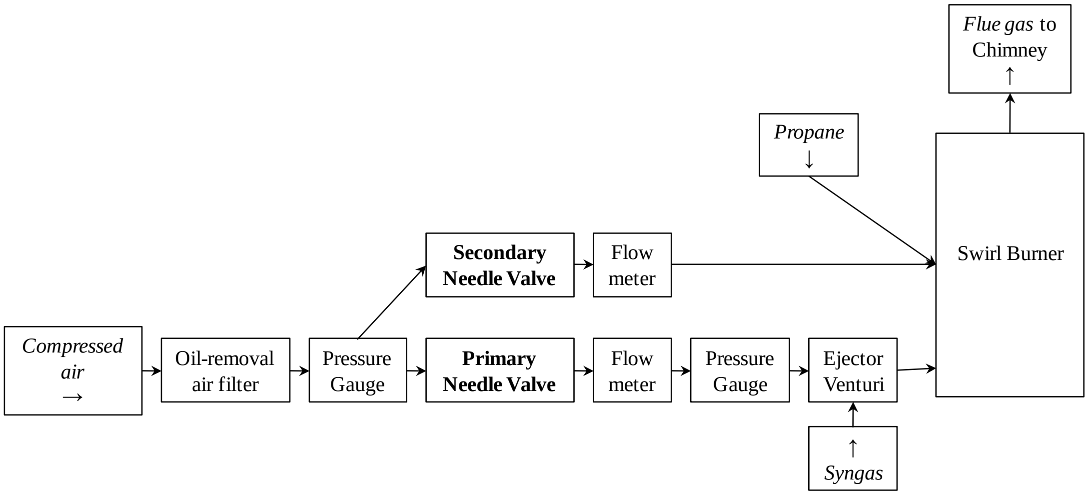

Fig. 2. Flow diagram of the swirl burner with ejector venturi and instrumentation

The exhaust gas sampling line used a stainless steel probe, a cotton filter (inside a 300 mm long and 12.7 mm diameter tube), and a 500 g calcium sulphate desiccant column (Fig. 3). The syngas sampling line was made of two glass impingers connected in series, and sitting in ice buckets (Fig. 4). The 500 g desiccant was also connected to the end of this sampling line. In both cases, a diaphragm vacuum pump (KNF Neuberger, Inc., Trenton, NJ, USA) was used and had a capacity of 2 m^3/hr and 91 kPa of maximum vacuum pressure. Both sampling lines were tested to prevent air leaks at the joints.

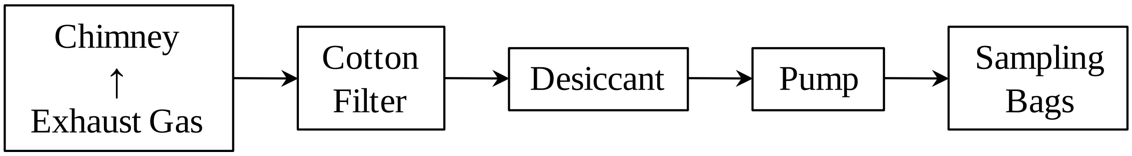

Fig. 3. Sampling train configuration for exhaust gas

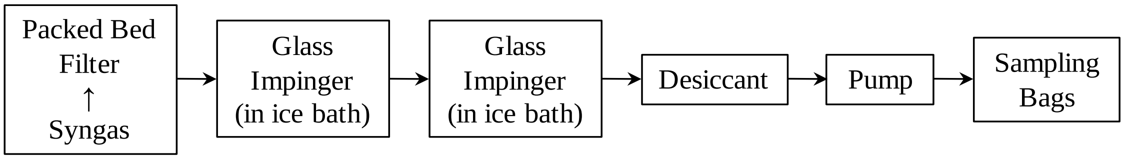

Fig 4. Sampling train configuration for syngas

Instrumentation

A Gasifier Control Unit (GCU) was developed by All Power Labs (Berkeley, CA, USA) to read and datalog the GEK instruments and control devices. All data were recorded in real time in a Toughbook laptop (CF-29, Panasonic, Kadoma, Osaka, Japan). An array of chromel-alumel (type K) sheathed thermocouples were installed at strategic locations on the gasifier and connected to the GCU. Four pressure ports were installed and connected to the differential gauge pressure transducer of the GCU.

Compressed air injection was monitored with two pressure gauges of 700 kPa, and two versa-mount dial-indicating flow meters, with capacity up to 42.5 m^3/hr (Fig. 3). A first pressure gauge monitored the incoming air from the compressor before the needle valves. A flow meter and a second pressure gauge were installed between the primary control needle valve and the ejector venturi. The second flow meter was placed at the exit of the secondary needle valve. Exhaust gas was measured directly through a chimney port using a TESTO 335 portable analyzer (Testo Inc., Lenzkirch, Germany) to measure gaseous concentrations of CO, O_2, NO, NO_2, and SO_2, together with calculated estimates of CO_2 and NO_x. The syngas sampling port was positioned at the top of the drum filter at point (B) on Fig. 1, before the ejector venturi, while the exhaust gas sampling port was connected through the chimney at point (A) (Fig. 1).

Exhaust gas was also sampled in SamplePro FlexFilm bags (SKC inc., Eighty Four, PA, USA) with single polypropylene fittings. Exhaust gas samples were analyzed for ethylene (C_2H_4) in a Hewlett Packard 5890A (Agilent, Santa Clara, CA, USA) gas chromatograph (GC) with a 60/80 carbopack B column of 1.83 m long and 45.7 mm diameter. The GC functioned with a flame ionization detector (FID) using helium as a carrier gas set at 35 mL/min. Ethylene at 27 ppm ± 5% in synthetic air was used as the calibration gas mixture (Praxair, Inc., Danbury, CT, USA). The GC was linked to the PeakSimple (version 3.56, SRI Instruments, Torrance, CA, USA) software for data collection. Syngas was collected in stronger FlexFoil sample bags (SKC Inc., Eighty Four, PA, USA) with single polypropylene fittings. Syngas samples were analyzed for hydrogen vol% in an Omnistar GSD 320 O1 (Pfeiffer Vacuum, Asslar, Germany) mass spectrometer (MS) with tungsten filament and an atomic mass range of 1 to 100 amu. The MS used the electron ionization method and a single quadrupole mass analyzer. Ultra high purity air was supplied by MEGS Specialty Gases, Inc. (Ville St-Laurent, QC, Canada) for calibration.

Methodology

The experiment was conducted without the use of a fume hood; instead, the equipment was operated outdoors in runs lasting one hour. The amount of wood pellet consumed during gasification was obtained by measuring the mass of wood pellets with a scale when refilling the reactor after an experiment. The mass added to the reactor was divided by the duration of the experiment to determine the consumption rate ($\dot{m}_{biomass}$). The gasifier operation was repeated according to the following sequence. Excess ash was removed below the grate of the reactor. Char pellets were added in the reactor, on top of the ash grate and up to the reactor core until they covered the air inlet nozzles for every trial. Fresh wood pellets were weighed and poured in the GEK. The gasifier was properly sealed and inspected thoroughly. The furnace heat exchanger blower was turned on to dissipate excess heat. Air from the compressor was allowed into the ejector venturi to create negative pressure (up to 0.25 kPa) and initiate air flow within the gasifier. Initial fresh air flow helped in performing a system air flush to remove residual gases from previous trials. Propane was injected and burned in the swirl burner to flare up the residual gases. A small propane torch was placed through the ignition port of the gasifier reactor to activate the combustion zone. The torch was used until the combustion sustained itself. The core temperature started rising above 70°C, and the ignition port was then sealed. During the ignition process, the vacuum in the gasifier was kept at 0.25 kPa, and the amount of propane fed in the swirl burner was decreased gradually as the core temperature increased. Once it reached the minimal gasification temperature of 700°C, the propane was disconnected from the swirl burner, and vacuum pressure was adjusted to the manufacturer's optimal conditions between 1.25 to 1.5 kPa to maintain a core temperature of 850°C and a temperature of 750°C below the reduction zone. The secondary air inlet was then set to flows of either: 0.0, 8.5, or 17.0 m^3/hr (0, 5, and 10 cfm) to vary the excess air to the burner depending on the trial. The syngas combustion was then self-sustained in the swirl burner.

Throughout the gasification sequence, the gasifier vacuum pressure was regularly adjusted to compensate for pressure changes occurring while the air compressor was filling or emptying. For every one of the 10 trials carried out, the portable analyzer was placed through the chimney port to perform exhaust gas analysis at 5 min intervals. The sample bags were used for exhaust gas and syngas sampling, which were taken every 15 min, for a total of three samples per experiment. For exhaust gas sampling, the stainless steel probe was inserted through the chimney port. The whole sampling line was rinsed with an equivalent of 10 times its volume with the exhaust gas. The sample bags were filled according to SKC Inc. guidelines (SKC Inc. 2010b). Syngas samples were taken at the top of the packed-bed filter, where the temperature dropped to 45°C. Tars and moisture were condensed in the impingers sitting in an ice bath since they had to be removed to allow analysis in a gas chromatograph or a mass spectrometer. The syngas sampling line was also rinsed with 10 times of its volume with syngas. Excess gas was vented outside. Two fresh air samples were taken for every experiment to provide background gas concentrations.

After one hour, shut down procedures were initiated, the reactor air inlet was sealed, and the experiment was terminated. The GEK was then monitored while cooling down. Following the gasification experiment, the gas samples were analysed.

RESULTS AND DISCUSSION

Gasifier Performance

Analysis of sawdust pellets

From the ultimate analysis of sawdust pellets, and with Eqs. 1 and 2, the $(A/F)_{stoich}$ was estimated to be 5.63 kg of dry air per kg feedstock. The wood pellets higher heating value (HHV), and lower heating value (LHV) obtained on a dry basis were 19.42 MJ/kg and 18.10 MJ/kg, respectively.

Combustion time

The duration of a gasification trial with sawdust wood pellets, from the ignition in the combustion zone until the sealing of the air inlet with the GEK, was an average of 67.1 ± 6.3 min. The time to gasification, defined as the period between ignition of the combustion zone and the reactor core thermocouple reaching the minimum gasification temperature of 700°C, was on average 6.1 ± 1.5 min. The difference of these two time periods represented the duration of syngas combustion, with an average of 61.0 ± 6.9 min. The average performance results from sawdust wood pellet gasification were estimated and are compiled in Table 3.

Table 3. Average Performance Results for Downdraft Gasification of Sawdust Wood Pellets of the 10 trials (average (Avg.) ± standard deviation (SD))

Air intake	(m^3/hr)	6.09	±	0.35
	(kg/hr)	7.33	±	0.42
Biomass consumption rate	(kg/hr)	7.70	±	0.76
Syngas flow rate	(m^3/hr)	13.40	±	0.77
	(kg/hr)	13.51	±	0.77
Production ratio	($m^3_{syngas}/kg_{biomass}$)	1.74	±	0.11
	($kg_{syngas}/kg_{biomass}$)	1.76	±	0.12
Power estimation				
from wood pellet combustion	(kW)	38.8	±	4.0
from syngas combustion	(kW)	23.2	±	1.3
Cold gas efficiency		60%	±	4%

The mass spectrometer analysis from syngas sampling yielded 19.2% H_2 (± 0.6%). Compared to the average measurement of 18.7% for H_2 provided by All Power Labs (2010), the measurement of 19.2% was considered acceptable, and was kept for the remaining analysis. However, in the absence of continuous measurements of the remaining syngas compounds, average measurements from All Power Labs were used for CO, CO_2, and CH_4 (Table 4). The amount of N_2 was estimated as the remaining syngas fraction.

Table 4. Volumetric Syngas Composition (dry basis) for the GEK Gasifier from Mass Spectrometry Analysis (H_2) and from All Power Labs (2010) Measurements (CO, CO_2, CH_4)

H_2	CO	CO_2	CH_4	N_2
19.2%	22.7%	9.6%	3.0%	44.7%

From the individual gas heating values in Table 4, syngas was characterized by a HHV of 6.74 MJ/m^3, a LHV of 6.24 MJ/m^3 and a density of 1.01 kg/m^3 (at 101.325 kPa and 20°C on a dry basis).

Potential for CO_2 enrichment & estimation of exhaust gas composition

The maximum theoretical CO_2 enrichment potential of the sawdust wood pellets was 1.73 kg of CO_2 per kg of biomass (Eq. 5), if used in complete direct combustion. Theoretically, when consumed at $\dot{m}_{biomass} = 7.70$ kg/hr, assuming complete combustion, the rate of enrichment would be 13.3 kg CO_2/hr, as obtained from Eq. 6. With a suggested rate of enrichment of 5.6 g $CO_2/(m^2 \cdot hr)$ to reach the optimal CO_2 concentration of 1000 ppm (Hicklenton 1988), the wood pellets could enrich a greenhouse with maximal surface area of 2379 m^2 (Eq. 7).

The same methodology was applied to obtain the actual enrichment potential of the gasifier following complete combustion of syngas. The syngas was estimated to be consumed at $\dot{m}_{syngas}$ = 13.51 kg/hr. Using Eq. 5 and the gas composition, m_{CO_2} from syngas was 0.64 kg of CO_2 per kg of syngas, while $\dot{m}_{CO_2}$ was 8.67 kg CO_2/hr. The GEK could theoretically enrich a greenhouse with a surface area of 1548 m^2 (Eq. 7). The enrichment potential for gasification, in terms of greenhouse surface area, was 65% of the potential for direct combustion.

The results compiled in Table 5 present the energy output per kg of sawdust wood pellets after complete direct combustion and gasification. The lower energy output of 10.69 MJ/kg, compared to 18.10 MJ/kg, is representative of the cold gas efficiency (from equation 4) of 59% for the gasifier. Table 5 compares the potential usable CO_2 emitted for enrichment with the potential heating value of conventional and non-conventional fuels. The CO_2 produced from natural gas and propane is less, and comes from a fossilized and non-renewable source of energy, while the CO_2 emitted from biomass thermo-chemical processes was absorbed from the atmosphere during the biomass growth. Results from this experiment show that biomass used as a CO_2 enrichment source could theoretically supply more CO_2 per unit of energy than propane and natural gas.

Table 5. Energy and CO_2 Yield after Complete Combustion of Sawdust Wood Pellets, Natural Gas, and Propane

	Wood pellets (kg)		Natural Gas (m^3)	Propane (L)
	After combustion	After gasification	After combustion	After combustion
MJ / unit of fuel	18.10	10.69	37.89 [a]	25.53 [a]
g CO_2/ unit of fuel	1729	1129	1891 [a]	1510 [a]
g CO_2/MJ	96	62	50	59

[a]: Data provided by the Agence de l'efficacité énergétique du Québec (AÉE, 2009)

Syngas Combustion

Equivalence ratio

Results of syngas and air mass flows into the swirl burner with the corresponding equivalence ratios were compiled for the gasification trials (Table 6):

Table 6. Compilation of Syngas and Air Mass Flow Rates into the GEK Swirl Burner with Respective Equivalence Ratios

Trial #	Syngas mass flow rate	Primary air mass flow rate	Secondary air mass flow rate	Total air mass flow rate	Equivalence Ratio
	(kg/hr)	(kg/hr)	(kg/hr)	(kg/hr)	
Avg.	13.51	43.89	11.32	55.20	2.60
SD	0.77	7.22	7.62	9.16	0.44

Syngas mass flow rates were estimated using the combination of Eq. 8 and 9. The average $\dot{m}_{syngas}$ was 13.5 kg/hr, and Q_{syngas} was 13.4 m^3/hr. These results translated to a production of 1.75 kg, or 1.74 m^3, of syngas per kg of gasified sawdust wood pellets. For syngas with this composition, the stoichiometric air-fuel requirement was 1.58 kg air per kg of syngas, for an air mass flow rate of 21.3 kg/hr. On average through the experiments, the air was supplied to the burner at a rate of 55.2 kg/hr, an average A/F of 4.1, and an average ER of 2.6 (Equations 1-3). For the trials, the total equivalence ratios varied between 1.94 and 3.44, which indicated lean combustion. From the literature, as the value of ER increases, the adiabatic temperature (maximal flame temperature achieved with complete combustion and no heat exchange) decreases, resulting in reduced NO_x emissions (Quaak *et al.* 1999). According to Quaak *et al.* (1999), the optimal ER range was found to vary between 1.6 and 2.5. The average observed ER was 2.6, and was in the higher limit of this optimal ER range (Table 6). However, a very high ER can lower the adiabatic flame temperature and reduce the efficiency of the heat exchanger from the boiler or the furnace in which combustion occurs. It was noted that the ER from the primary air inlet alone varied between 1.45 and 2.46, with an average of 2.06, indicating that the secondary air inlet may not be required.

Exhaust gas measurements

Following the experiments, flue gas compositions were measured with the portable analyzer (Table). The average measured flue gas temperature was 631.6°C.

Table 7. Compilation of Important Flue Gas Compounds from Syngas Combustion Following Sawdust Wood Pellets Gasification

Trial #	CO	NO_x	O_2	CO_2
	(ppm)	(ppm)	(%)	(%)
Avg.	8.8	23.6	0.2	8.9
SD.	4.6	2.8	0.0	1.7
Peak Value	44	50.9	-	-
Max Avg.	16.4	27.8	0.2	13.0
Min Avg.	4.4	20.4	0.1	7.0

Carbon monoxide

The emitted concentrations of CO, with an average of 8.8 ± 4.6 ppm, were close to the ASHRAE standards requirements of 11 ppm (Table 1). About 60% of the trials maintained an average CO concentration below the ASHRAE standard of 11 ppm, and 90% of the trials had CO concentrations below 20 ppm. The measurements did not show an actual trend according to ER values, but indicated that this particular burner emitted CO at concentrations between 16.4 and 4.4 ppm, when varying the ER from 2.0 to 3.5. The absence of a trend indicated that the varying ER did not impact the CO emissions linearly in this range. However, Bhoi and Channiwala (2009) had observed higher CO emissions at A/F ratio close to 1.00, and decreasing CO emissions with increasing A/F; a wider range of ER for future experimental trials would likely display similar observations.

Nitrogen oxide

The NO_x emissions reached an average of 23.6 ± 2.8 ppm, which was much higher than the ASHRAE standards. Normally, an opposing effect on CO and NO_x concentrations should be observed as a result of increasing excess air (De Nevers 2000); however, NO_x emissions did not show a particular trend with increasing ER. The burner performance for NO_x emissions fell between 20.4 and 27.8 ppm, with an ER varying between 2.0 and 3.5. Additional experimental data would be required, on a wider range of ER values, to validate this observation. These results indicated that NO_x emissions would be too high for CO_2 enrichment with direct flue gas utilisation. Thermal NO_x formation was promoted by a higher residence time for flue gases, probably due to the recirculation zone observable in the burner combustion chamber (Littlejohn *et al.* 2007), the high and sustained average flue gas temperature of 631.6°C in the chimney, and the low efficiency of the furnace heat exchanger.

Sulphur dioxide

From the portable analyzer measurements, SO_2 emissions were undetectable or within the margin of error for the instrument (< ± 10 ppm) at its best resolution (1 ppm). For premium quality sawdust wood pellets, SO_2 emissions were therefore considered insignificant at ppm resolution, as expected from the literature review. Measurements at parts per billion resolutions would be the next experimental step to confirm that SO_2 emissions respect ASHRAE standards, and ensure that the flue gas can be used directly for CO_2 enrichment.

Ethylene

Gas chromatography analyses for C_2H_4 emissions were very encouraging. The difference in C_2H_4 concentrations from flue gas and fresh air samples implied that syngas combustion added a mere 12 ppb (parts per billion) in the flue gas (Table 8). In certain trials, C_2H_4 concentrations from flue gas were even lower than in fresh air samples. These low ethylene emissions agreed with the observations from Hanan (1998), who concluded that C_2H_4 concentrations remained lower than the critical concentration of 50 ppb when CO concentrations were not exceeding 50 ppm. In this experiment, 90% of the trials showed CO emissions below 50 ppm. In fact, C_2H_4 emissions from syngas combustion were considered negligible and would not be a cause of plant damage if flue gas was injected in a greenhouse.

Table 8. Ethylene Emissions Following Combustion of Syngas from Sawdust Wood Pellets Gasification

	C_2H_4 in sample	C_2H_4 in fresh air
	(ppm)	(ppm)
Avg.	0.055	0.043
SD	0.060	0.006
Peak	0.336	-

Oxygen and carbon dioxide

Flue gas O_2 levels were measured while the theoretical estimations were obtained from Eq. 10, and gave results shown in Table 9. The portable analyzer calculated concentrations of CO_2 higher than the previously calculated value. However, the method of estimation was an indication of the maximum amount of CO_2 that could be emitted according to the fuel composition. This meant that the actual composition of syngas might have a higher content of CO, CO_2, or CH_4, compared to the estimated value used from All Power Labs. Actual measurements of CO, CO_2, and CH_4 in syngas would further validate the carbon mass balance of the syngas combustion. Nonetheless, average values for CO_2 emissions that were calculated as estimations can provide a range of CO_2 emissions useable for enrichment.

Table 9. Comparison between Estimated Values for Emissions of CO_2 and O_2 and Measured Values with a Portable Analyzer

	CO_2	O_2
Portable analyzer	11.9%	9.0%
Theoretical estimations	8.7%	8.4%

Recommendations

The analysis of the exhaust gas measurements helped determine the priorities to consider for future design modifications of the syngas burner in order to achieve CO_2 enrichment from syngas combustion without the necessity for flue gas post-combustion control. The average results shown in Table 7 hint that it could be possible to avoid a post-combustion remediation system for CO. The primary objective of the design improvements would be to reduce NO_x emissions, while maintaining the low CO and C_2H_4 emissions. The ultimate objective would be to obtain very low emissions directly at the chimney, which would ease flue gas utilization for CO_2 enrichment. With better flue gas quality, the absence of cleanup systems would reduce costs and the air dilution requirement before injecting into a greenhouse. Future comparative research should further assess the differences between combustion and gasification as well as study the economic feasibility.

Burner modifications

The Low Swirl Injector, studied by Littlejohn *et al.* (2010), is a particularly interesting burner design, which has proven to perform successfully with various fuels of lower heat content, such as biogas and syngas. The air-fuel lean mixture is injected through two passages: an outer ring of swirl blades allows a portion of the gas to swirl, while a center-channel leaves the remaining gases unswirled (Littlejohn *et al.* 2010). The center-channel has a screen with a determined blockage ratio, which influences the fluid divergence through the two passages and helps in matching the flow field of the incoming mixture with the flame speed, thus improving flame stability. The flow of the central passage with the divergent swirl flow helps in retarding the formation of a central recirculation zone in the burner, which in turn prevents an excess in residence time that would promote thermal NO_x formation (Littlejohn *et al.* 2010). This burner has been shown to maintain good flame stability, reduce risks of flame blow off, and to produce very low emissions at lean operating conditions (Littlejohn *et al.* 2010). This design ensures an optimal air-fuel mixing, which is necessary to achieve near complete combustion, and lower CO, VOCs and PAH emissions. The burner could be further tested with the operational condition of the GEK to assess its application for CO_2 enrichment.

Another approach to reduce CO or NO_x emissions in burner design is through the addition of a catalyst. A wide range of catalysts have been studied in the past for syngas and biogas combustion including magnesium-, platinum-, and hexaluminate-based materials. A catalytic mesh combustor was tested by Li *et al.* (2009) to reduce CO emissions. The experiment of interest used two wire-meshes in series, separated by a given distance, using various syngas composition, and achieved conversion ratios of CO to CO_2 at over 90%, while a single layer wire-mesh catalyst performed below 40% (Li *et al.* 2009). The double layer mesh catalyser could be an additional option to test in conjunction with the low-swirl burner to lower NO_x and CO emissions.

The syngas combustion would also benefit from a more efficient heat exchanger, such as water cooling. It was observed that the stack temperature rose up to 631.6°C, signifying heat losses due to low heat exchange efficiency and longer residence time at high temperatures for the flue gas which is prone to generate thermal NO_x. A better heat exchanger would improve heat recovery for use in a greenhouse.

From the experimental results, it was calculated that the primary air inlet supplied enough air to pre-mix with the syngas, and it provided adequate ER between 1.5 and 2.5, which fell in the optimal range mentioned by Quaak *et al.* (1999). To better compare the results with future experiments, the range of ER should therefore be kept between 1.0 and 4.0, while comparing the respective effects of the primary and the secondary air inlet. Since the flame often stretched outside of the burner, future design should also increase the burner diameter to reduce the air-fuel mixture injection velocity. Additionally, the use of experimental data coming from the manufacturer instead of direct measurements to estimate syngas flow rate introduced noise and uncertainties to results for equivalence ratios and theoretical exhaust gas compounds concentrations and should therefore be resolve in future experiments with comparative standard procedures.

Emissions measurements and instrumentation

Future research on this topic should assess the isokinetic measurement of fine particulate emissions to ensure that they respect ASHRAE standards (Eller *et al.* 1984; Reed *et al.* 1988; De Nevers 2000). Syngas composition and emissions of unburnt hydrocarbons (UHC) or VOCs should also be measured accordingly. This information would further improve the safety and understanding of CO_2 enrichment from syngas combustion.

CONCLUSIONS

1. An average CO concentration of 8.8 ppm can be obtained from a steel swirl burner operated with an average equivalence ratio of 2.6. Average results were below the ASHRAE standards in 60% of trials, and 90% below 20 ppm.
2. The average experimental concentration of NO_x emissions was 23.6 ppm, which would need to be reduced below the acceptable limit of 0.05 ppm during future research.
3. SO_x and ethylene emissions were negligible at ppm levels, and ethylene was below the critical concentration of 50 ppb for greenhouse CO_2 enrichment.
4. Theoretical exhaust gas concentrations of CO_2 were below the calculated concentrations obtained from the portable analyzer, which suggests that the syngas composition could be different than the estimated composition used in the calculations, and the actual CO_2 enrichment potential of GEK gasifier could be higher.

5. From empirical data, the GEK operating with sawdust wood pellets could enrich up to 1540 m^2 of greenhouse surface area. Results indicate that gasified biomass has the potential to provide more CO_2 for greenhouse enrichment than propane or natural gas.
6. A future burner design should aim at reducing NO_x emissions and improving the syngas combustion efficiency by integrating the low swirl design, mesh catalysers, better refractory material, and a better heat exchanger.
7. In order to prepare for actual tests inside a greenhouse, research should improve the controls of the gasifier operation, modifying the burner design, comparing performances using other sources of biomass (such as greenhouse crop residues), and assessing the exhaust gas for VOC and particulate matter emissions.

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