Biomass Gasification for Carbon Dioxide Enrichment in Greenhouses

by

Louis-Martin Dion

Degree of Master of Science

Department of Bioresource Engineering
McGill University
Montreal, Quebec, Canada

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Abstract

Biomass heating is used more and more by the greenhouse industry to reduce costs and the environmental footprint of production. The objective of this research project was to investigate the possibility of using the carbon dioxide (CO_2) from the exhaust gas of a biomass heating system to enrich greenhouses with CO_2 and improve crop yield. When compared to direct combustion, biomass gasification technology offers better control, which helps in reducing atmospheric emissions. Gasification is a thermo-chemical reaction, which converts solid biomass into a gaseous fuel, known as syngas. Experiments were performed at McGill University (Montreal, QC, Canada) using a downdraft gasifier to monitor its performance, with sawdust wood pellets as feedstock. Temperature and pressure monitoring provided valuable insights on optimal gasification temperatures, biomass fuel depletion in the reactor, ash grate shaking requirements, micro-explosions detection, char bed packing and pressure drop across the packed bed filter. The gasifier operated with an average equivalence ratio (the actual air to fuel ratio relative to the stoichiometric air to fuel requirement) of 0.17, below the optimal value of 0.25, and achieved a cold gas efficiency of 59%. Syngas combustion emissions produced an average of 8.8 ppm of carbon monoxide (CO), with 60% of the trials below the ASHRAE standards for indoor air quality and 90% below 20 ppm. The sulphur dioxide (SO_2) emissions were below ppm levels, while ethylene (C_2H_4) emissions were below the critical concentration of 50 ppb for CO_2 enrichment. The average nitrogen oxides (NO_x) emissions were 23.6 ppm and would need to be reduced to allow commercial operations. From the empirical data, the gasifier operating with sawdust wood pellets, with a consumption of 7.7 kg/hr, could provide a maximum of 22.9 kW of thermal energy and could enrich a maximum of 1540 m^2 of greenhouse surface area. Results indicated that biomass, following combustion or gasification, could provide more CO_2 for greenhouse enrichment than propane or natural gas per unit of energy. Biomass gasification coupled with syngas combustion could be a promising renewable alternative to propane and natural gas for CO_2 enrichment in greenhouses.

Résumé

Le chauffage à la biomasse résiduelle est utilisé de plus en plus par l'industrie serricole afin de réduire les coûts d'opérations et les impacts environnementaux. L'objectif de cette recherche était d'examiner la possibilité d'utiliser le dioxyde de carbone (CO_2) des gaz d'échappement d'un système de chauffage à la biomasse afin d'enrichir les serres en CO_2 et favoriser le rendement des cultures. Par rapport à la combustion directe, la gazéification de la biomasse offrent un meilleur contrôle qui permet de réduire les émissions atmosphériques. La gazéification est une réaction thermochimique qui convertit la biomasse solide en un combustible gazeux, le syngas. Des expériences ont été réalisées à l'Université McGill (Montréal, QC, Canada) pour étudier les performances d'un gazogène à courant descendant, alimenté avec des granules de sciure de bois. Les données de température et de pression ont fourni des informations sur les températures de gazéification optimale, le niveau de combustible dans le réacteur, les besoins d'agitation de la grille de cendre, la détection de micro-explosions et les chutes de pression au travers du lit de charbon du réacteur et du filtre au charbon. Le gazogène a fonctionné avec un ratio d'équivalence (i.e. le ratio réel par rapport au ratio stoichiométrique d'air et de combustible) moyen de 0.17, inférieur à la valeur optimale de 0.25, et une efficacité de 59%. La combustion du syngas a produit une moyenne de 8.8 ppm de monoxyde de carbone (CO), où 60% des essais ont respecté les normes de qualité de l'air, et 90% ont été en dessous de 20 ppm. Le dioxyde de soufre (SO_2) a été indétectable à une résolution en ppm, et les émissions d'éthylène (C_2H_4) ont été inférieures à la concentration critique de 50 ppb pour l'enrichissement au CO_2. La moyenne d'oxydes d'azote (NO_x) a été de 23.6 ppm et devrait être réduite pour des opérations commerciales. Le gazogène alimenté aux granules de bois, avec une consommation de 7.7 kg/hr, pourrait fournir 22.9 kW d'énergie thermique et enrichir une serre d'une surface de 1540 m^2. Les résultats indiquent que la gazéification de biomasse, couplée à la combustion de syngas, est une alternative prometteuse au propane et au gaz naturel pour l'enrichissement des serres au CO_2, puisque davantage de CO_2 par unité d'énergie est fournie et ce, à partir d'un combustible renouvelable.

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Contribution of authors

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This thesis follows the manuscript-based format with three manuscripts.

Chapter 2: This chapter of literature review is based on a review paper which was submitted to *Biomass & Bioenergy*.

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Chapter 3: This chapter is a manuscript in preparation for submission to *Transactions of the ASABE*.

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Chapter 4: This chapter is a manuscript in preparation for submission to *HortTechnology*.

Dion, L-M., M. Lefsrud, V. Orsat. Combustion of syngas from biomass gasification for CO_2 *enrichment in greenhouses.*

Table of Content

Abstract ii

Résumé iii

Acknowledgements iv

Contribution of authors v

List of Tables ix

List of Figures xi

Chapter 1: General Introduction 13

  1.1 Hypothesis 15

  1.2 Objectives 15

  1.3 Scope 17

  1.4 References 18

Chapter 2: Literature Review 19

  2.1 Introduction 20

  2.2 CO_2 enrichment benefits 20

  2.3 Common practices for CO_2 enrichment 22

  2.4 CO_2 enrichment from exhaust gases 24

    2.4.1 Optimal management strategies 24

    2.4.2 Natural gas and other hydrocarbons 25

    2.4.3 CO_2 enrichment from renewable fuels 25

    2.4.3.1 Landfill Biogas 26

    2.4.3.2 Corn Furnace 26

  2.5 CO_2 enrichment from biomass heating systems 27

    2.5.1 Exhaust gas composition 28

    2.5.2 Strategies for clean CO_2 enrichment 32

    2.5.2.1 Internal Modification 33

    2.5.2.1.1 Gasification 34

    2.5.2.1.2 Syngas combustion 35

    2.5.2.1.3 Theoretical engineering estimations 36

    2.5.2.2 External Modification 37

    2.5.2.2.1 Scrubbing systems 37

    2.5.2.2.2 Membrane separation of CO_2 38

2.6 Future research development 40
2.7 Conclusion 42
2.8 References 43
Connecting Statement 47
Chapter 3: A performance assessment of a downdraft gasifier to produce CO_2 for greenhouse enrichment from renewable fuels 48
3.1 Abstract 48
3.1 Introduction 50
3.2 Literature Review 51
3.2.1 Feedstock: 51
3.2.2 Gasification 54
3.2.3 Thermodynamics of combustion and gasification 59
3.4 Materials & Method 62
3.4.1 Experimental setup 62
3.4.2 Instrumentation 65
3.4.3 Feedstock 67
3.4.4 Methodology 68
3.4.5 Experimental objectives 69
3.5 Results and Discussion 70
3.5.1 Feedstock 70
3.5.2 Temperature 71
3.5.3 Pressure 75
3.5.4 Gasifier performance 80
3.5.5 Potential of CO_2 production for enrichment 84
3.5.6 Recommendations 87
3.6 Conclusion 88
3.7 References 89
Connecting Statement 91
Chapter 4: Combustion of syngas from biomass gasification for CO_2 enrichment in greenhouses 92
4.1 Abstract 92
4.1 Introduction 94
4.2 Literature Review 97
4.2.1 Gasification 97

4.2.2 Thermodynamics of Syngas Combustion 99
4.2.3 By-products of combustion 102
4.2.4 Syngas Burners 104
4.3 Materials and Methods 108
4.3.1 Experimental Setup 108
4.3.2 Instrumentation 113
4.4.3 Feedstock 115
4.3.4 Methodology 115
4.3.5 Experimental objectives 117
4.4 Results and Discussion 119
4.4.1 Gasifier performance 119
4.4.2 Syngas Combustion 120
4.4.2.1 Equivalence ratio 120
4.4.2.2 Estimation of exhaust gas composition 122
4.4.2.3 Exhaust gas measurements 123
4.4.2.4 Carbon monoxide 124
4.4.2.5 Nitrogen oxide 125
4.4.2.6 Sulphur dioxide 126
4.4.2.7 Ethylene 127
4.4.2.8 Oxygen and carbon dioxide 127
4.4.3 Recommendations 128
4.4.3.1 Burner modifications 128
4.4.3.2 Instrumentation 131
4.5 Conclusion 133
4.6 References 134
Chapter 5: General Conclusion 137

List of Tables

Table 2.1 – Nomenclature 20

Table 2.2 – Examples of optimal CO_2 enrichment concentrations for typical greenhouse crops 22

Table 2.3 – ASHRAE standards to indoor environmental quality 29

Table 3.1 – Nomenclature 51

Table 3.2 – High heating value (HHV) and low heating value (LHV) of syngas combustible compounds 60

Table 3.3 – GEK performance according to vacuum pressures from manufacturer recommendations 64

Table 3.4 – Nomenclature and description for thermocouples and for temperature sensors of the portable analyzer 66

Table 3.5 - Nomenclature and description for pressure sensors 66

Table 3.6 – Ultimate analysis from sawdust pellets 70

Table 3.7 – Average temperature profile across the gasifier obtained from sawdust wood pellet gasification 72

Table 3.8 - Average pressure profile across the downdraft gasifier obtained from sawdust wood pellet gasification 75

Table 3.9 – Average performance results for downdraft gasification of sawdust wood pellets 81

Table 3.10 – Volumetric syngas composition for GEK gasifier 81

Table 3.11 – Energy and CO_2 yield for sawdust wood pellets, for natural gas and propane 86

Table 4.1 – Nomenclature 94

Table 4.2 – ASHRAE standards to indoor environmental quality 96

Table 4.3 - GEK performance according to vacuum pressures from manufacturer recommendations 110

Table 4.4 – Nomenclature and description for thermocouples and for temperature sensors of the portable analyzer 113

Table 4.5 - Nomenclature and description for pressure sensors 114

Table 4.6 – Volumetric syngas composition for the GEK gasifier from mass spectrometry analysis (H_2) and from All Power Labs measurements (CO, CO_2, CH_4).. 119
Table 4.7 – Average performance results for downdraft gasification of sawdust wood pellets 120
Table 4.8 – Compilation of syngas and air mass flow rates into the GEK swirl burner with respective equivalence ratios...................................... 120
Table 4.9 – Compilation of important flue gas compounds from syngas combustion following sawdust wood pellets gasification 123
Table 4.10 – Ethylene emissions following combustion of syngas from sawdust wood pellets gasification 127
Table 4.11 – Comparison between estimated values for emissions of CO_2 and O_2 and measured values with a portable analyzer................................ 127

List of Figures

Figure 1.1 – Photograph of the GEK gasifier used for experiments on CO2 enrichment from biomass 17

Figure 3.1 – Schematic of gasification zones and gas and biomass flows for Updraft, Downdraft and Crossdraft gasifiers 56

Figure 3.2 – Schematic and dimensions of the downdraft gasifier reactor 63

Figure 3.3 – Schematic of the gasifier coupled with the forced-air furnace. 63

Figure 3.4 – Instrumentation schematic of the gasifier coupled with the forced-air furnace 67

Figure 3.5 – Temperature profile of a typical trial of the downdraft gasifier with sawdust wood pellets 72

Figure 3.6 – Temperature profile of a sawdust wood pellet downdraft gasification trial experiencing instabilities and high temperature rise at the top of the reactor 74

Figure 3.7 – Pressure profile of a typical trial of the downdraft gasifier with sawdust wood pellets 76

Figure 3.8 – Pressure and temperature profile of a sawdust wood pellet downdraft gasification trial showing effects of excess ash grate shaking 77

Figure 3.9 - Pressure profile of a sawdust wood pellet downdraft gasification trial showing micro-explosions 78

Figure 3.10 – Variation of packed-bed filter pressure drop with increasing numbers of monitored trials 80

Figure 3.11 – Influence of sawdust wood pellet consumption rate in a downdraft gasifier on cold gas efficiency 81

Figure 3.12 – Influence of char bed pressure drop on the equivalence ratio of downdraft gasification of sawdust wood pellets 83

Figure 3.13 – Influence of char bed pressure drop on the cold gas efficiency of downdraft gasification of sawdust wood pellets 83

Figure 4.1 – Schematic of gasification zones and gas and biomass flows for Updraft, Downdraft and Crossdraft gasifiers 97

Figure 4.2 – Photographs and cross-sectional view of the low swirl combustor 105
Figure 4.3 – Schematic and dimensions of the downdraft gasifier reactor........ 109
Figure 4.4 – Schematic of the gasifier coupled with the forced-air furnace....... 109
Figure 4.5 – Flow diagram of swirl burner with ejector venturi and instrumentation... 111
Figure 4.6 – Photograph of the swirl burner with ejector venturi and instrumentation... 113
Figure 4.7 – Sampling train configuration for exhaust gas............................... 112
Figure 4.8 - Sampling train configuration for syngas...................................... 112
Figure 4.9 – Instrumentation schematic of the gasifier coupled with the forced-air furnace 114
Figure 4.10 – Effects of equivalence ratio on CO emissions from syngas combustion...123
Figure 4.11 - Effects of equivalence ratio on NO_x emissions from syngas combustion... 125
Figure 4.12 – Combined effect of equivalence ratio variation on CO and NO_x emissions... 125

Chapter 1: General Introduction

A worldwide shift in policy is currently pushing most industries and governments to reduce greenhouse gas emissions and reduce their dependence on fossil fuels by developing cleaner alternatives and improving energy efficiency. Many nations are seeking energy independence and security, by developing efficient technologies and using local sources of sustainable energy. In northern climates, the horticulture industry has not been spared of these changes due to their high energy consumption. Greenhouse operators must address this issue by balancing energy efficiency through structural or fuel saving techniques, while keeping growing conditions optimal in order to compete with international markets for commodities. Specifically, heating systems require improvements as they solicit around a quarter of the operational costs depending on the energy source (oil, gas, electricity, or biomass) (Chau et al., 2009). It is to the growers' advantage to reduce the annual energy cost and, consequently, the environmental footprint of greenhouse operation.

Within the last decade, fluctuations of fossil fuel prices have increased the necessity to explore alternative systems and this has allowed biomass heating to become an economically viable option (Chau et al., 2009). Biomass has been recognised as a sustainable renewable fuel alternative that can also reduce greenhouse gas production (Petersen Raymer, 2006). The life-cycle global warming potential of combined heat and power systems fuelled with biomass is much lower than for systems powered with natural gas (Eriksson et al., 2007). Carbon dioxide (CO_2) emissions from biomass heating systems still occur at the chimney due to the natural thermo-chemical reaction of combustion. However, considering that biomass combustion releases, at most, the same amount of CO_2 that was absorbed via photosynthesis in the plant's life cycle, the technology is thus considered carbon neutral (Basu, 2010). Biomass combustion technologies are well established, but gasification technologies are showing a lot of promise, both in research and commercial applications, to achieve high efficiency and cleaner energy production (Quaak et al., 1999; McKendry, 2002; Basu, 2010). Gasification is a thermo-chemical reaction that differs from combustion by being under partial oxidation, thus converting the material into a gaseous fuel. In its raw form, the gas is known as producer gas and can be used for power and heat production. Once removed from impurities, the gas is referred as a synthesis gas, which can be further converted into chemicals or liquid fuels (McKendry, 2002). For the sake of this research project, the term syngas is used in reference to the producer gas. Since a gaseous fuel is burned instead of a solid fuel, a gasification system allows biomass heating to be cleaner and easier to control, than direct combustion systems (Reed et al., 1988; Quaak et al., 1999; Whitty et al., 2008).

Using waste exhaust gases from a heating system can be beneficial to greenhouse plants by providing a viable source of carbon dioxide (Hicklenton, 1988). CO_2 enrichment is a well established technique to enhance photosynthesis resulting in improved yields and income (Chalabi et al., 2002). Enrichment is typically practiced with pure CO_2 in bulk or from combustion of hydrocarbon fuel (natural gas or propane). Usually, these fuels are employed in dedicated burners to provide CO_2, while a separate heating system provides most of the heat to the greenhouse (Hanan, 1998). CO_2 enrichment from the exhaust of a natural gas or propane heating system has proven to be feasible, but replacing these fuels with biomass could have further benefits. However, very few researchers have explored the feasibility of using CO_2 from heating systems supplied with renewable energy, apart from a corn furnace or the use of landfill biogas (Léveillée and Gendreau, 1998; Jaffrin et al., 2003). With the optimisation of carbon absorption by plants, a greenhouse fed with the clean exhaust of a biomass heating system could benefit from an overall greenhouse gases reduction. CO_2 enrichment from exhaust gases could be a means to reduce carbon emissions directly at the source through greenhouse grown plant uptake. Such an initiative could be part of a carbon market and sequestration incentive. The concept of solid waste, from municipal or industrial sources, is progressively being recognised as a resource, but capturing waste exhaust gas compounds can also provide a potential useful resource, while reducing atmospheric emissions and improving the overall efficiency of a process.

1.1 Hypothesis

Considering the current challenges of obtaining clean exhaust gas from biomass combustion, alternative thermo-chemical processes, which could be used for heating and supplying CO_2, were explored and the first hypothesis was established:

- Biomass gasification can provide a safe, sustainable and viable replacement to conventional CO_2 production technologies for enrichment in greenhouses.

Once the gasification process was well understood and tested in regard to its application for CO_2 enrichment, the second hypothesis was formulated:

- Near complete syngas combustion can relieve the need of post-combustion cleaning systems and produce a clean flue gas to be used for CO_2 enrichment in greenhouses.

1.2 Objectives

At the moment of writing, no known peer reviewed research had explored the feasibility of greenhouse CO_2 enrichment from the exhaust gas of a biomass heating system. Therefore, it was necessary, as a first objective, to give thorough attention to the literature review.

- **Objective 1**: To identify research avenues and directions to achieve CO_2 enrichment from a solid biomass heating system.

The second chapter of this thesis provides an overview of different CO_2 enrichment benefits and practices from exhaust gas recovery. The usual composition of exhaust gas is detailed to understand the various challenges in obtaining clean CO_2 from heating systems. This review concentrates on the potential of CO_2 enrichment from flue gases of biomass heating systems. For that purpose, common techniques are addressed, but the focus remains on exploring maturing technologies that may be applicable to address future research directions.

The third chapter delves deeper into the use of gasification technologies as a potential CO_2 production unit for greenhouses, by performing laboratory scale experiments.

- **Objective 2**: To monitor the performance of a pilot scale gasifier (downdraft type of 10 to 100 kW) to estimate the useable CO_2 production rate for enrichment per unit of biomass, while identifying the characteristics of the system that would affect CO_2 enrichment operations.

The experiments were performed to obtain average empirical data to estimate biomass consumption rate, air intake flow rate and syngas flow rate, which were needed to estimate the CO_2 enrichment potential of the unit. The gasifier performance was also monitored in terms of temperature, pressure and efficiency, by considering the use of densified biomass (sawdust wood pellets).

While understanding the gasifier performance is essential to ensure steady operation, the combustion of syngas remains a pivotal component to guarantee clean exhaust gas for safe use of CO_2 in greenhouses.

- **Objective 3**: To monitor the performance of a syngas burner in terms of exhaust gas composition and to identify potential improvements for the burner design aimed at its application for CO_2 enrichment in greenhouses.

The fourth chapter of this thesis looks at the exhaust gas emissions from a rudimentary syngas swirl burner. An outlook of the flue gas compounds formation and of the current syngas burner design is given. The experimental CO_2 enrichment potential of syngas combustion is compared with theoretical estimations. The goal of the research is to demonstrate that syngas combustion may present an interesting renewable alternative for CO_2 enrichment from a biomass heating system. Chapter 2, 3 and 4 are presented as standalone manuscripts for this engineering research project.

1.3 Scope

The experiments for this engineering research project were conducted from April to October 2010, at the Technical Services building of the Macdonald Campus of McGill University. The campus is located in Sainte-Anne-de-Bellevue, at the western tip of the island of Montreal (Quebec, Canada).

Figure 1.1 – Photograph of the GEK gasifier used for experiments on CO_2 enrichment from biomass

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Chapter 2: Literature Review

Table 2.1 – Nomenclature

A_{cover}	surface area of the greenhouse cover	(m^2)
c_p	specific heat capacity of air	($J/(kg \cdot K)$)
η_b	boiler or furnace efficiency	%
η_d	heat distribution network efficiency	
ρ	air density	(kg/m^3)
P_{peak}	Peak power output of the heating system	(W)
q	number of air exchange per hour	(hr^{-1})
$\dot{Q}_{air}$	convective heat loss by air exchange	(W)
$\dot{Q}_{cl}$	conductive heat loss through the greenhouse walls and roof	(W)
$\dot{Q}_{clp}$	conductive heat loss through the greenhouse perimeter	(W)
$\dot{Q}_t$	rate of total greenhouse heat loss	(W)
T_{in}	inside greenhouse operating temperature	(K)
T_{out}	minimum outside temperature	(K)
U_{cover}	heat transfer coefficient of the walls and roof materials	($W/(m^2 \cdot K)$)
U_p	thermal conductivity of the perimeter	($W/(m \cdot K)$)
V	greenhouse volume	(m^3)

2.1 Introduction

In practice, carbon dioxide (CO_2) enrichment from the exhaust gas of biomass boilers is still challenging and expensive considering the current equipment and exhaust gas composition (Chau et al., 2009b). However, recent technological developments could help reduce costs and make this process more feasible. This paper provides an overview of different CO_2 enrichment benefits and practices from exhaust gas recovery. The usual composition of exhaust gases will be detailed to understand the various challenges in obtaining clean CO_2 from heating systems. This review will also concentrate on the potential of CO_2 enrichment from biomass flue gas. For that purpose, common techniques will be addressed, but the focus will remain on exploring maturing technologies that may be applicable, in order to address future research directions.

2.2 CO_2 enrichment benefits

Carbon dioxide is fixed and reduced into simple sugars during photosynthesis.

$$6CO_2+12H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6+6O_2+6H_2O \tag{1}$$

The series of carbon-fixation reactions is called the Calvin cycle. However, CO_2 reaches the Calvin cycle through one of three metabolic pathways depending on the plant species (Graham et al., 2003). The C3 pathway is used by the majority of plants on Earth such as common cereal grasses, soybeans and potatoes. The C4 pathway is more efficient at fixing CO_2 and achieving higher net rates of photosynthesis, which make crops, such as corn and sugarcane, thrive. The CAM plants are common in arid and desert conditions. They also use the C4 pathway but operate at night to compensate for daytime high temperatures and reduce water losses. The C3 plants are the most common greenhouse crops, but they are less efficient at fixing CO_2 when concentrations are around ambient CO_2 levels, which is currently estimated at 388ppm (Tans, 2010). This reduced efficiency is due to photorespiration, which occurs in sunlight and is the consequence of the RuBisCO enzyme combining with oxygen (O_2) instead of CO_2 during the Calvin cycle. The plant releases some CO_2 during the day instead of O_2, and as much as half of the CO_2 fixed may be returned to the atmosphere (Graham et al., 2003). The main consequence of photorespiration for greenhouse operators is reduced biomass yield.

C4 and CAM plants have evolved to use better metabolic mechanisms to reduce photorespiration problems directly, but they do not represent the majority of agricultural and greenhouse crops. For C3 plants, raising CO_2 concentrations in a greenhouse limits photorespiration by reducing the binding affinity of RuBisCO in the plant to inadvertently absorb O_2 (Mortensen, 1987). Consequently, yields of C3 plants are improved because of a higher photosynthetic rate, creating more carbohydrates, which translate into increased biomass (Sánchez-Guerrero et al., 2009). Yield increases are observed in various plants whether it is through larger total dry mass, bigger and more numerous fruits, larger leaves and flowers, as well as earlier flowering time and reduced overall production time. High CO_2 levels have also been reported to promote hormonal responses in terms of enhanced secondary compounds such as essential oils and antioxidants (Tisserat and Vaughn, 2001; Wang et al., 2003). Benefits of CO_2 enrichment are widely documented for commercial greenhouse crops, including fruits, flowers and vegetables. Yields have been observed to increase from 21 to 61% in dry mass. Each crop responds differently and has a particular optimal enrichment CO_2 concentration level. On average, greenhouse crops benefit from an increase in CO_2 concentration varying between 700 to 1000 ppm (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).

Table 2.2 – Examples of optimal CO_2 enrichment concentrations for typical greenhouse crops (Yelle, 1988)

Crop	Optimal CO_2 Concentration
Tomato	1000 ppm
Cucumber	1200 ppm
Pepper	1000 ppm
Lettuce	1000 - 1500 ppm
Rose	1000 -1200 ppm

These optimal levels can help overcome the inherent C3 pathway inefficiency, but concentrations higher than 1500 ppm can cause permanent damage to some plants, such as chlorosis, necrosis and curling of the leaves (Mortensen, 1987). Moreover, the yield benefits from CO_2 enrichment can counterbalance any reduction in sunlight irradiance that would normally result in decreased plant growth. For instance, CO_2 enrichment can fully compensate a 30% decrease in daylight (Mortensen and Moe, 1983). Higher CO_2 concentration decreases the leaves stomatal aperture leading to lower transpiration rates, which correlates into enhanced water use efficiency (Leakey et al., 2006). Since less water is necessary under enrichment conditions, nutrient uptake by the plant is increased (Sánchez-Guerrero et al., 2009).

2.3 Common practices for CO_2 enrichment

CO_2 enrichment is recommended from sunrise until sunset and the rate will depend mostly on crop type, crop age, CO_2 loss and ventilation rates (Mortensen, 1987). As a general rule of thumb, Hinklenton's guideline suggested an injection rate of 5.6 g $CO_2/(m^2 \cdot hr)$ to achieve an average optimal concentration of 1000 ppm (Hicklenton, 1988). However in practice, it is not surprising to see producers injecting CO_2 at rates of 20 $g/(m^2 \cdot hr)$ and up to 50 $g/(m^2 \cdot hr)$ (Edwards, 2008). Ventilation is the major parameter that has the most influence on CO_2 enrichment performance. In winter, since ventilation is reduced, CO_2 can reach levels close to depletion if not supplied, while in summer, during full ventilation, most of the CO_2 injected will be lost to the atmosphere (Hanan, 1998). Both cases have economical impacts on the production. One management strategy is to inject

CO_2 only to prevent depletion, thus remaining at atmospheric levels, while benefiting from some yield improvements and lower costs (Kläring et al., 2007). Other strategies involve maintaining concentration at atmospheric levels during the ventilation period and enriching up to the desired optimal level when the greenhouse is kept closed (mornings and late afternoons during the summer and most of the winter) (Sánchez-Guerrero et al., 2005). Alternative cooling systems, such as geothermal or aquifer cooling, are also promising technologies to reduce the necessity of frequent air exchanges and preventing substantial losses of CO_2 (Sethi and Sharma, 2007). In addition, recent plant science research advocates for a plant based approach to CO_2 enrichment. It has been observed that plants only fix a portion of the generated CO_2 at a time (Edwards, 2008). An example with CO_2 enriched tomato cultures showed that the plants were accumulating an excess amount of starch compared to their ability to convert carbon for the benefit of fruit growth. Edwards (2008) suggested that the leaf mass per unit area could be used as a promising indication to determine if the plant had a surplus of carbon and if enrichment should be postponed. Therefore, a plant based approach for CO_2 enrichment, as suggested by Edwards (2008), could prevent overdosing and wasting of CO_2 to the atmosphere.

A common source of CO_2 is in a pure liquefied form, stored in a pressurized tank, which is a safe option to ensure quality gas injection (Wittwer and Robb, 1964). The reservoir capacity can range from 20 kg to 52,000 kg of CO_2. Pure CO_2 facilitates the control of desired concentrations, but remains the most expensive source (Hanan, 1998). In comparison, fuel combustion is a cheaper alternative in terms of both fixed and operational costs. Propane is a popular fuel and consists of a mixture of 65% propane and 35% propylene. The latter is phytotoxic following incomplete combustion. Small common burners will consume 1 kg of propane to produce around 3 kg of CO_2 (Hicklenton, 1988). Depending on the access to the supply, natural gas, when used for CO_2 enrichment only, is safe and economical which makes it an even more popular alternative (Hanan, 1998). A general burner will consume 1 kg of natural gas to produce 2.1 kg of CO_2 (Hanan, 1998).

2.4 CO_2 enrichment from exhaust gases

Exhaust gases taken from heating systems provide a “free” source of CO_2 for greenhouses enrichment. It can be considered “free” since it is a waste product of necessary heating. Larger heating systems may require adjustments and investments for installation and maintenance (Hicklenton, 1988), including distribution network, flue gas cooling and removing toxic compounds if necessary. Work by Chalabi et al. (2002) has also confirmed significant economic benefit of CO_2 enrichment from exhaust gases over pure CO_2.

2.4.1 Optimal management strategies

Using exhaust gas efficiently requires optimal management strategies since heating periods do not always coincide with CO_2 enrichment periods. Heating occurs mostly at night (depending on climate) while CO_2 enrichment is required only during daytime lighting periods for photosynthesis. A typical solution is to store the heat in a hot water or thermal fluid tank during the day when producing CO_2 for the plants. The heat reservoir acts as a buffer and the hot fluid can then heat the greenhouse at night via a forced air system or radiation pipes (Chalabi et al., 2002). A second option, suggested for mild winter climates, is to enrich only in the mornings and late afternoons, when the solar energy intake for the greenhouse is low. This morning/evening method has proven to be useful since ventilation typically does not function during these time periods and increases enrichment efficiency (Sánchez-Guerrero et al., 2005). It has been reported that injecting higher concentrations of CO_2 than required, starting one hour before sunrise and for two subsequent hours, has produced similar results to continuous daytime enrichment (Longuenesse, 1990). In general, optimal enrichment procedures during the daytime increase yields by 11% and this benefit increases to 24% when using heat storage strategies (Chalabi et al., 2002).

2.4.2 Natural gas and other hydrocarbons

Assuming proper combustion, natural gas is typically accepted by industry to produce clean CO_2, which can be directly injected into the greenhouse (Chalabi et al., 2002). It also serves as a better heat source than propane when supplying CO_2 (Hicklenton, 1988). Since heating and enrichment do not always coincide in the same time period, Chalabi et al. (2002) reported that enrichment using natural gas typically increases fuel consumption by 25% from what is used for meeting the greenhouse heating requirements only. However, this observed value could be reduced depending on optimal enrichment strategies, including use of heat storage tanks. Enrichment at the same time than heating periods does not increase fuel consumption (Chalabi et al., 2002). CO alarms are required inside the greenhouse since incomplete combustion of natural gas could be harmful, both for plants and humans. CO_2 concentration is typically controlled via on/off modulation of the burner linked to CO_2 sensors strategically placed in the greenhouse. Water vapour can also be a concern and should be removed via condensers as it can cause fungus and mould growth within the greenhouse (Chau et al., 2009b). Standard greenhouse practices dilute the exhaust gas with outside air, which condenses water vapour, decreases the flue gas temperature, and reduces harmful gas concentration to acceptable levels. The cool diluted gases are then distributed throughout the greenhouse with standard circulation fans or perforated plastic tubes (Chalabi et al., 2002).

2.4.3 CO_2 enrichment from renewable fuels

Heating systems fed with solid biofuels have now surpassed the proof of concept and have been implemented commercially in various regions of the world. Many of those still emit gaseous emissions, but when connected to a greenhouse, CO_2 can potentially be considered a co-product as long as it is cleaned of impurities and used efficiently for enrichment. Therefore, CO_2 could be harvested from heating systems running on biomass, biogas of anaerobic digestions or landfill, and even from gases emitted by large industrial size composters. Early research has explored the use of landfill biogas and a corn furnace.

2.4.3.1 Landfill Biogas

Combustion of biogas, collected from a landfill, has been promoted by research and proven viable to supply both heating and CO_2 (Jaffrin et al., 2003; Janes et al., 2005). In a demonstration project, the extracted gas was directed into a combustion boiler, which discharged the CO_2 inside a greenhouse once it was purified (Jaffrin et al., 2003). Since biogas was extracted from a heterogeneous landfill, its composition and toxicity varied significantly. For instance, methane (CH_4) content could range between 23 to 54% depending on the conditions. Toxic compounds were predominantly destroyed once the gas was flared at over 900^oC, while a gas scrubber, using a chemically reactive liquid, purified the gas from acid contaminants (Jaffrin et al., 2003). To reduce risks of toxicity, the exhaust gas was cooled down and diluted up to 50 times with fresh air. Jaffrin et al. (2003) reported that most toxic gases were found to be diluted and undetectable once injected in the greenhouse. Carbon monoxide (CO), while detectable, was well below ASHRAE safety regulations (Jaffrin et al., 2003). Thereafter, they observed a 30% yield increase in the supplemented greenhouse. These results show promising use of landfill biogas even though little additional research has been published on other commercial applications. Their methodology also hints at practices, such as high temperature combustion, the use of scrubbers and proper dilution, which could be applicable for biomass heating systems with contaminated exhaust gas.

2.4.3.2 Corn Furnace

The Quebec greenhouse research center, “Centre d'information et de développement expérimental en serriculture” (CIDES, Canada), has performed an experiment using corn as a fuel source to supply CO_2 to a greenhouse (Léveillée and Gendreau, 1998). A furnace designed specifically for this purpose ejected the exhaust gas directly in the greenhouse without requiring particulate or pollutant removal. They reported that 1.7 kg of CO_2 was produced from 1 kg of corn. In comparison, propane yields 3 kg of CO_2 per kg of fuel, while natural gas provides 1.8 kg of CO_2 per m^3. Depending on the local cost of these fuels, Léveillé and Gendreau (1998) had calculated that corn usually proved to be a more economical option. In that study, the concentrations of the nitrogen oxide (NO_x), sulphur oxide (SO_x), CO and ethylene (C_2H_4) were below toxicity levels, while fine particulates were not listed in the report (Léveillée and Gendreau, 1998). The design and combustion efficiency of the furnace used in the experiment were not described and could be areas of improvements for this CO_2 enrichment method. Nonetheless, these results reveal the potential of using solid dry biomass for CO_2 enrichment.

2.5 CO_2 enrichment from biomass heating systems

Biomass is a very broad term encompassing many sources of non-fossilized and biodegradable organic materials, which are derivatives of plants as a result of photosynthesis or are originating from animals and micro-organisms (Basu, 2010). Around 1% of the incoming solar radiation energy is converted by plants into chemical energy via photosynthesis (McKendry, 2002a). This available energy within biomass can then be released or converted into other high energy content products via thermo-chemical or bio-chemical processes. Biomass with lower moisture content (below 50%) can release energy, fully or in part, as heat through thermo-chemical processes such as combustion, gasification or pyrolysis (McKendry, 2002b). Biomass with, but not limited to, high moisture content can be converted with bio-chemical processes, such as fermentation and anaerobic digestions, into liquid and gaseous fuels (McKendry, 2002b). Common biomass resources can include products, by-products, residues and waste from agriculture and forestry industries along with non-fossilized, biodegradable industrial and municipal wastes (Basu, 2010). Whether provided in its raw form or processed as pellets, chips, brickets or others, biomass can be an appropriate fuel to provide both heat and CO_2 to a greenhouse via combustion or other thermo-chemical processes. Biomass is acknowledged to be renewable by many governmental institutions and has proven to be profitable in some commercial applications even when compared with natural gas (Chau et al., 2009a). Biomass heating is found to sustain heating requirements of large surface buildings in northern winters. Such high demands in thermal energy are difficult to satisfy whether practically, by other renewable resources such as solar and wind, or economically when using hydro-powered electrical or geothermal heating.

However, biomass combustion is not as clean as natural gas combustion. While it produces CO_2 and water vapour as well, it also leads to higher emissions of NO_x, SO_x, CO, and volatile organic carbons (VOCs). Still, the overall life-cycle greenhouse gas emissions of biomass compared to natural gas are much lower (Dones, 2003). Therefore, more CO_2 is emitted at the stack of the biomass boiler, but when considering resource extraction, transportation, transformation, use and disposal, and carbon fixation by trees, the carbon balance is better than with natural gas (Eriksson et al., 2007). In terms of enrichment applications, combustion of dry and clean wood biomass can produce two times more useful CO_2 than natural gas for the same energy unit (Chau et al., 2009b). Exact flue gas composition depends on furnace design and efficiency. Additionally, considering the vast selection of solid dry biomass with distinct properties, emission characteristics and efficiency may differ significantly from one source to another.

2.5.1 Exhaust gas composition

Ideally, complete combustion of organic compounds produces heat and emits CO_2 and water vapour. In practice, heating systems cannot reach 100% combustion efficiency whether it uses fossil fuels or biomass. Consequently, incomplete combustion generates pollutants that can be toxic when injected in a greenhouse atmosphere. They need to be treated and separated since these can be detrimental to plant health as much as ultra-high CO_2 concentrations. The main compounds found in the exhaust gas of inefficient biomass heating systems are CO, NO_x, SO_x, C_2H_4, other VOCs, and fine particulates (Hanan, 1998). Other compounds, emitted in low concentrations, include nitrous oxides (N_2O), hydrogen chloride (HCl) originating from some grasses, heavy metals (Cu, Pb, Cd, Hg) from impregnated or painted wood, polycyclic aromatic hydrocarbons (PAH), polychlorinated dioxins and furans (PCDD/F), ammonia (NH_3) and ozone (O_3) (Van Loo and Koppejan, 2008). PAH emissions have received growing concerns due to their carcinogenic effects (Van Loo and Koppejan, 2008).

For injection of CO_2 in greenhouses, human health and safety have to be prioritized, and control measures must be applied. Exhaust gases can contain hazardous compounds such as carbon monoxide, lethal for humans, and fine particulates, which can cause respiratory problems. Compiled data for concentration limits from ASHRAE (2009) standards are presented in Table 2.3. Indoor air quality standards for human beings are strict and should be applicable to maintain plant health. For instance, injuries from NO_x or SO_x to plants have been observed at concentrations higher than those established by ASHRAE (Bennett et al., 1975; Mortensen, 1987; Hanan, 1998). Therefore, respecting ASHRAE standards should ensure clean greenhouse air quality for both workers and crops.

Table 2.3 – ASHRAE standards to indoor environmental quality (ASHRAE, 2009)

Compound		Concentration limit	
Carbon Dioxide	CO_2	3500	ppm
Carbon Monoxide	CO	11	ppm (8h)
		25	ppm (1h)
Nitrogen Dioxide	NO_2	0.05	ppm
		0.25	ppm (1h)
Particles $PM_{2.5}$		40	$\mu g/m^3$ (8h)
		100	$\mu g/m^3$ (1h)
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).

Carbon monoxide is mostly damaging for humans since it is a chemical asphyxiant that prevents oxygen transport in the blood. CO becomes poisonous when inhaled in large quantities since it has more affinity with hemoglobin and forms carboxyhemoglobin (ASHRAE, 2009). Post-combustion CO emissions are due to insufficient levels of hydrocarbons oxidation, low temperatures (under 1000°C) and short residence time (Van Loo and Koppejan, 2008).

Incomplete combustion and improper air-fuel mixing will generate volatile organic compounds. These include a many different compounds that can vaporize easily and that contain organic carbon bonded with other carbon, hydrogen, nitrogen or sulphur (De Nevers, 2000). VOCs are usually regulated individually since some are not toxic to humans while others can be toxic and carcinogenic (De Nevers, 2000). In terms of toxicity on plants, ethylene is one of the most important VOCs. Ethylene acts as a plant hormone, which provokes early senescence (leaf drop) in plants (Mortensen, 1987). Hanan (1998) has concluded that C_2H_4 can remain lower than the critical concentration of 50 ppb as long as the flue gas CO does not exceed 50 ppm. Still, even the best combustion systems using propane or natural gas might not avoid ethylene production, but the concentration should remain low enough to be diluted and untraceable inside the greenhouse (Hicklenton, 1988).

The compounds of SO_x consist mostly of SO_2 and a small fraction of SO_3, which is usually negligible (De Nevers, 2000). Sulphur dioxide has been commonly observed as phytotoxic (Hicklenton, 1988). Plant leaves will show signs of necrosis under SO_2 exposures exceeding 0.5 ppm over a 4 hour period (Hicklenton, 1988). Since SO_2 is easily soluble in water, it will react with moisture when inhaled and irritate lungs (ASHRAE, 2009). However, SO_x are produced only if sulphur is present in the fuel (Bennett et al., 1975). For instance, SO_2 emissions were common when low quality kerosene was used, but are now significantly reduced with low-sulphur kerosene (less than 0.06% sulphur) (Mortensen, 1987). Sulphur can be found between 0.01 to 2% in biomass fuels (Reed et al., 1988), thus the resulting SO_x emissions are generally considered minor combustion products (Van Loo and Koppejan, 2008). In particular, wood pellets contain as low as 0.01% sulphur, which makes SO_x hardly measurable in the combustion stack (Todd, 2008). Nonetheless, SO_x should not be neglected since it remains one of the most important compounds for air pollution control (De Nevers, 2000).

Hydrogen chloride (HCl) is another compound emitted only if the compound, chlorine, is found in the fuel. Wood usually contains very low amounts of Cl, while it can be found in higher concentrations in grasses such as miscanthus, switchgrass and straw (Van Loo and Koppejan, 2008). HCl emissions can be prevented by fuel washing or with post-combustion control measures.

Nitrogen oxides, whether in the form of NO or NO_2, can be absorbed by plants and cause stresses such as chlorosis, necrosis or growth reduction (Mortensen, 1987). NO_x has been measured following enrichment using propane, kerosene, natural gas and biomass (Hicklenton, 1988). It can reduce photosynthesis significantly at levels above 0.25 ppm depending on the crop (Hanan, 1998). In terms of human health impacts, nitric oxide (NO) inhalation interferes with O_2 transport at the cellular level where effects of 3 ppm of NO are comparable to CO concentrations of 10 to 15 ppm (ASHRAE, 2009). Nitrogen dioxide (NO_2) is a corrosive gas which can cause lung damage (ASHRAE, 2009).

Particle emissions, also referred as particulate matter (PM), are regulated according to two criteria: concentration in mg/m^3 or $\mu g/m^3$ and aerodynamic diameter size in µm (ASHRAE, 2009). Particles include inorganic compounds from the solid fuel and heavy hydrocarbons which condense to form tars or unburnt carbon species creating soot (Van Loo and Koppejan, 2008). The main concern is with PM less than 2 µm, which can deposit in the lungs. Particles larger than 8 to 10 µm are typically filtered in the upper respiratory tract while intermediate sizes are deposited in the conducting airways of the lungs, but are usually cleared after being swallowed or coughed out. Submicron particles might not necessarily deposit inside the lungs and may be directly exhaled (ASHRAE, 2009). Most regulations limit PM emissions concentrations according to particle sizes. For instance, PM_{10} is a standard for particles smaller than 10 µm; $PM_{2.5}$ and

PM_1 are also common references (ASHRAE, 2009). Fine particulate matter ($PM_{2.5}$) can cause respiratory problems such as lung disease and asthma. High short term exposures are also linked with shortness of breath, eye and lung irritations, nausea and allergies (ASHRAE, 2009).

2.5.2 Strategies for clean CO_2 enrichment

Nowadays, most of the pollutants mentioned previously are due to incomplete combustion. The main factors contributing to complete combustion of a fuel are residence time, temperature and turbulence (Reed et al., 1988). The residence time depends on the combustion chamber dimension, while temperature is kept high with refractory materials, ceramics or high temperature metal alloys (Reed et al., 1988). Temperature is preferred over 1000°C to reduce CO emissions and under 1300°C to control NO_x emissions (Van Loo and Koppejan, 2008). Turbulence is promoted by various means of air injection to mix with the fuel and assure near complete fuel oxidation (Reed et al., 1988). The optimal combination of these three factors can reduce VOCs and large organic pollutants significantly (Van Loo and Koppejan, 2008). Additionally, most current commercial biomass combustion furnaces are regulated to meet local municipal regulations for gaseous and fine particulate atmospheric emissions. However, the main challenge is to reduce these emissions up to workplace safety regulations when injecting exhaust gas in a greenhouse with few or no post-combustion treatment system. For instance, typical regulations for stack PM emissions are usually found in the range of mg/m^3 while it should be reduced to $\mu g/m^3$.

Reducing PM emissions can be costly in terms of initial system investment or constant maintenance cost. Post-combustion particle separation devices are usually described by their cut diameter (D_{cut}), which is the diameter of a particle when capture efficiency is 50% (De Nevers, 2000). The cut diameter of a collection device does not necessarily indicate the particle concentration output as it depends on the combustion system and its operation. Cyclones, scrubbers, electrostatic precipitators (ESP) and fabric filters can typically stop particles of around 5, 0.5, 0.5 and 0.1 μm respectively (De Nevers, 2000). In terms of PM concentrations from large biomass boiler, it seems that an ESP is the most effective technology to achieve 40 mg/m^3 (Chau et al., 2009b). Unfortunately, this concentration is still higher than the desired 40 µg/m^3. Additionally, an ESP can increase initial costs substantially and decrease up to 70% the net present value of the whole system, making it only feasible for greenhouses larger than 7.5 ha (Chau et al., 2009b). It would be possible to combine various PM removal systems to reach µg/m^3 concentrations, but the cost would not be viable with current technologies. Ultimately, a more affordable technique is required for PM removal to practice safe and economical CO_2 enrichment from biomass. Ideally, the system should be designed to avoid post-combustion cleaning systems as seen with propane and natural gas CO_2 enrichment burners. There are several methods to reduce undesirable emissions for which primary methods are internal design optimisations made to the heating system that make use of one or various thermo-chemical processes, while secondary methods are post-combustion add-ons (Devi et al., 2003).

2.5.2.1 Internal Modification

The efficiency of biomass conversion into energy depends on the chosen thermo-chemical reaction. System design is crucial for reducing fuel consumption and pollution emissions. Implementing proper internal modifications may even alleviate the necessity of adding emission control devices. Amongst the main thermo-chemical processes for biomass conversion, combustion is widely applied for heating. It consists in an almost complete oxidation of the fuel resulting in heat production. Efficiency of combustion heating systems, by implementation of proper residence time, temperature and turbulence, varies depending on their design, manufacturing and operation. Various combustion technologies exists such as fixed bed, fluidized bed and pulverized bed combustion (Van Loo and Koppejan, 2008). The system may be built for the flame to be directed counter-current, co-current or cross-flow to the fuel. Biomass moisture content is recommended to be lower than 50% since it impacts the system's efficiency (McKendry, 2002b). The heating unit should have energy recovery measures to reduce heat losses. Combustion chamber should work at an optimal temperature, with sufficient residence time and proper oxygen supply to ensure better combustion depending on which feedstock is used and at what moisture content (Van Loo and Koppejan, 2008). A more efficient combustion decreases PM and toxic gas emissions. For most greenhouses, biomass boilers use a hot water (or other thermal fluid) distribution network for heating (Chau et al., 2009b). Since day and night temperatures can fluctuate by more than 15°C on the same day, the turn down ratio of boiler power requirement can be significant, thus increasing equipment wear and maintenance cost. High power fluctuations for biomass heating systems should be avoided since it reduces overall fuel use efficiency and increases equipment wear. Thermal fluid buffers are recommended and can maintain boiler operation at an optimal and more constant power output (Nederhoff, 2004). The buffer can accumulate excess heat and then redistribute it to compensate for higher peaks of thermal requirements, while the biomass boiler is operated more continuously (The Carbon Trust, 2009). This practice reduces the required power output of the boiler, and consequently, the initial investment cost of the system. Moreover, hot water tanks are already recommended for optimal CO_2 enrichment practices.

2.5.2.1.1 Gasification

In parallel, technologies using gasification are showing a lot of promise both in research and commercial applications (Quaak et al., 1999; McKendry, 2002c; Basu, 2010). Compared to combustion, gasification consists in partial oxidation of biomass under high temperatures, thus converting the material into a gaseous fuel. Therefore, gasification requires heat to store energy into chemical bonds while combustion breaks these bonds and releases energy as heat (Basu, 2010). Various types of feedstock can be used for gasification such as coal and a myriad of biomass sources. However, biomass has much higher volatile content than other solid fuels, up to 80%, which is ideal for gasification (Quaak et al., 1999). Depending on the gasifier design and feedstock, syngas is usually composed of hydrogen (H_2, 12-20%), CO (17-22%), CH_4 (2-3%), CO_2 (9-15%), water vapour (H_2O), nitrogen (N_2) and tar vapours (Reed et al., 1988; Quaak et al., 1999; McKendry, 2002c). In general, air is used as the oxidizing agent and results in a producer gas containing impurities such as tars. When impurities are removed or when pure oxygen is used instead of air, the resulting gas is known as synthesis gas, composed of CO and H_2. For the sake of this research, the term syngas is used in reference to the producer gas. When using air, the calorific value of syngas is usually around 4-6 MJ/m^3, while it can reach 12-20 MJ/m^3 with oxygen (McKendry, 2002c). In comparison, natural gas has an average energy content of 36 MJ/m^3. Syngas can be used for power and heat production and synthesis gas can be converted again into chemicals or liquid fuels. By coupling a gasification chamber to a combustion chamber, the syngas is burned separately from the biomass fuel to provide heat and CO_2. Since it is the gaseous fuel that undergoes combustion instead of the solid biomass, far less fine particulates are emitted in the stack (Whitty et al., 2008). Some inorganic and organic particulates might still be present in syngas and thus, syngas combustion efficiency will dictate how much of these particulates will be emitted. Overall, gasification coupled with syngas combustion for heat and power can achieve high efficiency and is recognised to make biomass heating cleaner and easier to control, compared to direct combustion of solid fuels (Reed et al., 1988; Quaak et al., 1999; Whitty et al., 2008). Consequently, gasification could be a first step at facilitating CO_2 enrichment of greenhouses with biomass.

2.5.2.1.2 Syngas combustion

Following gasification of biomass, the combustion efficiency of syngas may be the key for CO_2 enrichment. Syngas combustion could make CO_2 enrichment from biomass more convenient and on par with the performance of fossil fuel burners. It is generally recognized that syngas combustion produces lower undesirable gaseous emissions than direct combustion of fuel (Whitty et al., 2008). Specifically, air-fuel mixtures in burners are easier to control to reach near complete combustion than when dealing with solid fuels (Reed et al., 1988). The presence of CO, NO_x and VOCs in the exhaust gas depends mostly on the burner design and operation rather than the gas composition (Whitty et al., 2008) while SO_x emissions are linked to the presence or absence of sulphur in the biomass. Therefore, great importance should be put towards burner design and biomass selection to assure gaseous emissions respecting health standards.

2.5.2.1.3 Theoretical engineering estimations

Estimation of the CO_2 provided to a greenhouse by a biomass heating systems can be performed by two possible approaches. A first method would size the biomass heating system, whether a direct combustion boiler or close-couple gasifier, according to the overall greenhouse heat demand while the CO_2 injected would represent a fraction of the exhaust gas. The second method would evaluate the size of a gasifier reactor that would be needed in order to be dedicated to supplement the CO_2 requirement of the greenhouse. Excess heat would be accumulated in a thermal storage and a dedicated heating system would supply the remainder of the required thermal energy.

The estimation of a greenhouse building heat loss dictates the required power output of the biomass heating system. The heat loss is calculated based on a simplified method taking into account the architecture and materials of the greenhouse, the minimum outside temperature (T_{out}) and the inside greenhouse operating temperature (T_{in}) (Aldrich et al., 1992). The minimum outside temperature is usually taken as the lowest mean dry-bulb temperature of a given region and the value is chosen between the 99.0% or 99.6% design condition (ASHRAE, 2009). The rate of total heat loss ($\dot{Q}_t$) is then given by the following equation:

$$\dot{Q}_t = \dot{Q}_{cl} + \dot{Q}_{clp} + \dot{Q}_{air} \qquad (2)$$

where

$$\dot{Q}_{cl} = A_{cover} * U_{cover} * (T_{in} - T_{out}) = \text{Conductive heat loss, walls and roof (W)} \qquad (3)$$

$$\dot{Q}_{clp} = L * U_p * (T_{in} - T_{out}) = \text{Conductive heat loss, perimeter (W)} \qquad (4)$$

$$\dot{Q}_{air} = c_p * \rho * V * q * (T_{in} - T_{out}) = \text{Convective heat loss, air exchange (W)} \qquad (5)$$

and where U_{cover} is the heat transfer coefficient of the walls and roof materials ($W/(m^2 \cdot K)$), U_p is the thermal conductivity of the perimeter ($W/(m \cdot K)$). For heat loss by air exchange, c_p is the specific heat capacity of air ($J/(kg \cdot K)$), ρ is air density (kg/m^3), V is the greenhouse volume (m^3) and q is the number of air exchange per hour (hr^{-1}). The peak power output of the heating system is then calculated by considering the boiler or furnace efficiency (η_b) and the heat distribution network efficiency (η_d).

$$P_{peak} = \dot{Q}_t / (\eta_b \cdot \eta_d) \tag{6}$$

With this peak load sizing method, the biomass boiler can provide the total annual heat demand. Considering the limited turn down ratio of biomass boilers, they are preferred to be operated continuously at their most efficient power output. A second method include base-load sizing where the biomass boiler meets only the minimum heating demand continuously and peaks are supplemented by other furnaces with better turn down ratio. On the other hand, optimal thermal sizing includes the use of a heat storage tank to balance between peak and base load sizing. A rule of thumb will size the boiler at around 55% to 65% of the peak power output (The Carbon Trust, 2009). Nederhoff (2004) had approximated that the water heat storage is dimensioned between 100 to 200 m^3 per hectare of greenhouse. Thorough calculations of buffer size will not be covered here but would be performed depending on climate, boiler efficiency and the selected biomass type.

2.5.2.2 External Modification

2.5.2.2.1 Scrubbing systems

Over the last decade, it has been observed that the adverse nitrogen oxides and sulphur oxides found in exhaust gases could be transformed into valuable by-products. A research suggested the conversion of NO_x and SO_x into nutrients for greenhouse plant fertilization, by means of a scrubbing system with particular catalysts (Chou et al., 2005). For that system, the exhaust gas originated from a heating system fuelled with biogas extracted from a landfill. Sulphur oxide is usually reduced from flue gas when scrubbed with aqueous ammonia to form ammonium sulphate as a by-product (Long et al., 2004). The latter is quite valuable for fertilizer markets as several million tons are produced each year in the United-States (Chou et al., 2005). It was found that NO and SO_2 could be simultaneously eliminated by adding a certain catalyst into the standard aqueous ammonia solution. The process resulted in the conversion of NO into nitrite and nitrate, and the subsequent absorption and oxidation of SO_2 into sulphate. Conveniently, the process can be easily integrated in existing desulphurization scrubbers (Long et al., 2004). Further research is needed to assess the quality of fertilizers scrubbed from the exhaust gas. These scrubbing systems could supply nutrients directly into the irrigation network of the greenhouse while the leftover gas, composed mainly of CO_2, could be injected for enrichment.

2.5.2.2.2 Membrane separation of CO_2

In their research, Green and Maginnes (1978) developed a membrane based CO_2 system using an odorant free natural gas-fired turbine system for CO_2 enrichment. Exhaust gases exited the stack at around 450°C and contained about 2% CO_2, 16 ppm NO_x and no SO_2. The exhaust was cooled to 82°C and directed between the two covering layers of polyethylene of the greenhouse. The nature of the polyethylene cover allowed high permeability of CO_2 but prevented diffusion of NO_x, which were at toxic levels. While providing heat to the greenhouse, it also supplied considerable concentrations of CO_2, between 1500 to 6000 ppm. In terms of yields, the greenhouse produced 15% more fruit than the non-enriched area (Maginnes and Green, 1978). However, this particular application of polymer membranes was not widely adopted in the greenhouse industry and no known research continuing this specific application exists. Most current research focuses on membrane separation from fossil fuel combustion in large power plants as a means to capture and store CO_2 (Yang et al., 2008). However, membrane separation processes could be applied for CO_2 enrichment to reduce greenhouse gases at the source.

Compared to the conventional process of carbon dioxide capture, such as amine absorption process, membrane separation technology is more energy efficient and much simpler for CO_2 capture (Scholes et al., 2008). In a review article, Yang et al (2008) stated that the membrane separation process was the most promising technology for CO_2 separation and capture in terms of energy-saving, space-saving and ease for scale up. It is these exact characteristics that make membrane separation appealing for greenhouse application. Membrane separation of CO_2 is currently being considered for post-combustion and pre-combustion capture of CO_2 for the power generation industry (Zhao et al., 2008). Post-combustion capture occurs at the end of conventional combustion coal power plants and consists of separating CO_2 from nitrogen in the flue gas (The Carbon Trust, 2009). Pre-combustion capture is being evaluated to separate CO_2 from syngas produced from coal in integrated gasification combined cycle (IGGC) power plants. Syngas must be cleaned of impurities, such as particulates or acid gases, and then “shifted” by reacting with steam over a catalyst which will convert CO into CO_2 (Amelio et al., 2007). Membrane separation is applied to remove CO_2 from the hydrogen, which can be burned and passed through turbines for power generation. Most greenhouses heated with biomass use conventional combustion technologies and would apply post-combustion capture. While pre-combustion capture offers better separation efficiency, post-combustion capture is still regarded as a better CO_2 separation method compared to traditional techniques such as chemical absorption.

Regardless of the material composition, membranes need to have good thermal and chemical robustness along with good resistance to plasticisation and aging (Scholes et al., 2008). Those properties, combined with affordable manufacturing processes, ensure the cost-effective durability of the membrane. Although some materials may offer the purest quality of CO_2, the greenhouse industry has easy and affordable access to polyethylene and polycarbonate materials. Silicon membranes have also shown interesting diffusion properties in post-harvest storage of produce, an industry similar and close to the greenhouse industry (Stewart et al., 2005). Additional research needs to determine the permeation rate and selectivity to CO_2 of these particular materials. Given that those membranes are commercially available, they could offer interesting application possibilities for CO_2 separation from flue gas.

Issues to take into consideration are the accumulation of condensable vapour within the membrane matrix resulting in lower permeability and selectivity, as well as undesirable gases, such as CO, NH_3, H_2S, SO_x and NO_x, which can degrade the material prematurely (Scholes et al., 2008). Fine particulates may also accumulate on the membrane and block membrane pores. Limited research has been performed on the effect of these gases and particulates on membranes in terms of performance impacts, premature aging and maintenance requirements. Additional experiments could help in evaluating the durability and feasibility of this technology for greenhouse CO_2 enrichment.

2.6 Future research development

CO_2 enrichment from exhaust gas of biomass heating system has yet to overcome certain technical challenges. Concretely, future development could be divided in different research objectives:

- There is a wide range of usable types of biomass such as wood residues, grasses, agricultural residues, and municipal wastes, which can be used in the form of chips or pellets. Greenhouse residues re-used for CO_2 enrichment should be investigated as well. More research should look at their respective emissions, when used in combustion or close-coupled gasification heating systems.

- Currently, most large scale greenhouses that heat with biomass use combustion technology fuelled with wood chip. In order to maintain a link with direct commercial applications, research should continue exploring membrane separation of CO_2 for this particular application. Gasification is also a promising technology and should continue to be developed for large scale biomass combined heat and power.

- Post-combustion emission removal methods, such as wet scrubbing with catalysts to produce fertilizers, membrane separation of CO_2 or a combination of both, should be further developed and tested according to the biomass fuel used.

- Using water buffers for excess heat storage is usually recommended with biomass heating systems (Stritih and Butala, 2004; The Carbon Trust, 2009). Most of the research on thermal storage has been applied for solar energy systems (Hasnain, 1998). There is a need for thorough peer reviewed literature review on thermal storage applied for biomass heating systems to increase efficiency.

- Finally, data accumulated from different case studies should give enough information to complete a thorough comparative life-cycle analysis. CO_2 enrichment from biomass, fossil fuels and liquid CO_2 could be compared according to their common primary functions of supplying both heat and clean CO_2. Results and estimates could then be analyzed in terms of potential economic and environmental impacts.

2.7 Conclusion

Research on CO_2 enrichment from biomass can be subdivided in four directions:

1. Source and type of biomass
2. Thermo-chemical processes for heat and CO_2 production
3. Post-combustion emission removal methods
4. Optimal CO_2 enrichment management strategies

Supplementing CO_2 to a greenhouse from the exhaust of a biomass heating system could help improve the overall carbon footprint of greenhouse operations. Further research needs to be performed to optimize safe and clean CO_2 enrichment practices from biomass fuels. Optimal management practices reduce fuel consumption and increase enrichment benefits. By improving boiler efficiency, whether through combustion or gasification with syngas combustion, fewer VOCs and particles would be produced. Currently available scrubbers can clean NO_x and SO_x and could produce ammonium sulphate fertilizers to be used directly in a greenhouse. Additionally, membrane separation techniques could be very efficient in preventing fine particles and undesirable gases to be diffused into the greenhouse while keeping a CO_2 enriched greenhouse safe for workers. This research project addresses primarily the second research direction on CO_2 enrichment from biomass, by investigating CO_2 enrichment from biomass gasification. The first and third directions are also approached through the use of sawdust wood pellets as biomass type and the measurement of exhaust gas compounds to recommend emission remediation methods.

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Connecting Statement

The literature review from Chapter 2 addressed the various aspects of research on CO_2 enrichment from biomass heating systems. Chapter 3 focuses on several of these aspects, by examining the performance of a pilot scale gasifier to estimate the CO_2 production rate from sawdust wood pellets, while identifying the characteristics of the system that would affect CO_2 enrichment operations.

Chapter 3: A performance assessment of a downdraft gasifier to produce CO_2 for greenhouse enrichment from renewable fuels

3.1 Abstract

Biomass gasification could benefit the greenhouse industry by supplying both heat and carbon dioxide (CO_2) for enrichment. The objective of this research project was to monitor the performance of a downdraft gasifier to estimate the useable CO_2 production rate for enrichment per unit of biomass, while identifying the characteristics of the system that would affect CO_2 enrichment operations. Biomass gasification technology was selected, since it offered lower emissions and better control, when compared to direct combustion. Gasification is a thermo-chemical reaction, which converts solid biomass into a gaseous fuel, known as syngas. Experiments were performed at McGill University (Montreal, QC, Canada) using a downdraft gasifier to monitor its performance, with sawdust wood pellets as feedstock. Temperature and pressure monitoring provided valuable insights on optimal gasification temperatures, biomass fuel depletion in the reactor, ash grate shaking requirements, micro-explosions detection, char bed packing and pressure drop across the packed bed filter. The gasifier operated with an estimated average equivalence ratio (the actual air to fuel ratio relative to the stoichiometric air to fuel requirement) of 0.17, below the optimal value of 0.25, and achieved a cold gas efficiency of 59%. From the empirical data, the gasifier operating with sawdust wood pellets could provide a maximum of 22.9 kW of thermal energy and could theoretically enrich a maximum of 1540 m^2 of greenhouse surface area. Results indicated that biomass, following combustion or gasification, could provide more CO_2 for greenhouse enrichment than propane or natural gas per unit of energy.

Table 3.1 – Nomenclature

A	greenhouse surface area	m^2
$(A/F)_{actual}$	actual dry air to fuel ratio	
$(A/F)_{stoich}$	stoichiometric dry air to fuel ratio	
ER	equivalence ratio	
h_g	latent heat of steam	kJ / kg
HHV	higher heating value	kJ / kg fuel
i	element i (C, H, N, O or S)	
j	compound j (CO_2, N_2, O_2)	
LHV	lower heating value	kJ / kg fuel
MC	moisture content	%
M_i	molecular mass of element i	kg of i / kmole
M_j	molecular mass of compound j	kg of j / kmole
$\dot{m}_{biomass}$	solid biomass consumption rate	kg / hr
m_{CO_2}	mass of emitted CO_2 per kg of dry fuel	kg CO_2 / kg fuel
$\dot{m}_{CO_2}$	CO_2 mass flow rate	kg / hr
$\dot{m}_{syngas}$	syngas mass consumption rate	kg / hr
m_{O_2}	stoichiometric oxygen requirement	kg O_2 / kg fuel
η_b	heat exchanger efficiency	%
η_{CG}	gasification cold gas efficiency	%
ρ_{air}	air density	kg / m^3
$Q_{air\ in}$	gasifier reactor air intake volumetric flow rate	m^3 / hr
Q_{syngas}	syngas volumetric flow rate	m^3 / hr
x	number of carbon molecules	
X_i	mass fraction of element i	kg of i / kg fuel
y	number of hydrogen molecules	
Y_j	volume fraction of compound j	%

3.1 Introduction

The horticulture industry has not been spared in addressing issues of air pollution, waste disposal and energy efficiency. In northern climates, the high thermal energy requirements stimulate greenhouse operators to consider sustainable energy sources to reduce their dependence on fossil fuels for both economical and environmental reasons. Greenhouse producers must successfully balance energy efficiency through structural or fuel saving techniques, while keeping the plants growing conditions optimal in order to compete with ever changing and challenging international markets. Heating of large surface can be technically difficult for some renewable sources of energy, but biomass heating has proven to be an economically viable option (Chau et al., 2009). Biomass heating technology is readily available and has been recognised as a sustainable renewable fuel alternative that can reduce greenhouse gas production (Petersen Raymer, 2006). Considering that biomass combustion releases, at most, the same amount of carbon dioxide (CO_2) that was absorbed via photosynthesis in the plant's life cycle, the technology is thus considered carbon neutral (Basu, 2010). Biomass combustion technologies are well established, but gasification is showing a lot of promise, both in research and commercial applications, to achieve high efficiency and cleaner energy production (Quaak et al., 1999; McKendry, 2002b; Basu, 2010). Gasification is a thermo-chemical reaction that differs from combustion by being under partial oxidation, thus converting the material into a gaseous fuel. In its raw form, the gas is known as producer gas and can be used for power and heat production. Once removed of its impurities, the gas is referred as a synthesis gas, which can be further converted into chemicals or liquid fuels (McKendry, 2002b). For the sake of this research, the term syngas is used in reference to the producer gas. Since a gaseous fuel is burned instead of a solid fuel, a gasification system allows biomass heating to be cleaner and easier to control, than direct combustion systems (Reed et al., 1988; Quaak et al., 1999; Whitty et al., 2008). In addition, it is possible to further reduce the carbon footprint of a biomass gasifier heating system by injecting the CO_2 from the exhaust gas into a greenhouse. CO_2 enrichment is a common practice to enhance photosynthesis resulting in improved yields from 21 to 61% in dry mass (Mortensen, 1987; Chalabi et al., 2002). Greenhouse crops benefit from an increase in CO_2 concentration varying between 700 to 1000 ppm (Mortensen, 1987; Critten and Bailey, 2002). Enrichment can be performed with pure CO_2, or from dedicated natural gas or propane burners (Hicklenton, 1988). CO_2 enrichment from the exhaust of a natural gas or propane heating system is also currently feasible, but using renewable energy will improve the sustainability of the greenhouse operation. The recommended dose is to inject 5.6 g $CO_2/(m^2 \cdot hr)$ to reach the optimal CO_2 concentration of 1000 ppm (Hicklenton, 1988). Pure liquefied CO_2 tanks have a capacity that ranges from 20 kg to 52,000 kg and are able to supply CO_2 at the desired rate of application. Small burners consume 1 kg of propane to produce about 3 kg of CO_2, while natural gas provides 2.1 kg of CO_2 per kg (Hanan, 1998).

This research follows the hypothesis that biomass gasification could provide a sustainable and viable replacement to conventional CO_2 production technologies for enrichment in greenhouses. This project aims at monitoring the performance of a small downdraft gasifier (10 to 100 kW) to estimate the useable CO_2 production rate for enrichment per unit of biomass, while identifying the system's characteristics that would affect CO_2 enrichment operations.

3.2 Literature Review

3.2.1 Feedstock:

Biomass as a solid fuel occurs in a myriad of shapes and composition coming from wood residues, dedicated energy crops, agricultural residues, animal waste, or municipal waste. Solid biomass with moisture content below 50% is considered for thermo-chemical processes such as combustion, gasification or pyrolysis. Typical properties to assess the thermal conversion potential of biomass are moisture content, ash content, volatile matter content, elemental composition, heating value, bulk density and particle size and shape.

Biomass moisture content has significant impacts on combustion and gasification efficiency. For instance, combustion performs at 78.9% efficiency with biomass at 20% moisture (dry basis), and at 61.1% efficiency, for 60% moisture content (Reed et al., 1988). Moreover, high moisture affects syngas quality by reducing the production rate and increasing the tar content.

Ash content also varies according to the source of biomass (from 0.1% to 17.6%) and can be of concern depending on its composition and quantity (Reed et al., 1988). The most common elements found in ash of biomass fuels are Si, Ca, Mg, K, Na and P (Van Loo and Koppejan, 2008). The performance of a biomass heating systems can be affected due to ash melting under high temperature, leading to slagging, which is an agglomeration of melted minerals from the ash (Quaak et al., 1999).

Compared to other solid fuels, biomass has very high volatile matter (VM), up to 80%, which makes it ideal for gasification (Quaak et al., 1999). The VM can be determined by standard methods by heating the biomass at a given temperature and a given rate in a controlled environment (Basu, 2010). The amount of condensable and non-condensable vapours that is released in the process is defined as VM. The fixed carbon (FC) is then the fraction of the feedstock that remains once moisture, VM and ash are subtracted from the original feedstock mass. However, FC is not necessarily a fixed value as it is dependent on VM, which can also vary according to the temperature and the heating rate of the thermo-chemical process, whether it is gasification or pyrolysis (Basu, 2010).

Ultimate analysis provides the chemical composition (carbon, hydrogen, oxygen, nitrogen, sulphur, ash, etc.) of the dry fuel on mass fraction basis, which is used to estimate the heating value and the potential CO_2 emissions of fuel combustion. Some contaminants present in biomass include sulphur, which can contribute to sulphur oxide (SO_x) emissions, but is most often found in low quantity (0.01% to 2%) for a large variety of solid biomass sources (Reed et al., 1988). Similarly, wood usually contains very low amounts of chlorine, while it can be found in higher concentrations in grasses such as miscanthus, switchgrass and straw (Van Loo and Koppejan, 2008).

The heating value, or calorific value, is defined by the amount of thermal energy by unit of fuel mass or volume that is released after combustion has occurred and the flue gas has returned to a temperature of 25°C (Basu, 2010). The heating value is expressed by two values. The higher heating value (HHV or gross calorific value) is the maximal amount of heat that can be recovered from a fuel, including the latent heat from water vapour. The lower heating value (LHV or net calorific value) excludes the energy loss used for the vaporization of water and makes it a more conservative measure to use (Basu, 2010).

Biomass density and bulk density (kg/m^3) are important properties indicating the fuel energy density (MJ/kg) and relating to transport and storage costs (McKendry, 2002a). Solid biomass has a wide range of bulk density values, between 80 to 680 kg/m^3 (Reed et al., 1988). Biomass densification into pellets, brickets or cubes is common and viable to increase biomass energy content while reducing shipping and storage costs (Mani et al., 2006). The type of densified biomass for gasification also has an impact on gasification performance. It has been observed that wood pellets produced richer syngas and obtained higher gasification efficiency than pellets made of sugar cane bagasse or empty fruit bunch (oil palm waste) (Erlich and Fransson, 2011). Additionally, the size of densification can impact gasification as it was observed that 8 mm diameter pellets run more efficiently than 6 mm diameter pellets due to better flow properties (Erlich and Fransson, 2011).

Particle size and shape is important to forecast the ease or difficulty of biomass movement in a system (Reed et al., 1988). Some biomass feedstock may be more prone to channelling and bridging in the feeder and the reactor, or to plugging of the gasifier core, all of which will impair the stability of gasification. Fuel uniformity is preferred, but methods of stirring or shaking the reacting biomass bed may be implemented (Reed et al., 1988). Overall, the fuel properties such as morphology, bulk density and angle of repose can be causes of bridging, which affects the normal pressure drop and gas flow in a gasification reactor (Quaak et al., 1999).

3.2.2 Gasification

Gasification is a thermo-chemical reaction that occurs with partial biomass oxidation under high temperatures, converting the biomass into a gaseous fuel. Gasification uses heat to store energy into the chemical bonds of the gaseous fuel compounds while combustion releases this energy as heat. Depending on the gasifier design, the gas composition usually contains hydrogen (H_2, 12-20%), carbon monoxide (CO, 17-22%), methane (CH_4, 2-3%), CO_2 (9-15%), water vapour (H_2O), nitrogen (N_2) and tar vapours (Reed et al., 1988; Quaak et al., 1999; McKendry, 2002b). In general, air is used as an oxidizing agent, which results in a raw gas, syngas in reference to producer gas, containing impurities. When impurities are removed or when pure oxygen is used instead of air, the resulting gas is known as synthesis gas, composed of CO and H_2. Syngas is typically used for power and heat production, while synthesis gas can be converted into more complex chemicals or liquid fuels. The calorific value of syngas is usually around 4-6 MJ/m^3 when using air, while it can reach 12-20 MJ/m^3 with pure O_2 (McKendry, 2002b). Oxidizers can be mixed with steam as the catalyst of the reaction. The oxidizer selection will impact the syngas final composition (Puig-Arnavat et al., 2010).

Gasification technologies predate the 19th century and were first developed for industrial heat and power (Reed et al., 1988). Throughout the two World Wars, as some European countries were scarce on petroleum liquid fuels, close to a million automobiles, as well as boats, trains and electric generators were operating with compact gasifier systems (Reed et al., 1988; Quaak et al., 1999). Interest for gasification re-emerged during the 70's energy crisis and during the first decade of the 21st century with growing concerns over fluctuating fossil fuel prices, energy independence, energy security, air pollution, renewable and sustainable energy sources, etc.

The common process of gasification is a combination of four reactions including drying, pyrolysis, combustion and reduction (Figure 3.1).

Gasification is always initiated from the controlled combustion zone, sometime called oxidation zone, of a reactor. This combustion provides the necessary heat (up to1400°C) to the overall process and quickly depletes most oxygen from the reactor. It also generates CO_2 and H_2O.

As it is fed to the reactor, the first zone that the biomass feedstock reaches is the drying zone. In the drying zone, water is vaporized until 200°C is reached where biomass starts volatilizing.

As the temperature increases in the absence of air, the biomass enters the pyrolysis zone. At this step, the larger and complex molecules of the organic material break down into smaller compounds to form solids (char), liquids (tar, heavier hydrocarbons) and gases (H_2, CH_4, CO_2, H_2O, CO, volatile organic carbons VOCs).

The production of syngas occurs in the reduction zone, which is also addressed as the gasification zone. Reduction takes place next to the combustion zone and involves several reactions between the hot char and the gases in the reactor. Principally, CO_2 and H_2O from the combustion zone are reduced of one oxygen atom to form CO and H_2. Other products of the reduction zone reactions include CH_4, CO_2 and H_2O. The energy balance of reduction is endothermic and occurs between 700°C to 1000°C. Ideally, the reduction zone should reach temperatures over 850°C to ensure tar cracking and destruction of aromatic hydrocarbons (Reed et al., 1988).

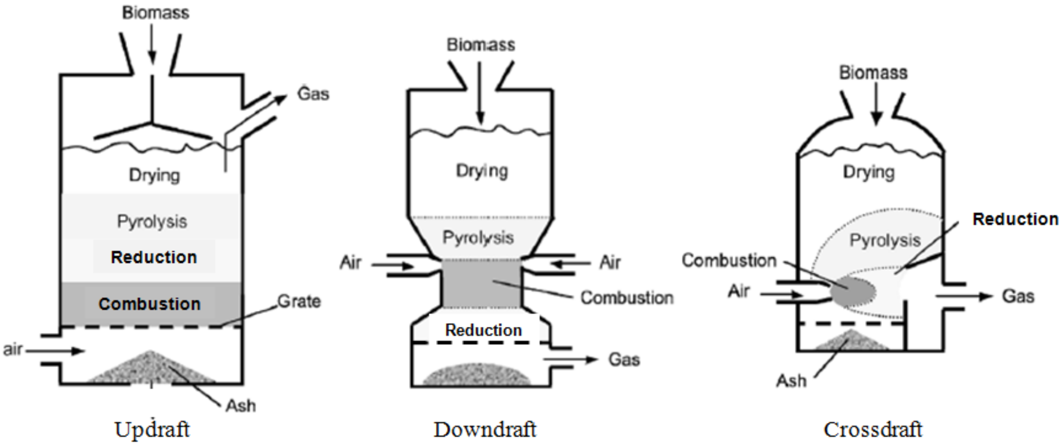

Figure 3.1 – Schematic of gasification zones and gas and biomass flows for Updraft, Downdraft and Crossdraft gasifiers (Basu, 2010)

There are many conventional designs for gasification of biomass such as fixed bed and fluidized bed types (Basu, 2010). The common fixed bed reactors are shown in Figure 3.1. They differ essentially due to the syngas flow in the system, including downdraft, updraft and crossdraft. These flow patterns affect the order at which the biomass feedstock undergoes the four main gasification reactions.

Updraft gasifiers are operated with air flow moving counter current to the feedstock flow. They are more common for larger scale thermal energy production of 1 to 30 MW and benefit from a turn-down ratio of 5 to 10. A high turn-down ratio is advantageous since it represents the ability of a heating system to operate at a fraction of its maximal power output without losing much efficiency or depreciating equipment prematurely. Updraft gasifiers can accommodate fuels with higher moisture content (60% max, wet basis) and ash content (25% max, dry-ash basis) (Quaak et al., 1999). However, the tars produced from the pyrolysis zone do not move through the reduction and combustion zone. Therefore, the syngas tar content is much higher, varying between 30 to 150 g/m^3 (Basu, 2010). For direct heating applications, updraft gasifiers become advantageous since the tars increase the gas heating value and the resulting gas is burned directly after being produced (Reed et al., 1988).

Downdraft gasifiers are operated with air flow moving along the biomass flow. The most common design type is the Imbert style gasifier used for nearly a million vehicles worldwide in the early 20th century (Reed et al., 1988). Their application range is from 10 kW up to 1 MW due to their intrinsic core design. As seen in Figure 3.1, downdraft gasifiers have a V-shaped narrow constriction at the reactor core. The role of this core is to create a high temperature zone (over 850°C) in which all pyrolysis products move through, thus enabling tar cracking. This results in the production of syngas with very low tar content from 0.015 to 3.0 g/m^3 (Basu, 2010). Air, or the oxidizer gas mixture, is supplied directly on top of the core from nozzles located along the circumference. The core diameter is a key indicator of the syngas production rate (Reed et al., 1988). Theoretically, the maximum syngas production rate of an Imbert gasifier was observed to be 0.9 m^3 per cm^2 of cross-sectional area at the core constriction per hour (0.9 m^3/(h·cm^2)), as reported by Reed et al. (1998). This design is limited in scalability since the larger the diameter, the more difficult it becomes for air coming from the nozzles to reach the center of the core. Larger core diameters reduce homogeneity of the combustion and reduction zones (Reed et al., 1988). Along with their limited size, they work optimally with feedstock of lower moisture content (25% max, wet basis), ash content (6% max, dry-ash basis) and turn down ratio (3 to 4) (Basu, 2010). The gas flow is usually generated by operating the gasifier under negative pressure (Reed et al., 1988). To work under positive pressure, a downdraft gasifier uses a blower but increases risks of leaking CO. On the other hand, working in vacuum can let small amount of air inside the gasifier, which can lead to small explosions, observed by sudden and short instances of high positive pressure peaks (Reed et al., 1988). Nonetheless, gasifier reactors are usually built with material that can sustain very high pressures (Reed et al., 1988). In short, the low tar content in the syngas makes downdraft gasifiers ideal for internal combustion engines.

Crossdraft gasifiers have similar biomass properties requirements as downdraft gasifiers. Their range of application varies from operating at small scale to large scale and producing low tar syngas (0.01 to 0.1 g/m^3). They are used mostly for charcoal gasification, which can lead to very high temperatures (>1500°C) and thus create potential problems on material unable to sustain such temperatures (Quaak et al., 1999).

Fluidized bed gasifiers operate with a reusable granular solid in a semi-suspended state maintained by the intake air flow velocity. As the biomass is mixed in the fluidized-bed, the temperature is more uniformly distributed amongst the reactor thus optimizing heat and mass transfer (Reed et al., 1988; Basu, 2010). Fluidized bed gasifiers also generate tars at a level around 10 g/m^3, between the performance of updraft and downdraft gasifiers (Basu, 2010). This makes fluidized bed gasifiers advantageous and energy efficient for large scale applications, although the added complexity of the system usually increases investment and maintenance costs.

Overall, gasification coupled with syngas combustion for heat and power can achieve high efficiency and is recognised to make biomass heating cleaner and easier to control, compared to direct combustion of solid fuels (Reed et al., 1988; Quaak et al., 1999; Whitty et al., 2008). Updraft or fluidized-bed gasifiers are appropriate for heating large scale greenhouses requiring over 1MW of thermal power. The potential use of their exhaust gas CO_2 would be determined by the quality and efficiency of the boiler. Additional emission cleaning systems and dilution would most likely be required for this application due to the large scale of these heating systems. On the other hand, downdraft gasifiers, due to their low tar content, could function as dedicated CO_2 production units for greenhouse enrichment. Greenhouse crop residues could even be fed to these small units to produce CO_2 and heat.

Before examining the performance of syngas combustion, it is important to assess the downdraft gasifier operation and characteristics that would affect its performance as a CO_2 enrichment device. Therefore, this research aims at investigating the theoretical CO_2 enrichment potential of a gasifier as well as setting up and operating a pilot unit for this application.

3.2.3 Thermodynamics of combustion and gasification

Since combustion and gasification reactions differ mainly by their level of oxidation, the equivalence ratio (ER) determines the actual oxygen (or air) to fuel ratio relative to the stoichiometric oxygen (or air) to fuel requirements. In both systems, the actual input of oxidizer will affect the syngas composition and reaction temperature. The stoichiometric air to fuel ratio is the theoretical mass of air required for complete combustion of a unit of mass of fuel (Basu, 2010). The stoichiometric oxygen requirement (m_{O_2}) follows the basic combustion equations and depends on the ultimate analysis of the fuel normally expressed by mass (De Nevers, 2000).

$$C_xH_y+\left(x+\frac{y}{4}\right)O_2\rightarrow x\,CO_2+\frac{y}{2}H_2O \qquad (1)$$

The mass of O_2 needed per kg of fuel is calculated based on (Van Loo and Koppejan, 2008):

$$m_{O_2}\left[\frac{\text{kg } O_2}{\text{kg fuel}}\right]=X_C\frac{M_{O_2}}{M_C}+\frac{X_H}{4}\frac{M_{O_2}}{M_H}+X_S\frac{M_{O_2}}{M_S}-X_O \qquad (2)$$

where

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

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

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

The mass fraction of oxygen subtracted in Equation 2 refers to the amount of oxygen present in the biomass. The stoichiometric dry air to fuel ratio ($(A/F)_{stoich}$) required is then computed as follows (Van Loo and Koppejan, 2008):

$$(A/F)_{stoich}\left[\frac{\text{kg air}}{\text{kg fuel}}\right]=m_{O_2}+m_{N_2}=m_{O_2}+m_{O_2}\frac{Y_{N_2}}{Y_{O_2}}\frac{M_{N_2}}{M_{O_2}} \qquad (3)$$

where

Y_j [%] : volume fraction of compound j in air (O_2 or N_2)

Subsequently, ER can be determined with this ratio:

$$ER = {(A/F)_{actual}}/{(A/F)_{stoich}} \qquad (4)$$

Typical equivalence ratio for gasification is ER = 0.25, while combustion would be specified by ER ≥ 1 and pyrolysis, by ER ≅ 0 (Reed et al., 1988). Based on typical biomass carbon ratios (dry and ash free basis) of $CH_{1.4}O_{0.6}$, the $(A/F)_{actual} = 1.5$ for gasification and combustion is indicated by $(A/F)_{actual} = 6.25$ while pyrolysis is still expressed by $(A/F)_{actual} \cong 0$ (Reed et al., 1988). Depending of the feedstock, the ER range is typically between 0.20 and 0.45 (Erlich and Fransson, 2011). It must be noted that some authors report fuel to air ratios (F/A), rather than air to fuel (A/F) (Littlejohn et al., 2010). It also influences their definition of equivalence ratio, which gives reversed values to the ones previously stated. For this research, ER is defined according to Equation 4.

The biomass heating value can be determined experimentally by standard procedures using a bomb calorimeter. It can also be estimated using empirical correlations using the mass % of compounds from the feedstock ultimate analysis. Many correlations exist, but the following is based on 15 correlations and 50 solid, liquid and gaseous fuels (Equation 5) (Basu, 2010).

$$\mathrm{HHV}\left[\frac{\mathrm{kJ}}{\mathrm{kg\ fuel}}\right] = 349.1 \cdot X_C + 1178.3 \cdot X_H + 100.5 \cdot X_S - 103.4 \cdot X_O - 15.1 \cdot X_N - 21.1 \cdot X_{ash} \quad (5)$$

The LHV is determined with the following relationship which considers the fuel mass % of hydrogen (X_H), the fuel moisture content (MC in %) and the latent heat of water vapour ($h_g = 2260$ kJ/kg) (Basu, 2010).

$$\mathrm{LHV}\left[\frac{\mathrm{kJ}}{\mathrm{kg\ fuel}}\right] = \mathrm{HHV} - h_g\left(\frac{9 \cdot X_H}{100} + \mathrm{MC}\right) \quad (6)$$

The syngas heating value depends on its volumetric % composition of H_2, CO and CH_4, and can be determined according to the heating values of each compound (Table 3.2).

Table 3.2 – High heating value (HHV) and low heating value (LHV) of syngas combustible compounds (Reed et al., 1988)

Component	Symbol	HHV (MJ/m^3)	LHV (MJ/m^3)
Hydrogen	H_2	13.2	11.2
Carbon Monoxide	CO	13.1	13.1
Methane	CH_4	41.2	37.1

Common theoretical LHV for moisture and ash free solid biomass is 20.4 MJ/kg, while typical LHV for syngas is around 5.5 MJ/kg or 5.8 MJ/m^3 (at 20°C and 101.325 kPa) when air is used as oxidizer. The heating value of syngas increases as the nitrogen content of air decreases. In combination with LHV, the measured solid biomass consumption rate of a boiler ($\dot{m}_{biomass}$) or the syngas flow rate output of a gasifier ($\dot{m}_{syngas}$) give the power output of both biomass heating systems. The efficiency of the heat exchange (η_b) can therefore determine the actual heat delivered to the greenhouse.

Flue gas carbon dioxide for CO_2 enrichment can be 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 is:

$$m_{CO_2}\left[\frac{\text{kg } CO_2}{\text{kg fuel}}\right] = \left(X_C \frac{M_{CO_2}}{M_C}\right) \tag{7}$$

By using $\dot{m}_{biomass}$ or $\dot{m}_{syngas}$ in kg/hr, one can estimate the CO_2 output useable for enrichment and compare with other enrichment systems.

$$\dot{m}_{CO_2}\left[\frac{\text{kg } CO_2}{\text{hr}}\right] = m_{CO_2} \cdot \dot{m}_{\text{biomass or syngas}} \tag{8}$$

Gasification efficiency is expressed as cold gas efficiency (η_{CG}, Equation 9), which calculates the energy contained in syngas over the potential energy from the solid fuel (Basu, 2010).

$$\eta_{CG} = \frac{LHV_{syngas} \cdot \dot{m}_{syngas}}{LHV_{biomass} \cdot \dot{m}_{biomass}} \tag{9}$$

Additionally, if the heating unit size is predetermined, the potential greenhouse surface area that can be enriched can be found using the recommended CO_2 injection rate of 5.6 g/(m^2·hr).

$$A\,[m^2] = \dot{m}_{CO_2} \Big/ \frac{0.0056 \text{kg } CO_2}{m^2 \cdot hr} \tag{10}$$

In summary, CO_2 production for greenhouse atmosphere enrichment from a biomass heating system can be estimated once the ultimate analysis of the fuel is known along with the system fuel consumption rate. In conjunction with this method, it is possible to further improve the sustainable practices of a greenhouse by using the accumulated plant residues and biomass waste as the source of heat and useable CO_2.

3.4 Materials & Method

3.4.1 Experimental setup

An Imbert style downdraft gasifier was selected for lab-scale experiments (Figure 1.1). The Gasifier Experimenters Kit (GEK) developed by All Power Labs (Berkeley, CA, USA) is based on the Imbert design, which proved reliable at producing syngas with low tar content (Reed et al., 1988; All Power Labs, 2010). This gasifier was selected for its affordability and flexibility in terms of potential modifications, instrumentation and uses, promoted by the open source philosophy of their developers, All Power Labs. The reactors dimensions are shown in Figure 3.2. From the reactor core diameter (7.62 cm) and using Reed et al. (1988) Handbook of Biomass Downdraft Gasifier Engine Systems, the maximal wood consumption rate of this system is 18.86 kg/hr, the maximal syngas output is 41.34 m^3/hr and the minimal output is 4.81 m^3/hr. The GEK 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 (Figure 3.3). The setup facilitated the flue gas flow of syngas combustion to be directed into the furnace chimney, where representative exhaust gas measurements were taken. The setup also allowed for future heat recovery using the furnace air-to-air heat exchanger.

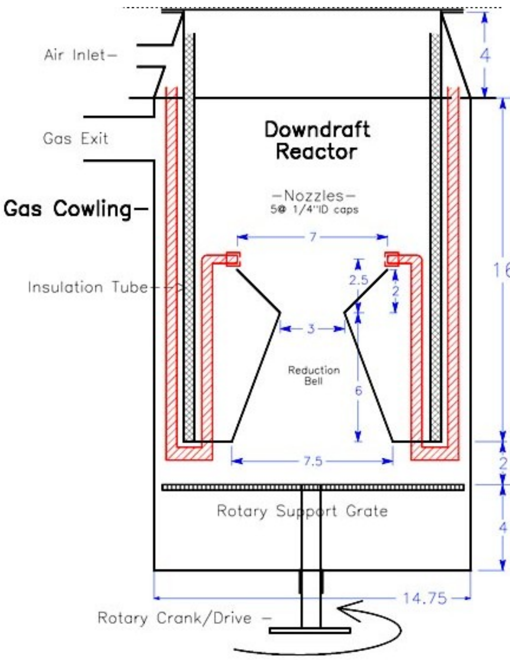

Figure 3.2 – Schematic and dimensions (provided in inches) of the downdraft gasifier reactor (courtesy of All Power Labs, 2010)

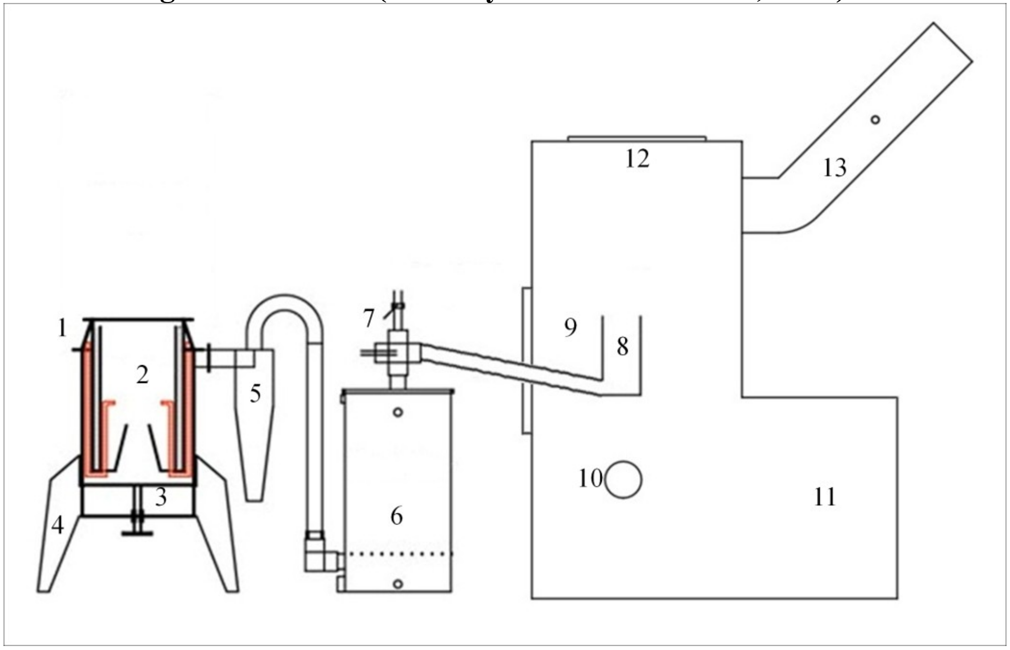

Figure 3.3 – Schematic of the gasifier coupled with the forced-air furnace. Compounds include: 1. three ports: Ignition, Air inlet, Instrumentation – 2. Reactor – 3. Ash grate – 4. Support legs – 5. Cyclone – 6. Packed bed filter – 7. Ejector venturi – 8. Swirl burner – 9. Furnace combustion chamber – 10. Furnace fuel inlet for direct combustion only – 11. Furnace blower for heat exchanger – 12. Air-air heat exchanger – 13. Chimney (GEK schematic courtesy of All Power Labs)

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 capacity of 19.4 m^3/hr at 275 kPa and 15.3 m^3/hr at 620 kPa (manufacturer recommendations were 10-14 m^3/hr at about 620-830 kPa). A needle valve, connected before the ejector, allowed to manually control the compressed air flow and therefore to operate the gasifier under negative pressure. Two water filled U-tube manometers served as a direct visual output of the gasifier operating conditions. One was connected to the bottom of the reactor core (P_core) and the second, at the top of the packed-bed filter (P_filter). All Power Labs previous experiences helped to identify the optimal vacuum condition for P_core to obtain an ideal core temperature over 850°C along with corresponding air intake flow rates when using wood pellets (Table 3.3). They produced the following empirical relationship which was only valid for the GEK using wood pellets (All Power Labs, 2010):

$$Q_{\text{air in}}\left[\frac{m^3}{hr}\right] = 2.4207 \cdot (\text{Vacuum Pressure}[\text{inH}_2\text{O}])^{0.5227} \qquad (11)$$

Table 3.3 – GEK performance according to vacuum pressures from manufacturer recommendations (All Power Labs, 2010)

Vacuum Pressure (inH_2O)	Vacuum Pressure (kPa)	Air Intake Flow rate (m^3/hr)	Performance Condition
10	2.49	8.1	Over pull
8	1.99	7.2	Maximum
6	1.49	6.2	Good
5	1.25	5.6	Ideal
4	1.00	5.0	Good
2	0.50	3.5	OK
1	0.25	2.4	Minimum
0 - 1	0 – 0.25		Under pull

The syngas mass flow rate was estimated by adding the air intake mass flow (extrapolated from Table 3.3 and using $\rho_{air} = 1.205$ kg/m^3) with the volatile fraction of the biomass consumption rate (estimated at 80%).

$$\dot{m}_{\text{syngas}}\left[\frac{\text{kg syngas}}{\text{hr}}\right] = Q_{\text{air in}}\left[\frac{m^3}{hr}\right] \cdot \rho_{\text{air}} + 80\% \cdot \dot{m}_{\text{biomass}}\left[\frac{kg}{hr}\right] \qquad (12)$$

The first gas conditioning system was a cyclone attached directly to the exit of the reactor, which helped to collect particles and tars droplets. Cyclones are usually recognised to catch particle sizes as small as 5 µm at up to 80% efficiency (Van Loo and Koppejan, 2008). Next to the cyclone was a standard 61 L (16 US gal) drum, which acted as a packed bed type filter. The drum was filled with standard barbecue charcoal of various sizes going from larger (1-2 cm) to finer (sawdust grain size), upward along the height of the bin. Research has shown that a 15 cm deep container packed with material of 1.3 cm can capture 50% of 2.5 µm droplets from a gas depending of its velocity (Reed et al., 1988). Compared to these dimensions, All Power Labs increased the packed bed filter to accommodate an available standard drum size (61 L), thus offering a conservative tar collection performance.

3.4.2 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 was installed at strategic locations on the gasifier and connected to the GCU (Table 3.4 and Figure 3.4). The 11 thermocouples were calibrated, in boiling water (100°C) and an iced bath (0°C), three times during the project (drift was less than 1%).

Table 3.4 – Nomenclature and description for thermocouples and for temperature sensors of the portable analyzer

Nomenclature	Description
(T1) T_core	Reduction zone at the reactor core (150 mm from the bottom of the reduction bell, seen in Figure 3.2)
(T2) T_combustion	Combustion zone (220 mm from the bottom of the reduction bell)
(T3) T_1	First intermediate point between reactor core and top (300 mm from the bottom of the reduction bell)
(T4) T_2	Second intermediate point between reactor core and top (400 mm from the bottom of the reduction bell)
(T5) T_top	Top of the reactor (480 mm from the bottom of the reduction bell)
(T6) T_bottom	Below the reduction zone
(T7) T_cyclone	Exit of the reactor before the cyclone
(T8) T_syngas	Top of the packed bed filter beside syngas sampling port
(T9) T_flame	Temperature of the burner material
(T10) T_ambient	Ambient temperature
(T11) T_flame2	Temperature in the flame
(T12) T_amb	Portable Analyzer ambient temperature measurements
(T13) T_stack	Portable Analyzer exhaust gas temperature

Four ports were installed on the gasifier to measure pressure, additional to the U-tube water manometer. Tubes of 6.35 mm inner diameter connected the pressure ports to the differential gauge pressure transducer of the GCU.

Table 3.5 - Nomenclature and description for pressure sensors

Nomenclature	Description
(P1) P_comb	Combustion zone
(P2) P_top	Top of the reactor
(P3) P_filter	Top of the packed bed filter
(P4) P_bottom	Below the reduction zone

A scale was used to weigh wood pellets before every filling. The amount of wood pellet consumed during gasification was obtained by measuring the mass of wood pellets when refilling the reactor after an experiment. The mass added to the reactor was the mass consumed previously. This mass was divided by the duration of the experiment to determine the consumption rate ($\dot{m}_{biomass}$). Compressed air injection was monitored with two pressure gauges of 700 kPa and two versa-mount dial-indicating flow meters of up to 42.5 m^3/hr. The TESTO 335 portable analyzer (Testo Inc., Lenzkirch, Germany) was used to measure CO, O_2, NO, NO_2 and SO_2,and to give calculated estimates of CO_2 and NO_x. The analyzer provided additional values for ambient and stack temperatures. The syngas sampling port was positioned at the top of the drum filter (point (B), Figure 3.4), before the ejector venturi, while the exhaust gas sampling port was connected through the chimney (point (A), Figure 3.4).

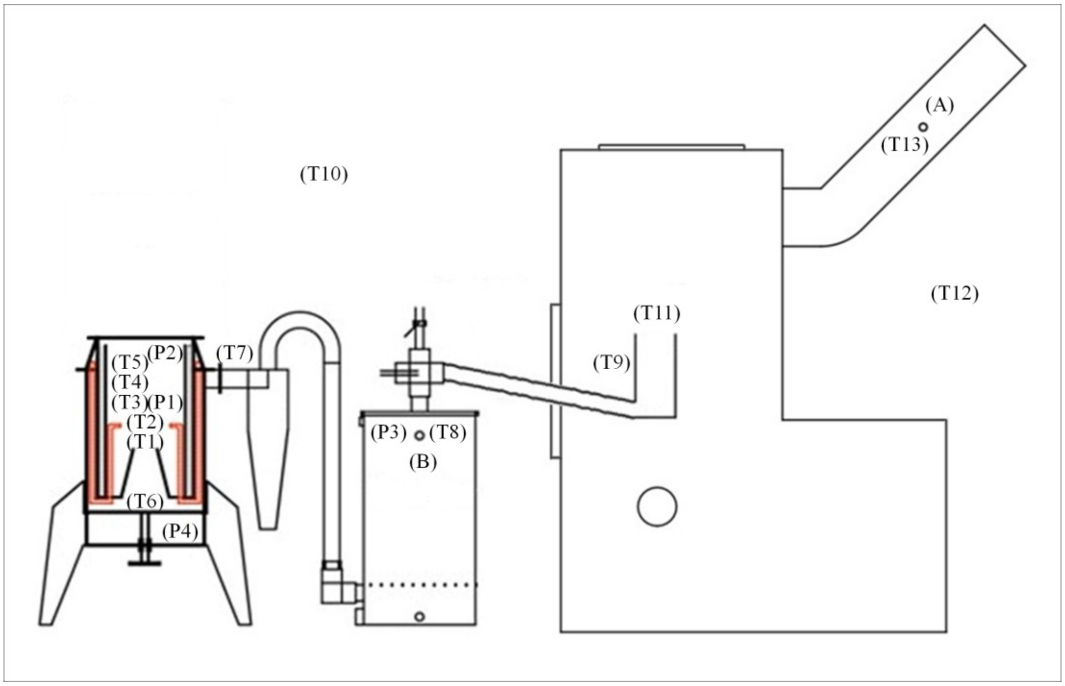

Figure 3.4 – Instrumentation schematic of the gasifier coupled with the forced-air furnace ((P1) to (P3): pressure sensors – (T1) to (T13) temperature sensors - (A): Exhaust gas sampling port – (B): Syngas sampling port)

3.4.3 Feedstock

Premium quality wood pellets were supplied by Energex Pellet Fuel Inc. (Lac-Mégantic, QC, Canada). They were fabricated from 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%.

3.4.4 Methodology

For safety reasons, the gasifier, the forced-air furnace and all instruments were operated outdoors. All components were mounted on a skid for ease of transport. The gasifier was operated in batches of one hour, permitting time for gas analysis on the same day and cool down of the reactor.

The gasifier operation was repeated according to the following sequence. Excess ash was removed below the grate of the reactor. The inside of the reactor was inspected for bridging or clogging of char pellets bed at the core that may have occurred during previous runs. 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. The char bed was required to allow for an easier gasifier start-up. The char bed level was the same for every trial. Fresh wood pellets were weighed and poured in the GEK. The top lid was then sealed. The gasifier was inspected thoroughly at every flange and connection to ensure proper seal. The furnace heat exchanger blower was then switched on. Air from the compressor was allowed in the ejector venturi to create negative pressure (up to 0.25 kPa) and begin air flow within the gasifier. The 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. Before ignition of the gasifier, the temperature and pressure datalogger was activated. 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 and the core temperature (T_core) started rising above 70°C. 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 T_core increased. Once T_core reached the minimal gasification temperature of 700°C (after 4 to 9 min), the propane was disconnected from the swirl burner and P_bottom was adjusted, with the ejector venturi needle valve, to a vacuum between 1.25 to 1.5 kPa. The syngas combustion was then self-sustained in the swirl burner. Throughout the gasification sequence, P_bottom was regularly adjusted to compensate for pressure changes occurring while the air compressor was filling or emptying. For every trial, 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. Shut down procedures were initiated when the gasifier started behaving abnormally (small explosions or unsustained syngas combustion) or if T_top increased to 100°C. Following one of these signs, P_bottom vacuum was decreased to 0.25 kPa, the reactor air inlet was sealed, and experiment was terminated. The GEK was then monitored while cooling down.

3.4.5 Experimental objectives

The goal of this experiment was to obtain, from the gasifier operation, average empirical data to estimate biomass consumption rate, air intake flow rate and syngas flow rate, which were needed to estimate the CO_2 enrichment potential of the unit. Therefore, the gasifier was operated constantly under its optimal condition set by the manufacturer. Referring to Table 3.3, the vacuum pressure was set between 1.25 to 1.5 kPa. While running at a steady vacuum condition, the gasifier performance was also monitored in terms of temperature and pressure considering the feedstock used. The objective was to ensure that the gasifier could function at optimal temperatures and equivalence ratio with a dense fuel such as sawdust wood pellets. The impact of the fuel density on the core pressure drop would also indicate the level of efficiency of the gasifier. Overall, these preliminary results would help reflect the potential of wood pellet downdraft gasification for CO_2 enrichment in greenhouses.

3.5 Results and Discussion

The average duration of sawdust wood pellet gasification trials with the GEK was 67.1 ± 6.3 min and the average time to gasification was 6.1 ± 1.5 min. The duration of a trial spanned from the ignition in the combustion zone until the sealing of the air inlet. The time to gasification was defined as the period between ignition of the combustion zone and the reactor core (T_core) reaching the minimum gasification temperature of 700°C.

3.5.1 Feedstock

The wood pellets elemental composition was obtained from literature by Reed et al. (1988), from an ultimate analysis performed on similar hardwood sawdust pellets (Table 3.6).

Table 3.6 – 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

From the ultimate analysis of sawdust pellets, the stoichiometric ratio $(A/F)_{stoich}$ can be estimated to 5.63 kg of dry air per kg feedstock using Equations 2 and 3. The wood pellets HHV, on a dry basis, is estimated to 19.42 MJ/kg from Equation 5, while the LHV is determined subsequently as 18.10 MJ/kg from Equation 6.

The premium wood pellets provided a homogeneous fuel in terms of moisture, ash, composition, heating value, bulk density and particle size. This was necessary to monitor the gasifier behaviour independently of biomass type and possible variation due to heterogeneity.

The smoother morphology of wood pellets eased the overall mechanical flow of the fuel and prevented bridging in the feeder and at the top of the reactor. However, after entering the drying and pyrolysis zone, it was observed that the sawdust pellets would lose their smooth morphology as they were changing into char pellets and could become prone to crumbling. Nonetheless, it was typically reported that wood pellets, due to their higher density, had reduced risks of bridging compared to other biomass types, such as wood chips (Erlich and Fransson, 2011). Bridging did occur during a few experiments, but only at the reactor core, which was solved by manual shaking of the ash grate. The use of agitation, stirring and ash grate shaking is commonly suggested to prevent and remediate core plugging or feedstock bridging (Reed et al., 1988). However, excessive agitation may be detrimental by reducing the residence time between each gasification zone and producing a tarry syngas (Reed et al., 1988).

The gasifier showed performance particularities that are unique to the intrinsic properties of small sawdust wood pellets, compared to others or non-densified fuels. The higher density of pellets can in fact create a denser bed at the reactor core. Indeed, other research had shown that wood pellets have higher char density with increasing temperatures up to 800°C, while wood chips char density would decrease continuously with increasing temperatures (Erlich et al., 2006). Consequently, the pellets could make it more difficult for air to fully penetrate the combustion zone and would increase core pressure drop. Moreover, this may induce a decrease of the equivalence ratio since there is more mass of biomass than mass of air. Still, it has been observed by Elrich et al. (2011) that denser char beds increase core pressure drop, which can both decrease or increase cold gas efficiency depending on the feedstock. The sawdust wood pellets diameter of 6.5 mm might have been a cause of gasification efficiency reduction since Elrich et al. (2011) had observed that larger pellets of 8 mm gave better efficiency than pellets of 6 mm.

3.5.2 Temperature

Average temperatures for the different data points are presented in Table 3.7. The overall thermocouple set up on the gasifier provided temperature profiles as seen in Figure 3.5.

Table 3.7 – Average temperature profile across the gasifier obtained from sawdust wood pellet gasification (missing data were due to accidental disconnections of thermocouples)

Trial #	T_core °C	T_combustion °C	T_1 °C	T_2 °C	T_top °C	T_bottom °C	T_cyclone °C	T_syngas °C	T_amb °C
1	862	-	-	-	-	774	184	41	20.61
2	-	995	32	36	38	754	182	48	17.17
3	884	821	43	28	33	817	208	45	27.20
4	835	842	37	28	30	732	136	52	14.75
5	864	877	27	27	26	790	184	25	19.41
6	880	930	35	32	34	796	188	48	13.88
7	847	1001	54	39	42	727	165	46	13.88
8	839	947	65	48	51	746	180	52	18.41
9	858	1003	76	37	37	628	141	47	8.16
10	856	1029	37	30	34	760	186	43	18.16
Avg.	858	927	46	34	37	751	174	45	17
SD	19	73	17	7	8	55	23	8	5

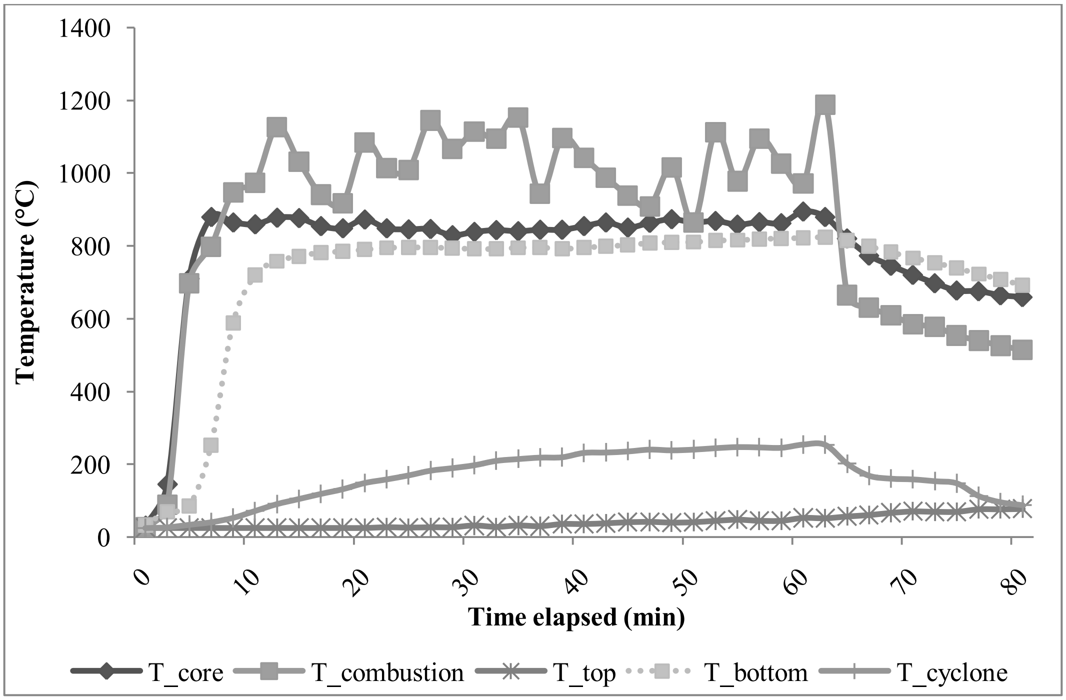

Figure 3.5 – Temperature profile of a typical trial of the downdraft gasifier with sawdust wood pellets (Trial #10)

The average temperature profile of the gasifier showed very good operational behaviour. Indeed, core temperatures were maintained around 858°C (T_core), close to the value of 850°C suggested by Reed et al. (1988) for tar cracking and aromatic hydrocarbons destruction. The bottom of the reduction zone was kept around 751°C (T_bottom). This demonstrated the expected endothermic effect of the reduction zone, reducing temperatures and ensuring syngas production. The combustion zone was kept at around 927°C (T_combustion) and showed high fluctuations as seen in Figure 3.5. These observations for T_combustion were consistent for all trials and could be due to the dynamics of air and biomass mass flows in that region.

The syngas temperature was 174°C (T_cyclone) at the exit of the reactor while it dropped to 45°C (T_syngas) at the top of the packed bed filter. T_syngas was low enough to indicate that some of the moisture and volatiles condensed throughout the filtering equipment (cyclone, packed bed filter), although this was not measured. The heat lost from the temperature drop between T_cyclone and T_syngas could reduce the overall gasifier efficiency. The temperature difference between T_1 (46°C) and T_combustion (927°C) indicated that the drying and pyrolysis zones were located within that 80 mm height region of the reactor. The measurements for T_2 (34°C) were lower than T_1, since it was further away from the reactor. It was observed that T_top (37°C) was a few degrees higher than T_2, which is most likely due to the gasifier top lid material (steel) heating from direct solar radiation. T_top was close to the lid and could have measured this interference. Slightly higher temperatures at T_top were also observed when the gasifier was at rest and under direct sunlight, which supported this possible explanation.

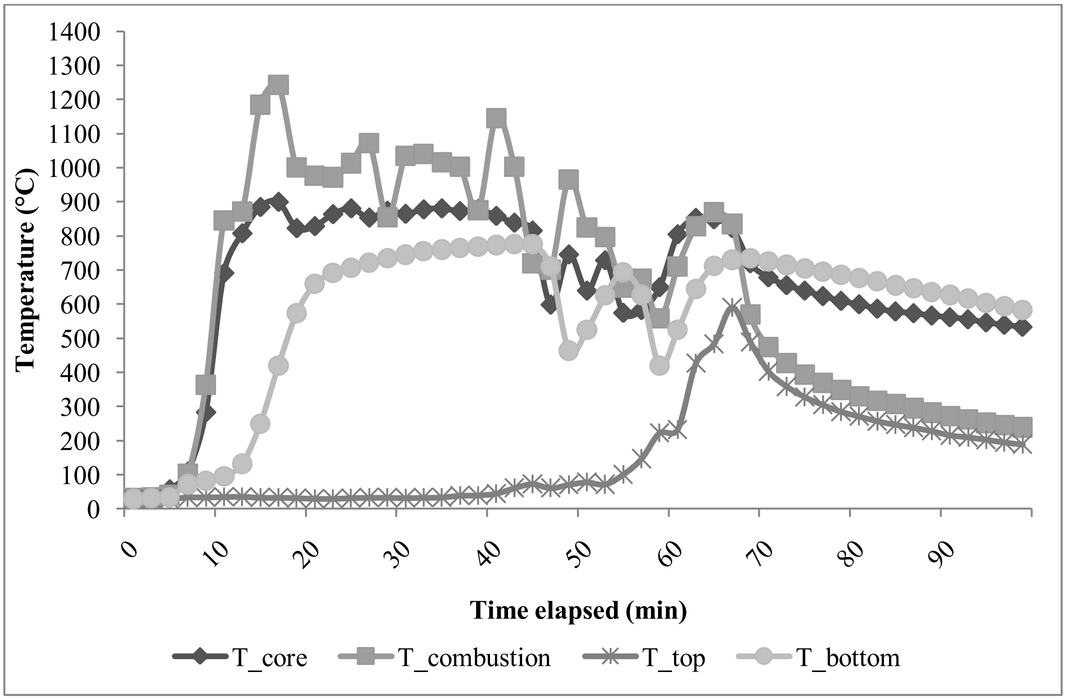

Figure 3.6 – Temperature profile of a sawdust wood pellet downdraft gasification trial experiencing instabilities and high temperature rise at the top of the reactor (Trial #9)

Temperature sensors were essential to monitor the performance of the gasifier assembly and to work as safety controls. Sensors above the combustion zone (T_1, T_2 and T_top) were important indicators of the level of remaining fuel in the reactor and were used as a signal to stop operations. T_top measurements varied between 26°C and 51°C. However, T_top had been observed to increase to 70°C and up to 400°C within 10 minutes at the end of a trial (Figure 3.6). It is hypothesized that when the feedstock was almost fully consumed, there was more air than fuel, which increased the air-fuel ratio. An increasing air-fuel ratio could have changed the reaction from gasification to combustion, thus affecting and increasing the temperatures of the overall gasifier vessel, as seen in Figure 3.6. Another possible explanation was that once all fresh biomass pellets were consumed in the combustion zone, the hot char in the reduction zone, which reached temperatures around 850°C, remained exposed. There were no more fresh pellets to receive the emitted heat as they would normally in the pyrolysis and the drying zone. The heat would then conduct and radiate easily and quickly to the top of the reactor reflecting the measurements taken by T_1, T_2 and T_top.

Either way, T_1, T_2 and T_top usually remained steady during trials and their sudden temperature increase was systematically associated with depletion of fresh feedstock in the reactor. Therefore, the gasifier was shutdown once T_top approached 100°C.

3.5.3 Pressure

Pressure sensors were required to establish the operational conditions of the gasifier and to measure pressure differentials across the major components of the gasifier, such as the core and the filtration devices. Pressure data is summarized in Table 3.8, which shows the average pressure profile of the gasifier running on sawdust wood pellets.

Table 3.8 - Average pressure profile across the downdraft gasifier obtained from sawdust wood pellet gasification (missing data for trial #10 were due to accidental disconnections of pressure sensors)

	Vacuum Pressure	Pressure Drops	
Trial	P_bottom	Core	Filter
#	kPa	kPa	kPa
1	1.66	0.67	0.14
2	1.23	0.33	0.19
3	1.52	0.53	0.17
4	1.50	044	0.21
5	1.70	0.76	0.16
6	1.43	0.51	0.21
7	1.47	0.58	0.20
8	1.27	0.40	0.19
9	1.34	0.38	0.22
10	-	-	-
Avg.	1.46	0.51	0.19
SD	0.16	0.14	0.03

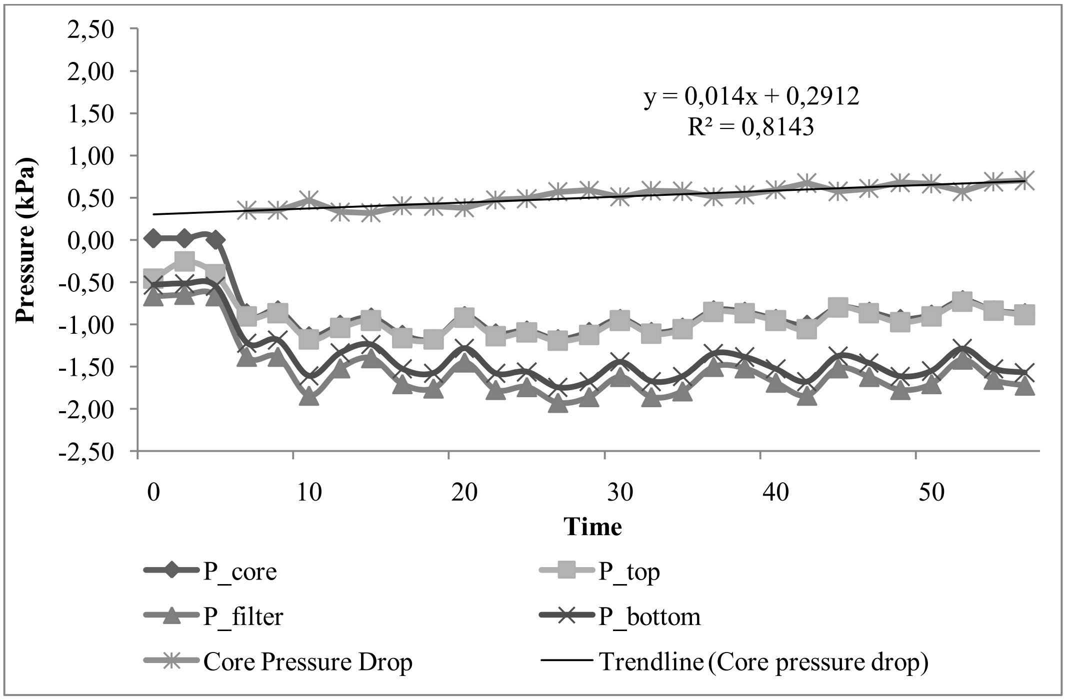

Figure 3.7 – Pressure profile of a typical trial of the downdraft gasifier with sawdust wood pellets (Trial #3)

Operational vacuum pressures were kept between 1.23 and 1.70 kPa, which helped in maintaining the core temperature around 850°C, as suggested by the gasifier manufacturer. The ideal vacuum pressure of 1.25 kPa was recommended for this gasifier, but most of our runs had vacuum pressures higher than 1.25 kPa. This is most likely due to the higher density of the wood pellets used for this experiment since the recommendation was meant for a biomass type of lower average density. Therefore, a stronger vacuum was necessary to ensure gas flow through the denser fuel bed. Sinusoidal like variations can be observed in sync between every pressure sensor. These variations were due to the continuous pressure fluctuations from the air compressor when it was filling and emptying. Adjustments had to be performed constantly by the gasifier operator with manual control of the needle valve at the ejector venturi. While the operation lacked the precision of automated controls, the operational vacuum pressure was kept at an average of 1.46 kPa.

An average pressure drop of 0.51 kPa was observed across the reactor core (the difference between P_core and P_bottom). Core pressure drop ranged between 0.33 and 0.76 kPa. Figure 3.7 presents an example of a curve for core pressure drop showing a slight increase as a function of time. The average rate of char bed packing, expressed as the increase of pressure differential over time, was determined as 5.80 ± 1.97 Pa/min or 348Pa/hr. As mentioned by Elrich et al. (2011), the pressure drop across the core reflects the level of char bed packing and density. For their trials, they had observed core pressure drops between 0.05 and 0.70 kPa for various types of densified biomass. Although our gasifier design and biomass differed from the ones used by Elrich et al. (2011), our results fell within the higher range they had observed. It can still confirm that the higher density sawdust wood pellets used in our experiment increase the bed char density and core pressure drop.

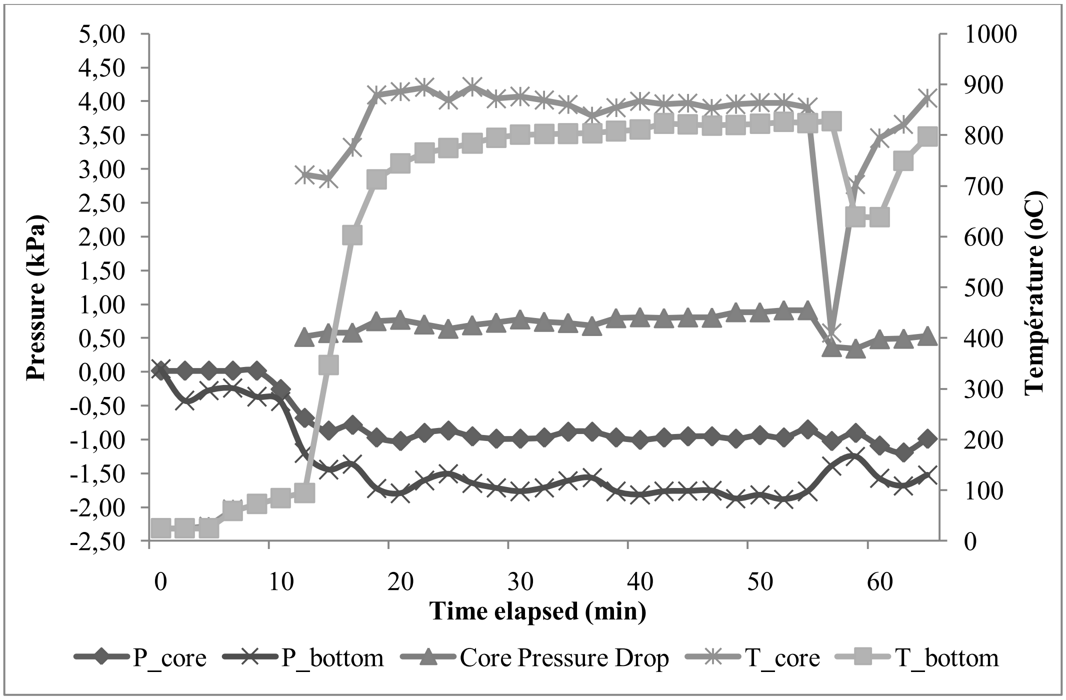

Figure 3.8 – Pressure and temperature profile of a sawdust wood pellet downdraft gasification trial showing effects of excess ash grate shaking (Trial #5)

In order to prevent excessive char bed packing at the core, the ash grate, below the reactor core, was shaken lightly during some experiments, as suggested by Reed et al. (1988). Figure 3.8 shows that the light agitations did not affect considerably the core pressure drop curve for most of the trial duration, except at the end of the experiment. A high decrease on the core pressure drop curve can be seen at 54 min and represents the impact of excessive ash grate shaking. As a consequence, the hot reacting char of the reduction zone fell onto the ash grate and was replaced by fresh wood pellets. In turn, the wood pellets reached the reduction zone without being processed through the drying, the pyrolysis and the combustion zone as they normally would. After the excess shaking, T_core dropped abruptly below ideal gasification temperatures, followed by T_bottom. Due to these abnormal temperatures, the gasification reactions were impaired, thus affecting the syngas quality and the potential use of the gasifier as a CO_2 enrichment device. A few minutes were required for temperatures to return to their steady optimal levels. Light reactor agitation is important to control char bed packing, but it may also interfere with gasification processes if performed in excess.

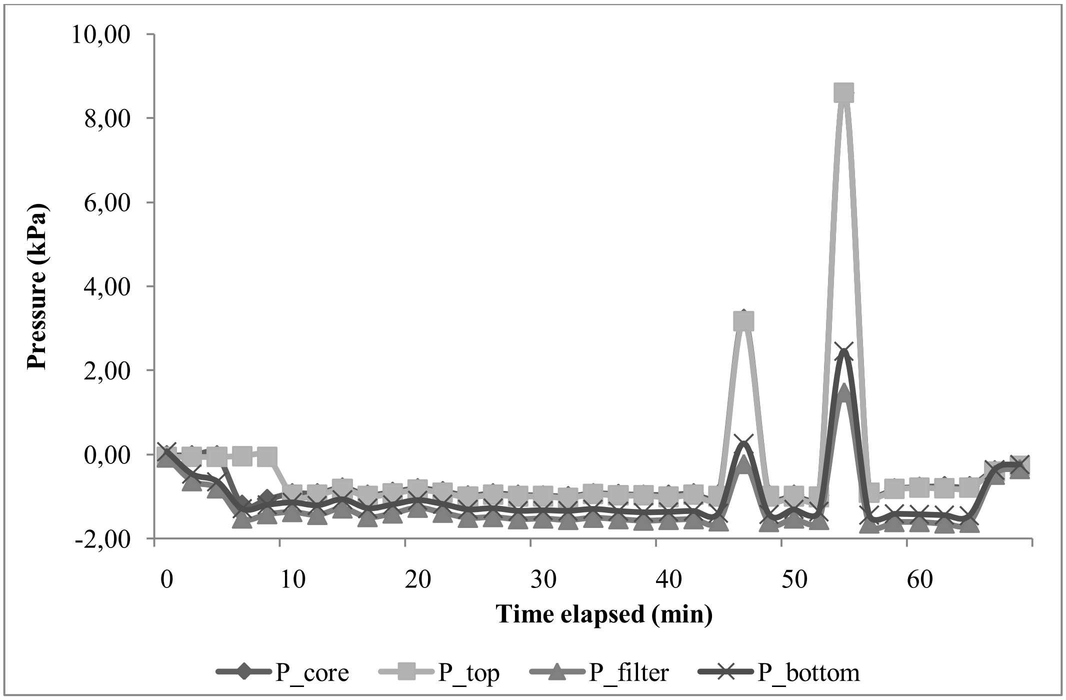

Figure 3.9 - Pressure profile of a sawdust wood pellet downdraft gasification trial showing micro-explosions (Trial #8)

Figure 3.9 displayed sudden and very short high positive pressure peaks that could be referred to as micro-explosions. These instances lasted less than a second and were higher at the top of the reactor, as measured by P_top. A micro-explosion could be observed, on site, as a very small amount of smoke being briefly spit out of the gasifier air inlet and through some flange seals. The gasifier would then continue to operate normally and no damage to the gasifier material was noticed after inspections. The occurrences of micro-explosions in a gasifier reactor are not often examined in literature. Quaak et al. (1999) had acknowledged that fixed bed gasifiers could be prone to explosions at start-up due to the residual gases from previous trials. When mixed with air, these residual gases could ignite instantly, thus creating sudden positive pressure peaks. Reed et al. (1988) also mentioned that for downdraft gasifiers, the level of these explosions was low enough that the material and joints could handle them without damage. It was suggested that spring-loaded lids or safety release valves should be included in the gasifier design to release the excess positive pressure from micro-explosions (Reed et al., 1988). For our experiments, these micro-explosions could have been due to an accumulation of combustible gases in certain regions of the gasifier, which were suddenly ignited when exposed to air. It was also acknowledged that the gasifier was not 100% sealed, thus enabling possible air leakage inside the system. Most of the flange joints were sealed with high temperature mortar while others were sealed with tightened nuts and bolts only, such as at the top lid. Indeed, it was essential to keep the top lid manoeuvrable for refilling and inspection of the reactor between experiments. However, it may have induced a weaker seal enabling some air leakage and explaining the higher pressure peaks measured by P_top. From Figure 3.9, it must be noted that the pressure profile, prior to an explosion, does not indicate signs, such as pressure changes, that would lead to a micro-explosion. Further research would be required to clarify the working parameters that favour these micro-explosions and their implications.

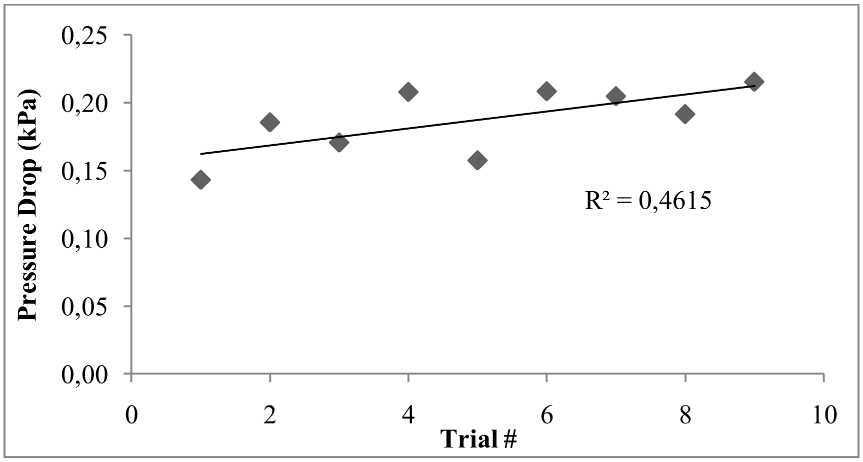

Figure 3.10 – Variation of packed-bed filter pressure drop with increasing numbers of monitored trials

An average pressure drop through the cyclone and packed bed filter of 0.19 ± 0.03 kPa was determined from the difference of P_bottom and P_filter. The pressure drop reached a maximum of 0.22 kPa, which was still far from the manufacturer recommended limit of 1.00 kPa as the indicator to replace the filter bed material. From the trendline seen in Figure 3.10, the packed bed filter had a pressure differential increase of approximately 6.3 Pa per experiment. These increases of pressure differential were most likely due to accumulation of particles and tars trapped in the packed bed filter. More experiments would be needed to test the saturation point of the filter, currently suggested at 1.00 kPa. Moreover, the container was not weighed before and after experiments to account for the accumulated mass of tars. The content of the filter being mostly charcoal of different size and shapes, it could be reused as a feedstock into the gasifier, once the filter pressure drop was more than 1.00 kPa.

3.5.4 Gasifier performance

The average performance results from sawdust wood pellet gasification were estimated and compiled in Table 3.9.

Table 3.9 – Average performance results for downdraft gasification of sawdust wood pellets (average ± standard deviation)

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)	13.33	±	0.76
	(kg/hr)	13.51	±	0.77
Production ratio	($m^3_{syngas}/kg_{biomass}$)	1.73	±	0.11
	($kg_{syngas}/kg_{biomass}$)	1.76	±	0.12
A/F_{stoich}		5.63		
A/F_{actual}		0.96	±	0.12
ER		0.17	±	0.02
Power				
from wood pellet combustion	(kW)	38.8	±	4.0
from syngas combustion	(kW)	22.9	±	1.3
Cold gas efficiency		59%	±	4%

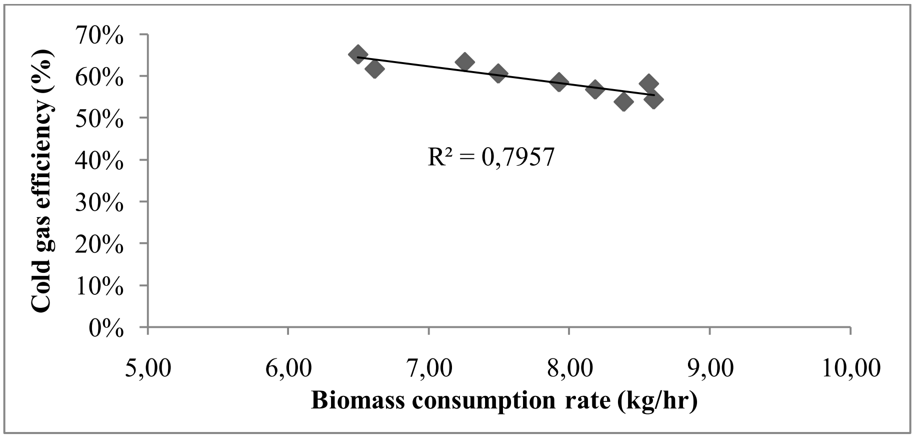

Figure 3.11 – Influence of sawdust wood pellet consumption rate in a downdraft gasifier on cold gas efficiency

In absence of continuous measurements of the syngas composition, measurements from All Power Labs were used, which provided average values of volumetric syngas composition, shown in Table 3.10:

Table 3.10 – Volumetric syngas composition (dry basis) for GEK gasifier (All Power Labs, 2010)

H_2	CO	CO_2	CH_4	N_2
18.7%	22.7%	9.6%	3.0%	44.7%

From the individual gas heating values in Table 3.2, this composition characterized syngas with an estimated HHV of 6.68 MJ/m^3 (LHV of 6.18 MJ/m^3) and a density of 1.01 kg/m^3 (at 101.325 kPa and 20°C on a dry basis). The air intake of 6.09 m^3/hr presented in Table 3.9 was estimated with the empirical relationship described by Equation 11 using the actual vacuum measurements in the gasifier. Without flow meters, the average syngas production rate was assumed as the sum of the air intake and the estimated volatile fraction of the biomass consumption rate. Therefore, from Equation 12, the average $\dot{m}_{syngas}$ is assumed to be 13.51 kg/hr and Q_{syngas} is 13.33 m^3/hr. These results translate to an approximated production of 1.76 kg, or 1.73 m^3, of syngas per kg of gasified sawdust wood pellets. Without being actual measurements, the results from Table 3.2 provided an order of magnitude of syngas production for the gasifier.

The cold gas efficiency of 59% presented in Table 3.9 was estimated using Equation 9. This calculated value was proportional to the LHV of both the syngas and the feedstock which were determined from literature and empirical data from the gasifier manufacturer. Equation 9 also considered the actual average biomass consumption rate, while using the estimated syngas production rate, and provided an acceptable approximation. If the actual cold gas efficiency was 59%, it would be considered satisfactory since it would have fallen in the average range observed by Elrich et al. (2011) for various biomass pellet types. From Figure 3.11, the highest estimated efficiency was reached at the lowest average consumption rate. Table 3.9 showed that the gasifier average biomass consumption rate of 7.70 kg/hr would have represented a thermal output of 38.8 kW for the same amount of biomass consumed with direct combustion. Following gasification and syngas combustion, the thermal power output was estimated at around 22.9 kW for the GEK. The lower thermal power of the gasifier corresponded to the cold gas efficiency and did not consider the energy content still present in the remaining char or from the tars trapped in the gasifier filters.

The empirical estimations of gasifier performance were compared with theoretical predictions from gasification literature. The average wood pellet consumption rate of the gasifier was 40.4% of the maximal theoretical output (18.86 kg/hr) reported by Reed et al. (1988) for the specific reactor core diameter of the GEK gasifier. Using the LHV value for sawdust wood pellets and based on the theoretical maximal biomass consumption rate from the gasifier reactor core diameter, the maximal GEK power output should be 94.8 kW. Similarly, the theoretical gas output of the gasifier was 41.34 m^3/hr, for a maximal production ratio of 2.2 m^3 of syngas produced per kg of biomass consumed. Based on an average heat value of syngas of 5.80 MJ/m^3 (Reed et al., 1988), the maximal theoretical power output of syngas combustion was 66.6 kW, for a gasifier cold gas efficiency of 70%. Additional empirical data from the gasifier operation would be required to explain the differences between theoretical and actual performance.

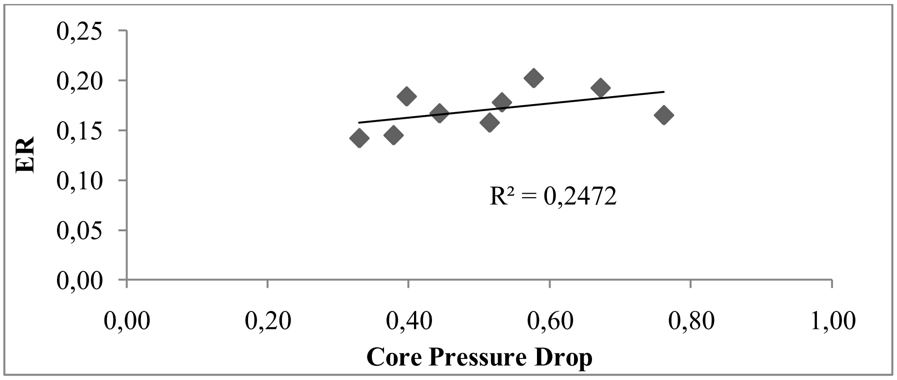

Figure 3.12 – Influence of char bed pressure drop on the equivalence ratio of downdraft gasification of sawdust wood pellets

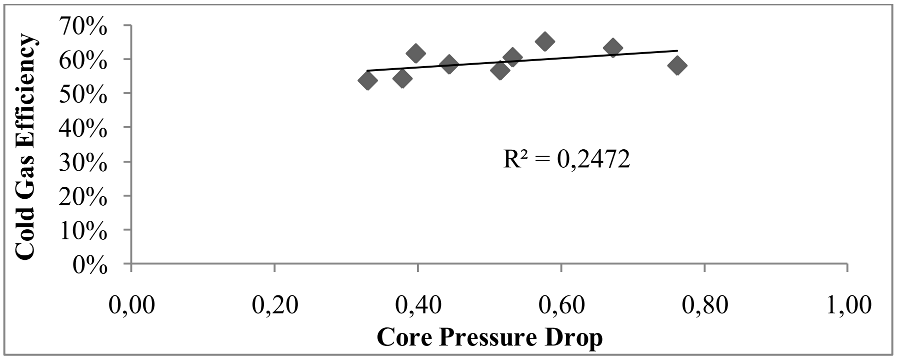

Figure 3.13 – Influence of char bed pressure drop on the cold gas efficiency of downdraft gasification of sawdust wood pellets

From Table 3.9, the estimated equivalence ratio of 0.17 was evocative of gasification, but below the optimal average value of ER = 0.25. The ER was obtained from the air inlet flow rate and the actual biomass consumption rate. Since the latter value represented an average for a whole gasification experiment, it was not possible to evaluate the instantaneous consumption rate, and thus the instantaneous ER, at different stages of time during gasification. If the actual ER had been 0.17, it would have been lower than the common range of 0.20 to 0.45 reported by Elrich et al. (2011). The lower ER value might be due to the tendency of wood pellets to create a denser fuel bed at the core. With more mass of fuel than mass of air at the core, the ER could decrease. Elrich et al. (2011) had observed that wood pellets ER and cold gas efficiency would decrease with higher core pressure drop. However, Figure 3.12 and Figure 3.13 show opposite tendencies of increasing ER and cold gas efficiency with increasing core pressure drops. Although they were using a downdraft gasifier with a different design, Elrich et al. (2011) had noticed this effect on other types of pellets. They explained that higher core pressure drops also allowed for longer residence time for the biomass, which could result in increased char conversion and higher efficiency. This explanation seems to reflect Figure 3.12 and Figure 3.13. However, the estimations of both ER and cold gas efficiency were directly proportional to the air inlet flow rate, which depended on the vacuum pressure measurements (P_bottom). As P_bottom would increase, the core pressure drop, the ER and the cold gas efficiency increased as well. Therefore, more empirical data of actual performance would have been required to fully assess the relationship shown in Figure 3.12 and Figure 3.13. Additionally, since ER was below the usual range for gasification, it seems logical that the cold gas efficiency would increase as ER increased closer to the optimal value of 0.25.

3.5.5 Potential of CO_2 production for enrichment

The maximum CO_2 enrichment potential of the sawdust wood pellets was 1.73 kg of CO_2 per kg of biomass (Equation 12), if used in complete direct combustion. When consumed at $\dot{m}_{biomass}$ = 7.70 kg/hr, assuming complete combustion, rate of enrichment would be 13.3 kg CO_2/hr, obtained from Equation 13. With a suggested rate of enrichment of 5.6 g $CO_2/(m^2 \cdot hr)$, the wood pellets could enrich a greenhouse with maximal surface area of 2379 m^2.

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 Equation 12 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 8.62 kg CO_2/hr. The GEK could presently enrich a greenhouse with a surface area of 1540 m^2. The enrichment potential for gasification, in terms of greenhouse surface area, is 65% of the potential for direct combustion. Nonetheless, as suggested by many authors, gasification coupled with syngas combustion is cleaner and easier to control than direct combustion (Reed et al., 1988; Quaak et al., 1999; Whitty et al., 2008), which would compensate for the lower surface of greenhouse enrichment. Future comparative research should further assess the differences between combustion and gasification.

Table 3.11 – Energy and CO_2 yield for sawdust wood pellets (assuming complete direct combustion and complete syngas combustion following sawdust wood pellet gasification), for natural gas and propane (assuming complete combustion for both fossil fuels)

	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	1123	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)

The results compiled in Table 3.11 presents the energy output per kg of sawdust wood pellets after complete direct combustion and after gasification. The value after gasification is the energy output from complete combustion of the syngas per kg of the wood pellets processed in the gasifier. The lower energy output of 10.69 MJ/kg, compared to 18.10 MJ/kg, is representative of the cold gas efficiency of 59% for the gasifier. The data from Table 3.11 allows comparing the potential usable CO_2 emitted for enrichment with the potential heating value of conventional and non conventional fuels. The CO_2 emitted from natural gas and propane is in lesser amount, but comes from a fossilized and non renewable source of energy. On the other hand, the CO_2 emitted from both thermo-chemical processes for biomass had been absorbed from the atmosphere during the biomass growth. Results show that biomass used as a CO_2 enrichment source could supply more CO_2 per unit of energy than propane and natural gas.

By performing a simplified mass balance for carbon content, we observed that for 1 kg of sawdust wood pellets there was 0.47 kg of carbon. Using the mass ratio of 1.76 kg of syngas per kg of wood pellets along with syngas composition, we determined that 0.31 kg of carbon was present in the gas. Therefore, 0.17 kg of carbon remained in the gasifier, in the form of charcoal, tars, oils, unburnt volatile gases, per kg of gasified wood pellets. Consequently, approximately 65% of the carbon content of the wood pellets that was absorbed during the biomass growth was re-emitted in the atmosphere following complete combustion of syngas. When used for CO_2 enrichment, a certain amount of this 65% of carbon could be absorbed by the plants in the greenhouse, thus further reducing the balance of carbon released to the atmosphere. Close to 35% of the carbon content remained in the gasifier as co-products, such as char below the reactor or as tars and fine particulates in the cyclone and the packed bed filter. The exact distribution of these co-products between the various sections of the gasifier would need to be addressed in future studies. Further analysis of char composition in terms of remaining volatile carbon and fixed carbon, along with other essential properties could help determine if this gasification char is suitable as biochar and for soil amendment.

3.5.6 Recommendations

Future research work should look at improving the accuracy to determine the ER. An air flow rate meter at the gasifier air inlet could help in validating Equation 11 when used with sawdust wood pellets. The fixed bed gasifier (including all of its components) could be set up on a high capacity scale. This method could indicate accurately the mass loss over time. It could even determine the different fuel consumption rates during ignition, operation and cool down of the gasifier. Additionally, the observations derived from the temperature and pressure measurements should be integrated into an automated control system to apply a downdraft gasifier as a CO_2 enrichment device. Problems arising from fluctuations in optimal gasification temperatures, depletion of the biomass fuel in the reactor, from micro-explosions, excessive char bed packing at the core or excessive ash grate shaking can all be detected by the temperature and pressure sensors to activate an alarm or a shut down procedure.

3.6 Conclusion

The objective of this experiment was to setup and monitor the performance of a pilot scale gasifier to estimate the CO_2 production rate, while identifying the characteristics of the system that would affect CO_2 enrichment operations. The sawdust wood pellets used for gasification caused less bridging than other types of solid biomass fuel and created a denser char bed at the core. The gasifier was able to operate with optimal gasification temperatures for the majority of the time. Temperature fluctuations provided indications of biomass fuel depletion in the reactor and showed the effects of excessive ash grate shaking. The pressure sensors validated the extent of a pressure drop increase across the reactor core and the packed bed filter. The pressure sensors were helpful in detecting micro-explosions, which might have suggested sealing flaws on the gasifier. The gasifier operated with an average equivalence ratio of 0.17, below the optimal value of 0.25, and the cold gas efficiency was 59%. An increase of cold gas efficiency was observed with increasing core pressure drop due to the longer residence time of the wood pellets in the reduction zone. From the empirical data, the GEK running with sawdust wood pellets could provide a maximum of 22.9 kW of thermal energy and could enrich a maximum of 1540 m^2 of greenhouse surface area. Results indicate that biomass, following combustion or gasification, could provide more CO_2 for greenhouse enrichment than propane or natural gas.

These observations lead to recommendations to improve the downdraft gasifier as a CO_2 enrichment device and to indicate future research avenues. The results were compared with current literature, which contributed to the general knowledge on biomass gasification. This research project was a first step in demonstrating CO_2 enrichment from biomass gasification, which was not known to have been documented in peer reviewed literature.

3.7 References

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Connecting Statement

In Chapter 3, the various parameters influencing the operation of wood pellet gasification were studied to formulate recommendations, which would improve the performance of the system as a CO_2 enrichment device. The focus of Chapter 3 was on the wood pellet gasification to produce syngas, while the focus of Chapter 4 is on the syngas combustion to produce CO_2 for enrichment. Chapter 4 examines the performance of a syngas burner in terms of exhaust gas composition, to identify potential improvements for the burner design.

Chapter 4: Combustion of syngas from biomass gasification for CO_2 enrichment in greenhouses

4.1 Abstract

Near complete combustion of syngas is essential to achieve greenhouse carbon dioxide (CO_2) enrichment from biomass gasification and safety for plants and greenhouse workers. The objective of this research project was to monitor the performance of a syngas burner in terms of exhaust gas composition and to identify potential improvements for the burner design aimed at its application for CO_2 enrichment in greenhouses. A steel swirl burner was operated with an average equivalence ratio (the actual air to fuel ratio relative to the stoichiometric air to fuel requirement) of 2.6 following gasification of sawdust wood pellets. Carbon monoxide (CO) was produced at an average concentration of 8.8 ppm. About 60% of the trials were below the ASHRAE standards for indoor air quality of 11 ppm, while 90% were below 20 ppm. The average concentration of nitrogen oxides (NO_x) emissions was 23.6 ppm and would need to be reduced to allow commercial operations. The sulphur dioxide (SO_2) emissions were below ppm levels, while ethylene (C_2H_4) emissions were below the critical concentration of 50 ppb for CO_2 enrichment. The theoretical exhaust gas CO_2 concentrations were calculated as part of this project and were below the calculated concentrations obtained from the portable gas analyzer. This difference indicated that the actual syngas composition was different than the estimated composition used in the calculations and that the actual CO_2 enrichment potential of the gasifier could have been higher. Improvements to the syngas burner design were suggested to reduce NO_x emissions and further improve the syngas combustion efficiency, by integrating the low swirl design, the use of mesh catalysers, better refractory material and a better heat exchanger. Continuing research on this topic should look at emissions of particulate matter and volatile organic compounds (VOCs).

Table 4.1 – Nomenclature

A	greenhouse surface area	m^2
$(A/F)_{actual}$	actual dry air to fuel ratio	
$(A/F)_{stoich}$	stoichiometric dry air to fuel ratio	
ER	equivalence ratio	
HHV	higher heating value	kJ / kg fuel
i	element i (C, H, N, O or S)	
j	compound j (CO_2, H_2O, N_2, O_2)	
LHV	lower heating value	kJ / kg fuel
M_i	molecular mass of element i	kg of i / kmole
M_j	molecular mass of compound j	kg of j / kmole
$\dot{m}_{air\ in}$	gasifier reactor air intake mass flow rate	kg / hr
$\dot{m}_{biomass}$	solid biomass consumption rate	kg / hr
m_{CO_2}	mass of emitted CO_2 per kg of dry fuel	kg CO_2 / kg fuel
$\dot{m}_{CO_2}$	CO_2 mass flow rate	kg / hr
$\dot{m}_{flue\ gas}$	flue gas mass flow rate	kg / hr
$\dot{m}_{syngas}$	syngas mass consumption rate	kg / hr
m_{O_2}	stoichiometric oxygen requirement	kg O_2 / kg fuel
ρ_{air}	air density	kg / m^3
$Q_{air\ in}$	gasifier reactor air intake volumetric flow rate	m^3 / hr
Q_{syngas}	syngas volumetric flow rate	m^3 / hr
x	number of carbon molecules	
X_{air}	mass fraction contribution of air to flue gas	kg air / kg flue gas
X_i	mass fraction of element or compound i	kg of i / kg fuel
X_j	mass fraction of compound j	kg of j / kg fuel
X_{syngas}	mass fraction contribution of syngas to flue gas	kg air / kg flue gas
y	number of hydrogen molecules	
Y_j	volume fraction of compound j	%

4.1 Introduction

Impacts of carbon dioxide (CO_2) on plant growth have been observed for over 200 years for contributing to photosynthesis.

$$6CO_2 + 12H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6O_2 + 6H_2O \qquad (1)$$

Practices of CO_2 enrichment in controlled growth environments have been pursued since the early 1900s with wide ranges of success (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 acceptance 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). Enrichment is performed with pure CO_2 in bulk, or from dedicated natural gas or propane burners (Hicklenton, 1988). CO_2 enrichment using the exhaust gas of heating systems fuelled with natural gas or propane is currently feasible considering efficient and clean combustion. However, using renewable energy could increase environmental and economical benefits of greenhouse productions. Currently, biomass heating is showing a lot of promises for its ability to provide thermal energy for very large greenhouses at competitive costs (Chau et al., 2009). Biomass, as a solid fuel, encompasses many sources of organic vegetal matter and their derivatives, such as wood residues, dedicated energy crops, agricultural residues, animal waste, or municipal waste. Biomass combustion for heating or cogeneration is recognised as a sustainable renewable fuel alternative that can also reduce greenhouse gas production (Petersen Raymer, 2006). The life-cycle assessment of biomass used for combined heat and power shows better performance and lower impacts than for natural gas (Dones, 2003; Eriksson et al., 2007). Therefore, CO_2 enrichment from the exhaust of a biomass heating system could be promising, but is limited since biomass combustion is not as efficient and complete as with fossil fuels. Emissions of carbon monoxide

(CO), nitrogen oxide (NO_x), sulphur oxide (SO_x), volatile organic carbons (VOCs) and fine particulates can impair plant production. Therefore, improvements are required to make CO_2 enrichment from biomass heating systems a viable and safe option.

While biomass combustion technologies are well established, gasification is showing a lot of promise both in research and commercial applications to achieve high efficiency and cleaner energy production (Quaak et al., 1999; McKendry, 2002; Basu, 2010). Gasification is a thermo-chemical reaction that differs from combustion for being under partial oxidation, thus converting the material into a gaseous fuel. Various types of feedstock can be used for gasification such as coal and a myriad of biomass sources. However, biomass has much higher volatile content than other solid fuels, up to 80%, which is ideal for gasification (Quaak et al., 1999). Depending on the gasifier design, the gas is usually composed of hydrogen (H_2, 12-20%), CO (17-22%), methane (CH_4, 2-3%), CO_2 (9-15%), water vapour (H_2O), nitrogen (N_2) and tar vapours. The raw gas containing some impurities is called producer gas while it is referred as synthesis gas when refined into a higher quality mixture (CO and H_2). For the sake of this research the term syngas is used in reference to producer gas. Syngas has a calorific value around 4-6 MJ/Nm^3 when using air as an oxidizer (Reed et al., 1988; Quaak et al., 1999; McKendry, 2002). Syngas can be used for power and heat production or to be further converted into chemicals or liquid fuels in the form of a synthesis gas (McKendry, 2002). Gasification coupled with syngas combustion for heat and power can achieve high efficiency and is recognised to make biomass heating cleaner and easier to control, compared to direct combustion of solid fuels (Reed et al., 1988; Quaak et al., 1999; Whitty et al., 2008). Consequently, syngas combustion as a CO_2 enrichment device could work as a renewable alternative to propane and natural gas.

Efficient combustion of syngas is the key to achieve this goal. In order to inject exhaust gases in a greenhouse, compliance with air quality and workplace safety must be met (Table 4.2).

Table 4.2 – ASHRAE standards to indoor environmental quality (ASHRAE, 2009)

Compound		Concentration limit	
Carbon Dioxide	CO_2	3500	ppm
Carbon Monoxide	CO	11	ppm (8h)
		25	ppm (1h)
Nitrogen Dioxide	NO_2	0.05	ppm
		0.25	ppm (1h)
Particulate		40	$\mu g/m^3$ (8h)
		100	$\mu g/m^3$ (1h)
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).

The main compounds found in the exhaust gas of inefficient biomass heating systems are CO, NO_x, SO_x, ethylene (C_2H_4), other VOCs, and fine particulates (Hanan, 1998). They can affect both plants and human beings. Plants are mostly affected by ethylene, which acts as a plant hormone by provoking early senescence in plants (Mortensen, 1987) and should be kept below 0.05 ppm (Hanan, 1998). Proper syngas combustion should keep these compounds below acceptable levels.

Syngas from biomass gasification presents some challenges since the burner has to cope efficiently with a gas whose composition and flow rate may vary. Even when operated at steady conditions, a biomass gasifier may perform variably due to the nature of the solid biomass fuels, as seen in Chapter 3. This research project looks at exhaust gas emissions from a rudimentary syngas swirl burner. An outlook of the flue gas compounds formation and of the current syngas burner design is given. The experimental CO_2 enrichment potential of syngas combustion is compared with theoretical estimations. The objective of the research is to demonstrate that syngas combustion may present an interesting renewable alternative for CO_2 enrichment from a biomass heating system.

4.2 Literature Review

4.2.1 Gasification

There are many conventional designs for gasification of biomass such as fixed bed and fluidized bed types, all of which influence the syngas composition and quality (Basu, 2010). The common fixed bed reactors are shown in Figure 4.1.

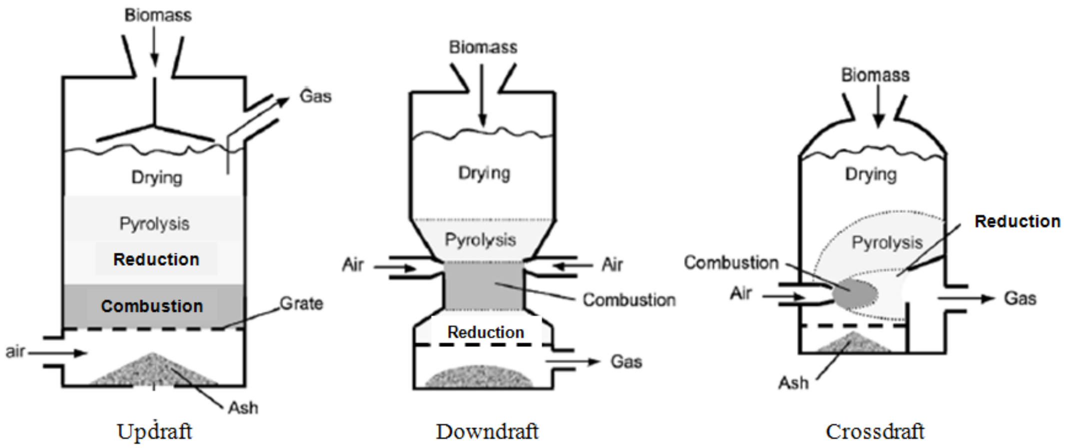

Figure 4.1 – Schematic of gasification zones and gas and biomass flows for Updraft, Downdraft and Crossdraft gasifiers (Basu, 2010)

They differ essentially due to the syngas flow in the system, including downdraft, updraft and crossdraft. These flow patterns affect the order at which the biomass feedstock undergoes the four main gasification reactions: drying, pyrolysis, combustion and reduction (Figure 4.1).

Updraft gasifiers are more common for larger scale thermal energy production of 1 to 30 MW. They accommodate fuels with higher moisture content (60% max, wet basis) and ash content (25% max, dry-ash basis) (Quaak et al., 1999). However, the syngas tar content is much higher, varying between 30 to 150 g/m^3 (Basu, 2010). For direct heating applications, updraft gasifier become advantageous since the tars increase the gas heating value and the resulting gas is burned directly after being produced (Reed et al., 1988).

The most common type of downdraft gasifiers are the Imbert style gasifiers used for nearly a million vehicles worldwide in the early 20th century (Reed et al., 1988). Their application range is from 10 kW up to 1 MW due to their intrinsic core design. As seen in Figure 4.1, the V-shaped narrow constriction at the reactor core creates a high temperature zone that ensures tar cracking. This results in the production of syngas with very low tar content from 0.015 to 3.0 g/m^3, which makes downdraft gasifiers ideal for internal combustion engines (Basu, 2010). The Imbert style design is limited in scalability and works optimally with feedstock of lower moisture content (25% max, wet basis) and ash content (6% max, dry-ash basis).

Fluidized bed gasifiers operate with a reusable granular solid in a semi-suspended state maintained by the intake air flow velocity. As the biomass is mixed in the fluidized-bed, the temperature is more uniformly distributed amongst the reactor thus optimizing heat and mass transfer (Reed et al., 1988; Basu, 2010). Fluidized bed gasifiers also generate tars at a level around 10 g/m^3, between the performance of updraft and downdraft gasifiers (Basu, 2010). This makes fluidized bed gasifiers advantageous and energy efficient for large scale applications, although the added complexity of the system usually increases investment and maintenance costs.

Updraft or fluidized-bed gasifiers are appropriate for heating large scale greenhouses requiring over 1MW of thermal power. The potential use of their exhaust gas CO_2 would be determined by the quality and efficiency of the boiler. Additional emission cleaning systems and dilution would most likely be required for this application. On the other hand, downdraft gasifiers, due to their low tar content, could function as smaller dedicated CO_2 production units for greenhouse enrichment.

4.2.2 Thermodynamics of Syngas Combustion

Combustion is a thermo-chemical reaction between a fuel and an oxidizer. Theoretically, complete combustion of a fuel is achieved when the stoichiometric air requirement is met, following the general combustion equation.

$$C_xH_y + \left(x + \frac{y}{4}\right)O_2 \rightarrow x\,CO_2 + \frac{y}{2}H_2O \qquad (2)$$

The air or oxygen requirement depends on the chemical composition of the fuel, which can be obtained from its ultimate analysis (normally expressed by mass) (De Nevers, 2000). If more air is mixed with the fuel than the stoichiometric air requirement, the mixture is referred as a lean mixture. As the ratio of air to fuel increases, the mixture reaches a limit where it has too much air and is too lean to burn. This limit of air to fuel ratio is known as the lower flammability limit (LFL or lean limit) beyond which combustion will not occur (De Nevers, 2000). Similarly, if less air is mixed with the fuel than the stoichiometric air requirement, the mixture is referred as a rich mixture. As the ratio of air to fuel decreases, the mixture reaches the upper flammability limit (UFL or rich limit), where there is not enough air and combustion cannot occur (De Nevers, 2000). Therefore, every fuel has an optimal stoichiometric air to fuel ratio and a flammability range between the LFL and the UFL. These limits are to be considered when mixing fuel and oxidizer depending of the flame being produced. When mixing occurs only at the burner, it generates a diffusion flame. The required oxygen diffuses through the outer surface of the flame to react with the incoming fuel. This generates a large flame with peak temperatures around 1090°C depending of the fuel (De Nevers, 2000). With premixed flames, the fuel and oxidizer are completely or partly mixed before ignition in the combustion chamber. In these conditions, combustion is much faster resulting in smaller and much hotter blue flames, also referred as non-luminous flames, reaching up to 2200°C (De Nevers, 2000). It is important that the premix gases be injected to the burner at a velocity higher or equal to the flame speed, otherwise flashback will occur. Flashback happens when the flame propagates faster than the air-fuel injection velocity. The flashback potency of a mixture depends on the fuel composition (Dam et al., 2011). For instance, syngas with high H_2 content can increase flashback potency by increasing flame speed. Even a small amount of H_2 increases the risks of flashback since it alters the kinetics and the thermo-physical properties of the gas mixture (Dam et al., 2011). Air-fuel mixture preheating is generally not recommended since it promotes flashback (Littlejohn et al., 2007).

With a homogeneous mixture of air fuel, most of the fuel is burned and converted to H_2O and CO_2. However, when air and fuel are not pre-mixed, a diffusion flame is produced which generally leaves some carbon particles unburnt and soot is formed. These small carbon particles glow due to the flame temperature and give the yellow-orange colour of the flame. Soot can then deposit in chimney walls or equipment as soot, thus increasing maintenance (De Nevers, 2000). Therefore, premix or partly premix flames would be most applicable for CO_2 enrichment.

The mass of O_2 needed per kg of fuel is calculated based on (Van Loo and Koppejan, 2008):

$$m_{O_2}\left[\frac{\text{kg } O_2}{\text{kg fuel}}\right] = X_C\frac{M_{O_2}}{M_C} + \frac{X_H}{4}\frac{M_{O_2}}{M_H} + X_S\frac{M_{O_2}}{M_S} - X_O \tag{3}$$

where

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

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

The mass fraction of oxygen subtracted in the previous equation refers to the amount present in the biomass. The stoichiometric air to fuel ratio ($(A/F)_{stoich}$) is the theoretical mass of air required for complete combustion of a unit of mass of a fuel (Basu, 2010). The $(A/F)_{stoich}$ is then computed as follows (Van Loo and Koppejan, 2008):

$$(A/F)_{stoich}\left[\frac{\text{kg air}}{\text{kg fuel}}\right] = m_{O_2} + m_{N_2} = m_{O_2} + m_{O_2}\frac{Y_{N_2}}{Y_{O_2}}\frac{M_{N_2}}{M_{O_2}} \tag{4}$$

where

Y_j [%] : volume fraction of compound j in air (O_2 or N_2)

The equivalence ratio (ER) determines the actual oxygen to fuel ratio relative to the stoichiometric oxygen to fuel requirements (Equation 5).

$$\mathrm{ER} = {(A/F)_{\mathrm{actual}}} \Big/ {(A/F)_{\mathrm{stoich}}} \tag{5}$$

Typical equivalence ratio for gasification is when the $\mathrm{ER} = 0.25$, while combustion would be generally specified by an $\mathrm{ER} \geq 1$ and pyrolysis, by an $\mathrm{ER} \cong 0$ (Reed et al., 1988). Therefore, combustion of syngas is expected to have an ER of 1 or higher. Values greater than one indicates that excess air is mixed with the fuel (lean mixture). It must be noted that some authors use fuel to air ratios (F/A) rather than air to fuel (A/F) (Littlejohn et al., 2010). The F/A ratio influences the definition of equivalence ratio, which gives reversed values to the ones previously stated. For this research, ER is defined according to Equation 5, which implies that a lean mixture is indicated by $\mathrm{ER} > 1$ and a rich mixture, by $\mathrm{ER} < 1$.

The maximal quantity of flue gas CO_2 which could be used for enrichment can be estimated according to the carbon content of the syngas. Assuming complete combustion of the fuel, the mass of emitted CO_2 per kg of dry fuel is:

$$m_{CO_2}\left[\frac{\mathrm{kg\ CO_2}}{\mathrm{kg\ fuel}}\right] = \left(X_C \frac{M_{CO_2}}{M_C}\right) \tag{6}$$

By knowing the syngas consumption rate, $\dot{m}_{\mathrm{syngas}}$ in kg/hr, one can estimate the CO_2 output useable for enrichment and compare with other enrichment systems.

$$\dot{m}_{CO_2}\left[\frac{\mathrm{kg\ CO_2}}{\mathrm{hr}}\right] = m_{CO_2} \cdot \dot{m}_{\mathrm{syngas}} \tag{7}$$

Additionally, the potential greenhouse surface area that can be enriched with the gasifier is found using the recommended CO_2 injection rate of 5.6 $\mathrm{g/(m^2 \cdot hr)}$.

$$A\,[\mathrm{m^2}] = {\dot{m}_{CO_2}} \Big/ {\frac{0.0056\mathrm{kg\ CO_2}}{\mathrm{m^2 \cdot hr}}} \tag{8}$$

4.2.3 By-products of combustion

Carbon monoxide is a chemical asphyxiant that prevents oxygen transport in the blood and can become poisonous when inhaled in large quantities (ASHRAE, 2009). Post-combustion CO emissions are due to insufficient levels of hydrocarbons oxidation, low temperatures and short residence time (Van Loo and Koppejan, 2008). Equivalence ratios between 1 and 2 produce the lowest CO emissions for general biomass boilers with temperatures over 1000°C (Van Loo and Koppejan, 2008). Higher ER might reduce the combustion temperature and increase CO concentrations. Syngas with high CO and H_2 content usually have wider flammability limits than common fossil fuels (Whitty et al., 2008). Wider flammability limits for an air-fuel mixture implies that the mixture can burn under richer and leaner conditions than it could when, for example, the fuel had less H_2. A wider flammability limit for an air-fuel mixture helps in reducing the risks of combustion blow off, even with an unsteady flow of syngas or with a poor air-fuel mixing. The extended operation range reduces the probability of syngas combustion emitting CO. However, syngas with high H_2 content can also increase the risks of flashback (Dam et al., 2011).

Nitrogen oxides, mainly NO and NO_2, are formed by three different mechanisms: fuel NO_x, thermal NO_x and prompt NO_x (Van Loo and Koppejan, 2008). Fuel NO_x occurs from the oxidation of nitrogen containing compounds such as NH_3 or HCN produced during the gasification process (Whitty et al., 2008). These can be controlled using air staging or two-stage combustion. The staging limits O_2 contact with nitrogen compounds by limiting initial mixing at the combustion zone and further injecting downstream (Whitty et al., 2008). Thermal NO_x are emitted following the reaction of N_2 with oxygen radicals at temperatures above 1300°C (Van Loo and Koppejan, 2008). This reaction is the most prominent NO_x formation mechanism and it increases in concentration as temperature, O_2 concentration and residence time increase. It has also been observed that thermal NO_x are less influenced by syngas composition (Whitty et al., 2008). Peak flame temperatures can be reduced by means of flue gas recirculation or water injection in the combustion zone (Whitty et al., 2008). In fuel rich conditions, prompt NO_x occurs when N_2 reacts with active hydrocarbons, CH, to form HCN later generating fuel NO_x (Van Loo and Koppejan, 2008). This implies that syngas with higher CH_4 content increases prompt NO, but thermal NO is still the dominant reaction (Whitty et al., 2008). Since the temperature of combustion can impact the level of emissions, a compromise between 1000°C and 1300°C is usually recommended to reduce both CO and NO_x emissions. In terms of health impacts, nitric oxide (NO) inhalation interferes with O_2 transport at the cellular level and nitrogen dioxide (NO_2) can cause lung damage (ASHRAE, 2009). Both gases can cause stresses to plants and reduce photosynthesis significantly at levels above 0.25 ppm depending on the crop (Hanan, 1998).

Sulphur dioxide compounds are emitted only if sulphur is present in the fuel and if it is properly oxidized. Sulphur is found between 0.01 to 2% in biomass fuels (Reed et al., 1988), thus the resulting SO_x emissions are generally considered minor combustion products and around 40% of the fuel sulphur remains in the ashes (Van Loo and Koppejan, 2008). SO_x consist mostly of SO_2 and a small fraction of SO_3, which is usually negligible (De Nevers, 2000). Incomplete combustion of fuel sulphur forms H_2S (Van Loo and Koppejan, 2008). SO_x emissions can be reduced by removing sulphur from the fuel, by limestone injection or by post-combustion treatments (Van Loo and Koppejan, 2008; Whitty et al., 2008). If found in a greenhouse, SO_2 is a lung irritant for humans while it is phytotoxic for plants (Hicklenton, 1988; ASHRAE, 2009).

Hydrogen chloride (HCl) is a compound that is emitted only if chlorine is found in the fuel in a similar manner as with sulphur. Wood usually contains very low amounts of Cl, while it can be found in higher concentrations in grasses such as miscanthus, switchgrass and straw (Van Loo and Koppejan, 2008). HCl emissions can be prevented by fuel washing or with post-combustion measures.

Incomplete combustion and improper air-fuel mixing will generate volatile organic compounds. Other heavier organic compounds include PAH and fine particulates. While fine particulates can be inorganic compounds from the solid fuel, they can also be heavy hydrocarbons which condense to form tars or unburnt carbon species creating soot (Van Loo and Koppejan, 2008). Emissions of these organic compounds depend mostly on the design and the operation of the burner, rather than the syngas composition (Whitty et al., 2008). They can be reduced effectively with a proper combustion temperature, residence time and oxygen mixing (Van Loo and Koppejan, 2008). Moreover, gaseous fuels have lower risks of producing VOCs than liquid fuels (Whitty et al., 2008), and in general, close-coupled biomass gasifier burner systems are cleaner than direct combustion systems (Reed et al., 1988). Gasification is generally regarded to offer cleaner emissions due to its higher controllability (Quaak et al., 1999).

4.2.4 Syngas Burners

Formation of pollutants indicates that successful CO_2 enrichment from a biomass gasifier resides mostly on the design of the syngas burner. 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; Wood et al., 2009). Many of those have been evaluating combustion of syngas with different gas composition (Whitty et al., 2008). Others have looked at syngas from coal gasification (Littlejohn et al., 2007). In general, there is a need for burners adaptable to gases with varying compositions to cope with the increase interest towards alternative fuels such as syngas, biogas and biodiesel (Littlejohn et al., 2007).

Typically, raw syngas used for heat and power is burned directly in a furnace or a boiler. 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). The main factors contributing to complete combustion of a gas are residence time, temperature and turbulence (Reed et al., 1988). 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 et al., 1988).

A degree of air and fuel premixing is required to achieve hotter and non-luminous flames, which prevent soot production and help to achieve near complete combustion. For instance, general gas appliances work with partly pre-mix flames with around 25% of the stoichiometric air requirement (De Nevers, 2000). In that case, once the rich pre-mix mixture is ignited at the stove's burner, it reaches the surrounding air which completes the fuel combustion. Using a partly pre-mix mixture contributes to efficient combustion while preventing flashback by remaining over the UEL. Alternatively, many internal combustion engines or turbines work with leaner pre-mix mixture, which helps in reducing NO_x formation downstream and achieving near complete combustion (Biagioli, 2006).

Injectors or ejectors can ease the task of entraining gas flow. For most of those devices, a fluid jet creates a vacuum pulling gas from another stream to allow them to mix downstream without a pump. The fluids continue to mix in a passage of constant cross-sectional area, which then increases to let them diffuse in the actual burner combustion chamber (Lawn, 2003). This type of venturi mixer can then be connected to various types of burners.

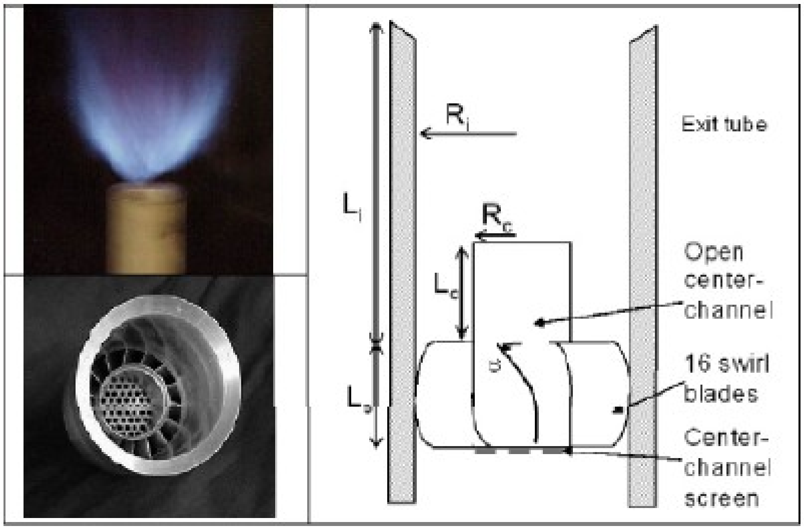

Figure 4.2 – Photographs and cross-sectional view of the low swirl combustor (Littlejohn et al., 2007)

The Low Swirl Injector presented in Figure 4.2 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 design consists of an "aerodynamic flame stabilization mechanism that utilizes a diverging flow to allow a premixed turbulent flame to freely propagate" (Littlejohn et al., 2007). This burner is adapted for lean premixed combustion where the ER suggested is around 0.6 according to a fuel to air definition of ER, which corresponds to ER = 1.67 from Equation 5 (Kang et al., 2007). The air-fuel lean mixture is injected through two passages (Figure 4.2).

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. The divergence created by the two passages 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 would increase residence time and promote thermal NO_x formation (Littlejohn et al., 2010). Appropriate selection of swirl number, vane angles, radii ratios and exit tube length have been thoroughly studied by Littlejohn et al. (2007). Since flashback is a main concern for burners, they have observed that flashbacks are prevented by reducing the swirl number or increasing the operating velocity. This burner has 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).

A common approach to reduce CO or NO_x emissions in burner design is through the addition of a catalyst. A catalytic mesh combustor was tested by Li et al. (2009) to reduce CO emissions. A wide range of catalysts have been studied in the past for syngas and biogas combustion including magnesium, platinum and hexaluminate based materials. Most of these researches observed that, compared to conventional hydrocarbons, H_2 from syngas combusted very close to the catalyst, while CO and CH_4 burned further away from the mesh. The early ignition of H_2 led to premature sintering of the catalyst due to the local high combustion temperatures (Li et al., 2009). The suggested design by Li et al. (2009) used two wire-meshes in series, separated by a given distance. The double-layer wire-mesh catalyst with a blockage ratio of 48% provided high mass and heat transfer and a low pressure drop. Using various syngas composition, this catalyst configuration 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).

Porous burners have been studied for the lean premixed combustion of fuels of varying composition and lower heat content, such as syngas (Alavandi and Agrawal, 2008; Wood and Harris, 2008). Working under lean pre-mixed condition reduces emissions significantly but a lean mixture with varying composition is more at risk of reaching its lower flammability limit (LFL), also referred as lean blow-off limit, when too much air is mixed with the fuel. When a mixture reaches its LFL, it becomes too lean to burn, which can increase CO emissions or stop combustion completely (Alavandi and Agrawal, 2008). The design consists of filling a cylindrical burner with a porous bed of refractory material, ceramics or high temperature metal alloys (Wood et al., 2009). The porous material is usually in the form of pellets, spheres, lamella structure or saddles depending on the desired pressure drop (Wood et al., 2009). The porous solid helps in transferring the combustion heat to pre-heat the incoming lean air-fuel mixture. This preheating decreases the LFL of the mixture, thus allowing the burner to function under even leaner conditions (Wood et al., 2009). Additionally, this thermal mass increases the combustion velocity and allows higher volumes of gas to be consumed. Wood et al. (2009) demonstrated that a porous burner could operate with a natural gas mixture of 1.1 vol% while the conventional lean limit is 4.3 vol%. A porous burner maintains stability with various flow rates and reduces emissions of CO, NO_x and unburnt hydrocarbons (UHC) (Wood et al., 2009).

In summary, biomass gasification coupled with syngas combustion has the potential to provide a clean and an easy to control mean to provide CO_2 for enrichment in greenhouses using a renewable fuel. To be equivalent to natural gas or propane CO_2 enrichment burners, syngas combustion should be freed of post-combustion exhaust gas cleaning as much as possible. Near complete combustion of syngas is necessary and can potentially be achieved through adequate burner design. The gasifier operation can also influence the burner design since it affects the syngas composition, and thus, the relative extent at which the various exhaust gas compounds will be emitted. Therefore, in order to select an appropriate burner design, this research aims at identifying which important exhaust gas compounds are emitted and at which concentration range when a small scale downdraft gasifier is operated at the manufacturer's optimal conditions.

4.3 Materials and Methods

4.3.1 Experimental Setup

A downdraft gasifier was selected to produce the required syngas (Figure 1.1). The Gasifier Experimental Kit (GEK) developed by All Power Labs (Berkeley, CA, USA) is based on the Imbert design, which has proven reliable at producing syngas with low tars content (Reed et al., 1988; All Power Labs, 2010). This gasifier was selected for its affordability and flexibility in terms of potential modifications, instrumentation and uses, promoted by the open source philosophy of their developers, All Power Labs. The reactor dimensions are shown in Figure 4.3. The GEK 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 (Figure 4.4). The setup facilitated the flue gas flow of syngas combustion to be directed into the furnace chimney, where representative exhaust gas measurement were taken. The setup allowed for future heat recovery using the furnace air-to-air heat exchanger.

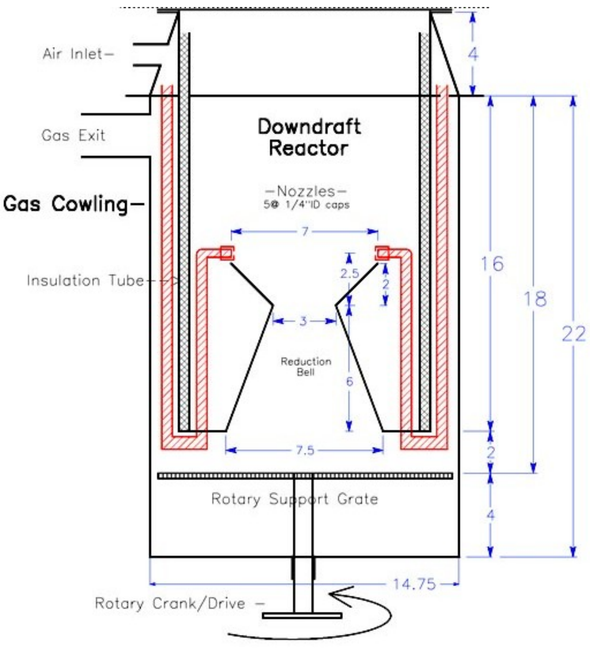

Figure 4.3 – Schematic and dimensions (provided in inches) of the downdraft gasifier reactor (courtesy of All Power Labs)

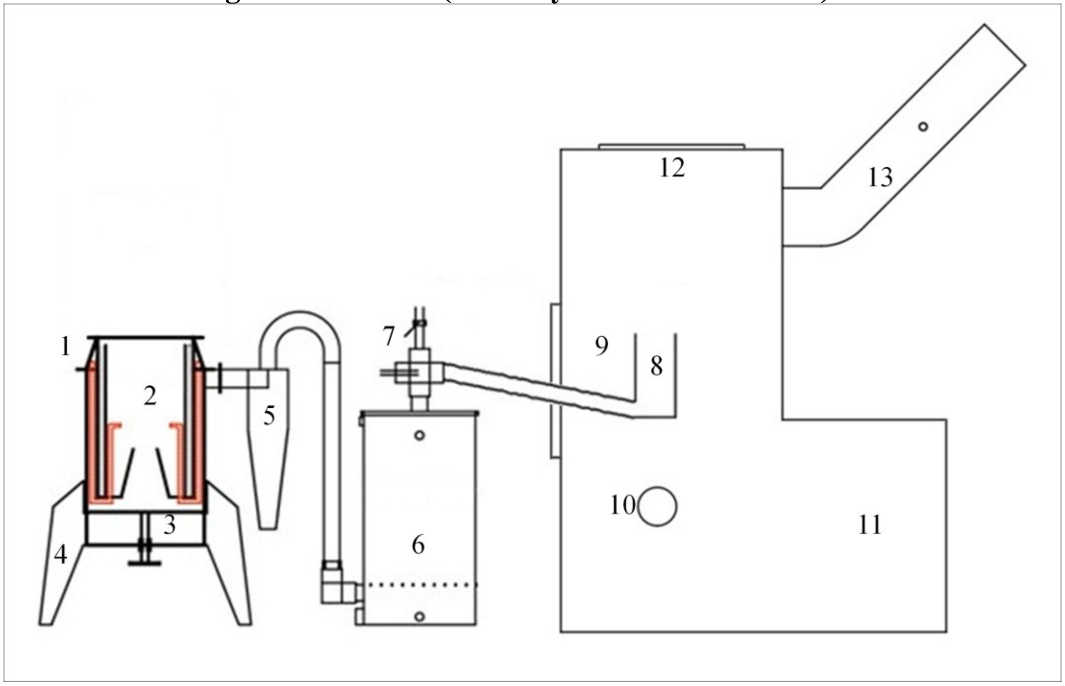

Figure 4.4 – Schematic of the gasifier coupled with the forced-air furnace. Compounds include: 1. three ports: Ignition, Air inlet, Instrumentation – 2. Reactor – 3. Ash grate – 4. Support legs – 5. Cyclone – 6. Packed bed filter – 7. Ejector venturi – 8. Swirl burner – 9. Furnace combustion chamber – 10. Furnace fuel inlet for direct combustion only – 11. Furnace blower for heat exchanger – 12. Air-air heat exchanger – 13. Chimney (GEK schematic courtesy of All Power Labs)

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 capacity of 19.4 m^3/hr at 275 kPa and 15.3 m^3/hr at 620 kPa (All Power Labs recommendations were 10-14 m^3/hr at about 620-830 kPa). A needle valve, connected before the ejector, allowed to manually control the compressed air flow and therefore to operate the gasifier under negative pressure. Two water filled U-tube manometers served as a direct visual output of the gasifier operating pressure conditions. One was connected to the bottom of the reactor core (P_core) and the second, at the top of the packed-bed filter (P_filter). All Power Labs previous experiences helped to identify the optimal vacuum condition for P_core to obtain an ideal core temperature over 850°C along with corresponding air intake flow rates when using wood pellets (Table 4.3). They produced the following empirical relationship, which was only valid for the GEK using wood pellets (All Power Labs, 2010):

$$Q_{\text{air in}}\left[\frac{m^3}{hr}\right]=2.4207\cdot(\text{Vacuum Pressure}[\text{inH}_2\text{O}])^{0.5227} \tag{9}$$

Table 4.3 - GEK performance according to vacuum pressures from manufacturer recommendations (All Power Labs, 2010)

Vacuum Pressure (inH_2O)	Vacuum Pressure (kPa)	Air Intake Flow rate (m^3/hr)	Performance Condition
10	2.49	8.1	Over pull
8	1.99	7.2	Maximum
6	1.49	6.2	Good
5	1.25	5.6	Ideal
4	1.00	5.0	Good
2	0.50	3.5	OK
1	0.25	2.4	Minimum
0 - 1	0 – 0.25		Under pull

The syngas mass flow rate was estimated by adding the air intake mass flow (extrapolated from Table 4.3 and using ρ_{air} = 1.205 kg/m^3) with the volatile fraction of the biomass consumption rate (estimated at 80%).

$$\dot{m}_{\text{syngas}}\left[\frac{\text{kg syngas}}{\text{hr}}\right]=Q_{\text{air in}}\left[\frac{m^3}{hr}\right]\cdot\rho_{\text{air}}+80\%\cdot\dot{m}_{\text{biomass}}\left[\frac{kg}{hr}\right] \tag{10}$$

The first gas conditioning system was a cyclone attached directly to the exit of the reactor, which helped to collect particles and tars droplets. Cyclones are usually recognised to catch particle size as small as 5 µm at up to 80% efficiency (Van Loo and Koppejan, 2008). Next to the cyclone was a standard 61 L (16 US gal) drum, which acted as a packed bed type filter. The drum was filled with standard barbecue charcoal of various sizes going from larger (1-2 cm) to finer (sawdust grain size), upward along the height of the bin. Research has shown that a 15 cm deep container packed with material of 1.3 cm can capture 50% of 2.5 µm droplets from a gas depending of its velocity (Reed et al., 1988). Compared to these dimensions, All Power Labs increased the packed bed filter to accommodate an available standard drum size (61 L), thus offering a conservative collection performance.

The ejector venturi premixed the syngas with air controlled from the primary needle valve (Figure 4.5). 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 (Figure 4.5). 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.

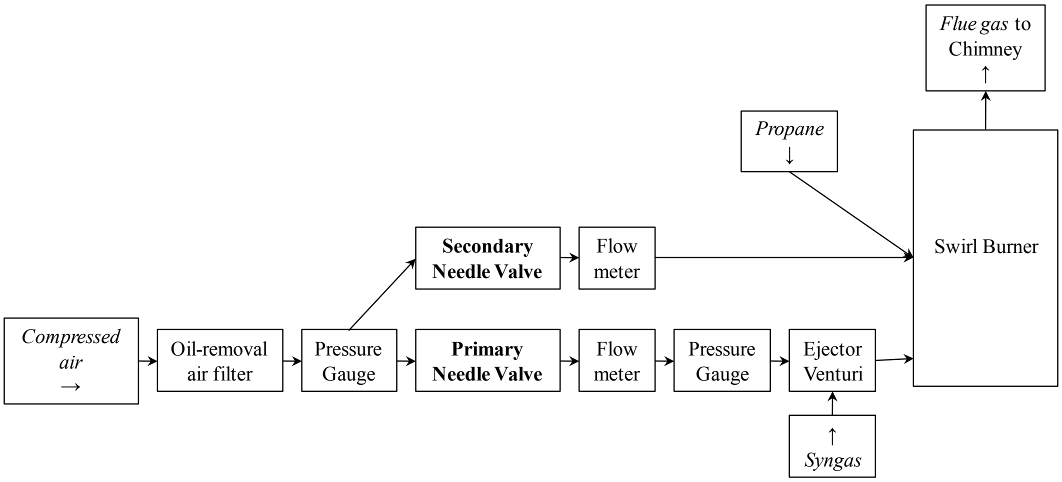

Figure 4.5 – Flow diagram of the swirl burner with ejector venturi and instrumentation

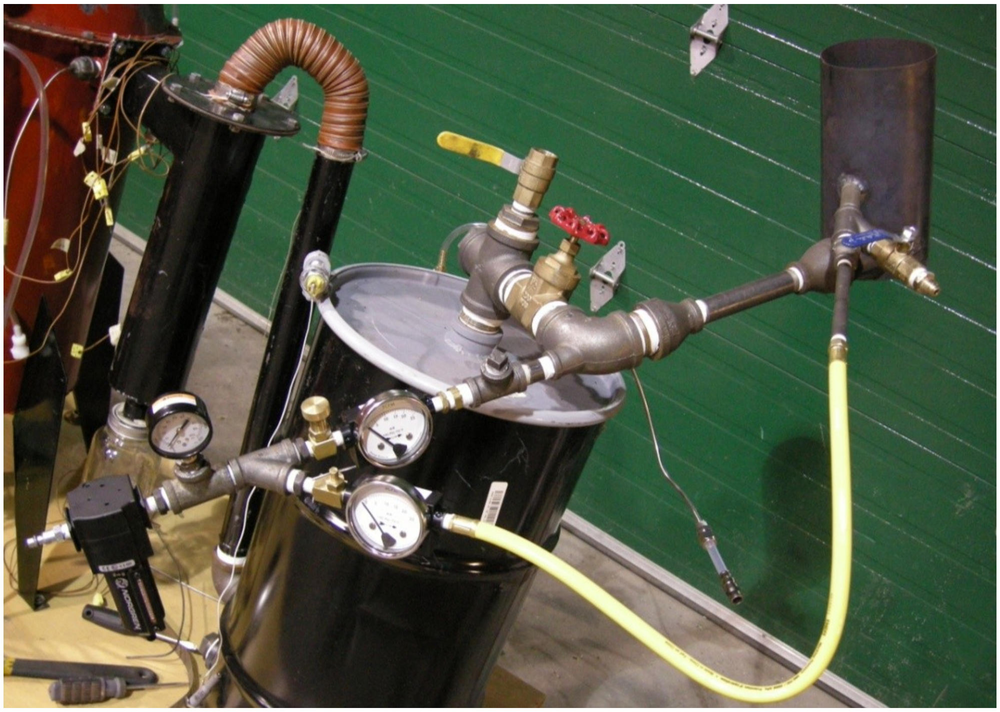

Figure 4.6 – Photograph of the swirl burner with ejector venturi and instrumentation

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 (Figure 4.6). The syngas sampling line was made of two glass impingers connected in series and sitting in ice buckets (Figure 4.7). 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.

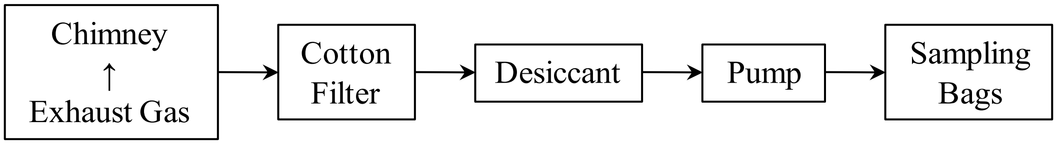

Figure 4.7 – Sampling train configuration for exhaust gas

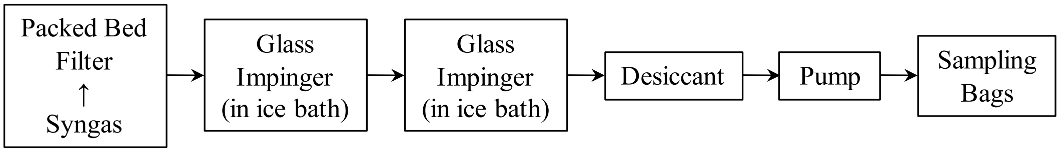

Figure 4.8 - Sampling train configuration for syngas

4.3.2 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 was recorded in real time in a Toughbook laptop (CF-29, Panasonic, Kadoma, Osaka, Japan). An array of chromel-alumel (type K) sheathed thermocouples was installed at strategic locations on the gasifier and connected to the GCU (Table 4.4 and Figure 4.8). The 11 thermocouples were calibrated, in boiling water (100°C) and an iced bath (0°C), three times during the project (drift was less than 1%).

Table 4.4 – Nomenclature and description for thermocouples and for temperature sensors of the portable analyzer

Nomenclature	Description
(T1) T_core	Reduction zone at the reactor core (150 mm from the bottom of the reduction bell, seen in Figure 4.3)
(T2) T_combustion	Combustion zone (220 mm from bottom of reduction bell)
(T3) T_1	First intermediate point between reactor core and top (300 mm from bottom of reduction bell)
(T4) T_2	Second intermediate point between reactor core and top (400 mm from bottom of reduction bell)
(T5) T_top	Top of the reactor (480 mm from bottom of reduction bell)
(T6) T_bottom	Below the reduction zone
(T7) T_cyclone	Exit of the reactor before the cyclone
(T8) T_syngas	Top of the packed bed filter beside syngas sampling port
(T9) T_flame	Temperature of the burner material
(T10) T_ambient	Ambient temperature
(T11) T_flame2	Temperature in the flame
(T12) T_amb	Portable Analyzer ambient temperature measurements
(T13) T_stack	Portable Analyzer exhaust gas temperature

Four ports were installed on the gasifier to measure pressure, additional to the U-tube water manometer. Tubes of 6.35 mm inner diameter connected the pressure ports to the differential gauge pressure transducer of the GCU.

Table 4.5 - Nomenclature and description for pressure sensors

Nomenclature	Description
(P1) P_comb	Combustion zone
(P2) P_top	Top of the reactor
(P3) P_filter	Top of the packed bed filter
(P4) P_bottom	Below the reduction zone

A scale was used to weigh wood pellets before every filling. Compressed air injection was monitored with two pressure gauges of 700 kPa and two versa-mount dial-indicating flow meters of up to 42.5 m^3/hr (Figure 4.5). A first pressure gauge monitored the incoming air from the compressor before the needle valves. Between the primary control needle valve and ejector venturi were installed a flow meter and a second pressure gauge. 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 CO, O_2, NO, NO_2 and SO_2 and to give calculated estimates of CO_2 and NO_x. The analyzer provided additional values for ambient temperatures and stack temperatures. The syngas sampling port was positioned at the top of the drum filter (point (B), Figure 4.8), before the ejector venturi, while the exhaust gas sampling port was connected through the chimney (point (A), Figure 4.8).

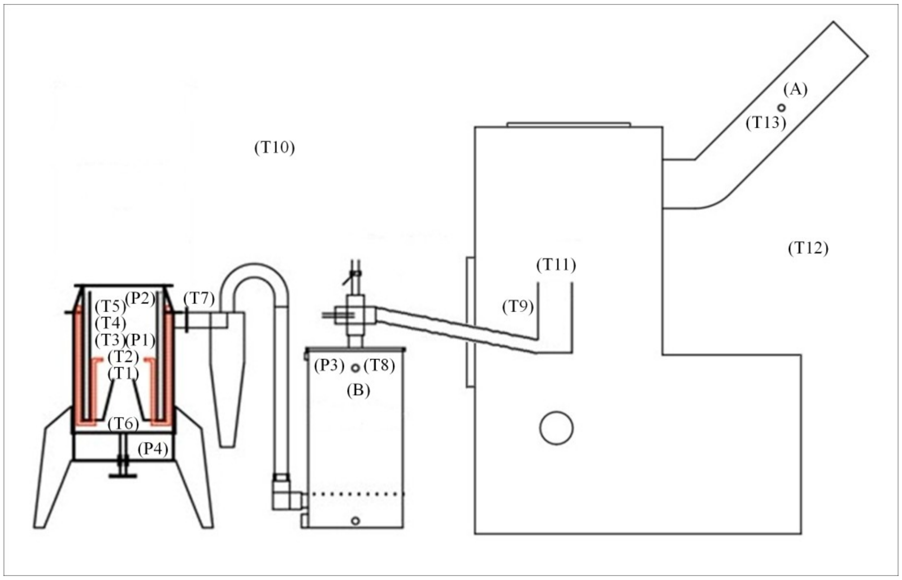

Figure 4.9 – Instrumentation schematic of the gasifier coupled with the forced-air furnace ((P1) to (P3): pressure sensors – (T1) to (T13) temperature sensors - (A): Exhaust gas sampling port – (B): Syngas sampling port)

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 calibration gas mixture from Praxair, Inc. (Danbury, CT, USA). The GC was linked to the PeakSimple (version 3.56) 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 a 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.

4.4.3 Feedstock

Premium quality wood pellets were supplied by Energex Pellet Fuel Inc. (Lac-Mégantic, QC, Canada). They were fabricated from 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 for the sawdust wood pellets was 7%.

4.3.4 Methodology

For safety reasons, the gasifier, the forced-air furnace and all instruments were operated outdoors. All components were mounted on a skid to ease transport. The gasifier was operated in batches of one hour, permitting time for gas analysis on the same day and cool down of the reactor.

The gasifier operation was repeated according to the following sequence. Excess ash was removed below the grate of the reactor. The inside of the reactor was inspected for bridging or clogging of the char pellets bed at the core that may have occurred during previous runs. 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. The char bed was required to allow for an easier gasifier start-up. The char bed level was the same for every trial. Fresh wood pellets were weighed and poured in the GEK. The top lid was then sealed. The gasifier was inspected thoroughly at every flange and connection to ensure proper sealing. The furnace heat exchanger blower was then switched on. Air from the compressor was allowed in the ejector venturi to create negative pressure (up to 0.25 kPa) and begin air flow within the gasifier. The 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. Before ignition of the gasifier, the temperature and pressure datalogger was activated. 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 and the core temperature (T_core) started rising above 70°C. 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 T_core increased. Once T_core reached the minimal gasification temperature of 700°C (after 4 to 9 min), the propane was disconnected from the swirl burner and P_bottom was adjusted to a vacuum between 1.25 to 1.5 kPa with the ejector venturi needle valve. 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, respectively) to vary the excess air to the burner depending on the trial. The syngas combustion was then self-sustained in the swirl burner.

For every trial, the portable gas 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. (Eighty Four, PA, USA) guidelines (SKCinc., 2010b). Syngas samples were taken at the top of the packed-bed filter. During syngas sampling, the pull from the ejector venturi had to be decreased at a lower vacuum than the one initiated by the sampling pump, otherwise the pump was not strong enough to pull syngas into the sampling bag. Tars and moisture were allowed to condensate 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. Syngas sample bags were also filled according to SKC inc. (SKCinc., 2010a) guidelines. Two fresh air samples were taken for every experiment to provide background gas concentrations, to be used for laboratory gas analysis.

Shut down procedures were initiated when the gasifier started behaving abnormally (small explosions or unsustained syngas combustion) or if T_top increased to 100°C. Following one of these signs, P_bottom vacuum was decreased to 0.25 kPa, the reactor air inlet was sealed, and experiment was terminated. The GEK was then monitored while cooling down. Following the gasification experiment, the gas samples were taken for their respective analyses. Once the analyses were completed, the sample bags were rinsed three times with air filtered through 500 g of desiccant. The sample bags were then fully purged of air to be re-used for a subsequent experiment.

4.3.5 Experimental objectives

The objective of this experiment was to monitor exhaust gas composition after syngas combustion. A downdraft gasifier, operated at steady optimal conditions as suggested by the manufacturer (Table 4.3), supplied the syngas in a burner with varying A/F ratios. To run at optimal conditions, the gasifier vacuum was set manually between 1.25 to 1.5 kPa using the primary needle valve. This implied that the primary needle valve was influencing the gasifier vacuum and was premixing the syngas and the primary air flow before directing them to the swirl burner. Therefore, setting the gasifier vacuum at a steady state was regulating the primary air inlet to the burner at a steady flow. The secondary air inlet served to further vary the excess air coming to the burner. The primary air was varied between equivalence ratios of 1.5 to 2.5, creating a lean mixture. The secondary air inlet increased the total equivalence ratio in the burner up to 4.0 approximately. Each experimental trial was set at a steady equivalence ratio within the range of 1.5 to 4.0. Consequently, the level of exhaust gas emissions was monitored in relation to the excess air in the burner. Exhaust gases concentrations, including O_2, CO, NO, NO_2 and SO_2, were measured by a portable analyzer, which also provided calculated estimates for NO_x and CO_2. Exhaust gas was also sampled using sampling bags to analyze for C_2H_4 content with a GC. Finally, syngas was sampled in sampling bags to determine the level of hydrogen with a mass spectrometer. Exhaust gas analysis with the portable analyzer and with sampling bags were performed for every experiment, while syngas sampling was obtained for three trials.

4.4 Results and Discussion

4.4.1 Gasifier performance

The average duration of the sawdust wood pellet gasification trials using the GEK was 67.1 ± 6.3 min and the average time to gasification was 6.1 ± 1.5 min. The duration of a trial spanned from the ignition in the combustion zone until the sealing of the air inlet. The time to gasification was defined as the period between the ignition in the combustion zone and the reactor core (T_core) reaching the minimum gasification temperature of 700°C. Hence, the difference of these two time periods represented the duration of syngas combustion with an average of 61.0 ± 6.9 min.

The mass spectrometer analysis from syngas sampling yielded 19.2% H_2 (± 0.6%). This value was very close to the average measurement of 18.7% for H_2, used in Chapter 3, provided by the gasifier manufacturer. 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, presented in Table 4.6. The amount of N_2 was estimated as the remaining syngas fraction.

Table 4.6 – 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 4.6, this composition characterized syngas with a higher heating value (HHV) of 6.74 MJ/m^3, a lower heating value (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). The average performance results of the gasifier reactor operating on sawdust wood pellets were compiled in Table 4.7.

Table 4.7 – Average performance results for downdraft gasification of sawdust wood pellets (average ± standard deviation)

Biomass consumption rate	(kg/hr)	7.70	±	0.76
Syngas flow rate	($\mathrm{m^3}$/hr)	13.40	±	0.77
	(kg/hr)	13.51	±	0.77
Production ratio	($\mathrm{m^3_{syngas}/kg_{biomass}}$)	1.74	±	0.11
	($\mathrm{kg_{syngas}/kg_{biomass}}$)	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%

4.4.2 Syngas Combustion

4.4.2.1 Equivalence ratio

Results of syngas and air mass flows into the swirl burner with the corresponding equivalence ratios were compiled for the gasification trials in Table 4.8.

Table 4.8 – Compilation of syngas and air mass flow rates into the GEK swirl burner with respective equivalence ratios

Trial #	Syngas mass flow rate (kg/hr)	Primary air mass flow rate (kg/hr)	Secondary air mass flow rate (kg/hr)	Total air mass flow rate (kg/hr)	Equivalence Ratio
1	13.66	44.98	20.44	65.42	3.04
2	13.42	30.79	10.34	41.13	1.94
3	13.50	44.00	9.99	53.99	2.54
4	13.79	33.88	20.85	54.74	2.52
5	14.81	57.37	10.26	67.63	2.89
6	13.81	46.04	10.46	56.50	2.59
7	12.58	46.04	0.00	46.04	2.32
8	12.13	45.32	20.59	65.91	3.44
9	13.91	45.08	10.24	55.32	2.52
10	13.35	45.36	0.00	45.36	2.16
Avg.	13.51	43.89	11.32	55.20	2.60
SD	0.77	7.22	7.62	9.16	0.44

Air mass flow rates were determined using ideal gas relationship considering the ambient temperature (T_amb) and measurements from dial flow meters and pressure gauges. While the primary air inlet was meant to operate at steady conditions to create a vacuum in the gasifier, the mass flow rate did vary between trials. Adjustments to the primary needle valve were sometimes required to modify the internal vacuum pressure of the gasifier and to keep a core temperature of 850°C. Additionally, the ambient temperature varied between 27.2 and 8.2°C. Hence, variations of pressure and ambient temperature (in absolute values) affected the air density, contributing to these mass flow rate variations.

Syngas mass flow rates were estimated using the combination of Equations 9 and 10. Therefore, the average $\dot{m}_{syngas}$ was 13.5 kg/hr or 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 is 1.58 kg air per kg of syngas, which represents 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, which represents an average A/F of 4.1 and an average ER of 2.6. For the various trials, the total equivalence ratios varied between 1.94 and 3.44 indicating lean combustion. For general combustion applications, it is common to find ER > 1 to ensure complete combustion. However, as ER increases over unity, the adiabatic temperature (maximal flame temperature achieved with complete combustion and no heat exchange) decreases, which can reduce NO_x emissions (Quaak et al., 1999). The average ER of 2.6 fell in the higher limit of the optimal ER range that has been noted to vary between 1.6 and 2.5 according to Quaak et al. (1999). Since a very high ER lowers the adiabatic flame temperature, it can 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.

4.4.2.2 Estimation of exhaust gas composition

The exhaust gas composition was first estimated theoretically before comparing with the analyzer measurements.

$$\dot{m}_{\text{flue gas}}\left[\frac{\text{kg flue gas}}{\text{hr}}\right] = \dot{m}_{\text{air in}}\left[\frac{\text{kg}}{\text{hr}}\right] + \dot{m}_{\text{syngas}}\left[\frac{\text{kg}}{\text{hr}}\right] \tag{11}$$

Using an experimental average $\dot{m}_{\text{air in}}$ of 55.20 kg/hr (dry basis) along with the previous $\dot{m}_{\text{syngas}}$ of 13.51 kg/hr, we obtained $\dot{m}_{\text{flue gas}}$ = 68.71 kg/hr. Assuming complete combustion, the flue gas compounds mass fractions, X_{CO_2} , X_{H_2O} , and X_{N_2} were obtained by the following equation:

$$X_j\left[\frac{\text{kg of j}}{\text{kg flue gas}}\right] = \left(X_{\text{air}}\left[\frac{\text{kg air}}{\text{kg flue gas}}\right]\cdot X_i\left[\frac{\text{kg of i}}{\text{kg air}}\right] + X_{\text{syngas}}\left[\frac{\text{kg syngas}}{\text{kg flue gas}}\right]\cdot X_i\left[\frac{\text{kg of i}}{\text{kg syngas}}\right]\right)\cdot\frac{M_j}{M_i} \tag{12}$$

Where j was for compounds CO_2, H_2O and N_2 and i stood for elements C, H, and N. The flue gas X_{O_2} was obtained similarly but with subtraction of O_2 fraction found in CO_2 and H_2O. The volumetric flue gas fractions were obtained with Equation 13 (Van Loo and Koppejan, 2008).

$$Y_j = \frac{X_j}{M_j}\Big/\sum_i\frac{X_j}{M_j}\ , \quad \text{where } \sum_i\frac{X_j}{M_j} = \frac{X_{CO_2}}{M_{CO_2}} + \frac{X_{H_2O}}{M_{H_2O}} + \frac{X_{O_2}}{M_{O_2}} + \frac{X_{N_2}}{M_{N_2}} \tag{13}$$

As such, the volumetric flue gas composition was estimated to be 8.67% CO_2, 6.50% H_2O, 8.38% O_2 and 76.45% N_2. From the ideal gas law, the density of the flue gas was determined to be 0.39 kg/m^3 at the average measured flue gas temperature of T_stack = 631.6°C and absolute atmospheric pressure. With this density and the cross-sectional area of the chimney (15.24 cm diameter), the estimated flue gas velocity was 2.67 m/s.

$$\dot{m}_{CO_2} = X_{CO_2}\left[\frac{\text{kg of } CO_2}{\text{kg flue gas}}\right]\cdot\dot{m}_{\text{flue gas}}\left[\frac{\text{kg flue gas}}{\text{hr}}\right] \tag{14}$$

Using Equation 14, a CO_2 production rate of 8.67 kg/hr was estimated. At this rate, syngas produced from the GEK could enrich the atmosphere of a 1548 m^2 greenhouse (Equation 8).

4.4.2.3 Exhaust gas measurements

Following the experiments, flue gas composition, as measured with the portable analyzer, was summarized in Table 4.9.

Table 4.9 – Compilation of important flue gas compounds from syngas combustion following sawdust wood pellets gasification

Trial #	CO (ppm)	NO_x (ppm)	O_2 (%)	CO_2 (%)
1	14.7	24.8	0.2	7.0
2		Outlier		
3	11.6	22.6	0.2	8.6
4	8.1	23.1	0.2	7.7
5	4.7	27.3	0.2	13.0
6	5.2	20.8	0.2	9.2
7	16.4	20.4	0.2	8.9
8	4.4	25.3	0.2	9.2
9	4.9	27.8	0.1	7.8
10	8.8	20.8	0.2	8.3
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

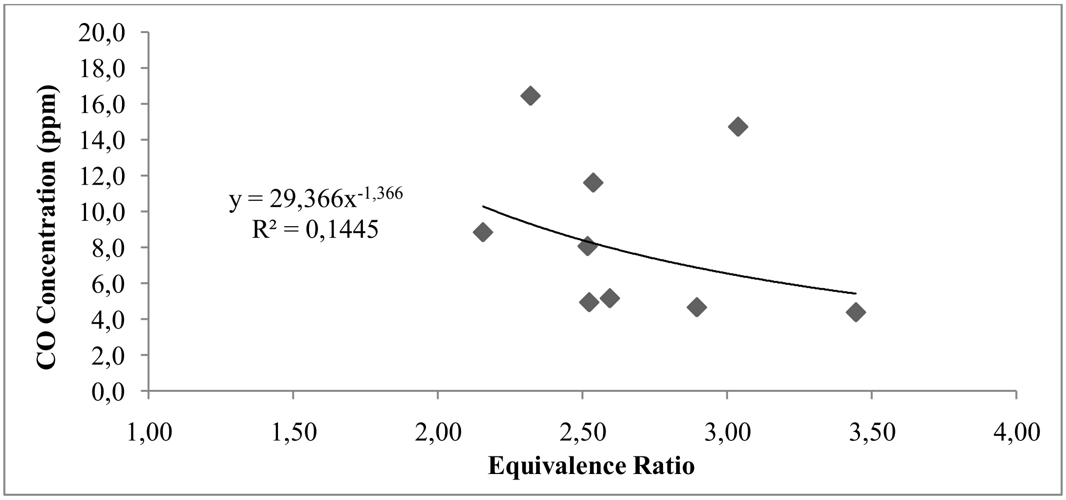

Figure 4.10 – Effects of equivalence ratio on CO emissions from syngas combustion

4.4.2.4 Carbon monoxide

The emitted concentrations of CO, with an average of 8.8 ± 4.6 ppm, were quite close to the ASHRAE standards requirements of 11 ppm (Table 4.2). From Table 4.9, about 60% of the trials maintained an average CO concentration below the ASHREA standard of 11 ppm, and 90% of the trials had CO concentrations below 20 ppm. The highest peak and average CO concentrations measured were observed during trial #2, with 102 and 80.6 ppm respectively. This trial was considered an outlier since the concentrations were unexpectedly high at the given experimental conditions, which, when reproduced, did not achieved such high concentrations. Figure 4.10 displayed the burner performance in terms of CO emissions. The scattered points did not show an actual trend, 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 seem to affect 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. This observation would be also valid for ER, since the equivalence ratio is defined as the ratio between actual and stoichiometric A/F. A wider range of ER for future experimental trials would likely display similar observations. This CO emission performance was thus considered specific to the particular burner used in these experiments. Additionally, it seemed that increasing the ER over 3.5 with additional excess air would not necessarily decrease the CO emissions and would be considered too high according to Quaak et al. (1999).

Nonetheless, the average results shown in Table 4.9 hinted that it could be possible to avoid post-combustion remediation system for CO. The parameters that should be modified in future experiments, to reduce and maintain CO emissions below ASHRAE standards, would be through burner design improvements. For commercial applications, a CO detector would still be needed as it is usually recommended with CO_2 enrichment systems for worker’s safety (Hanan, 1998).

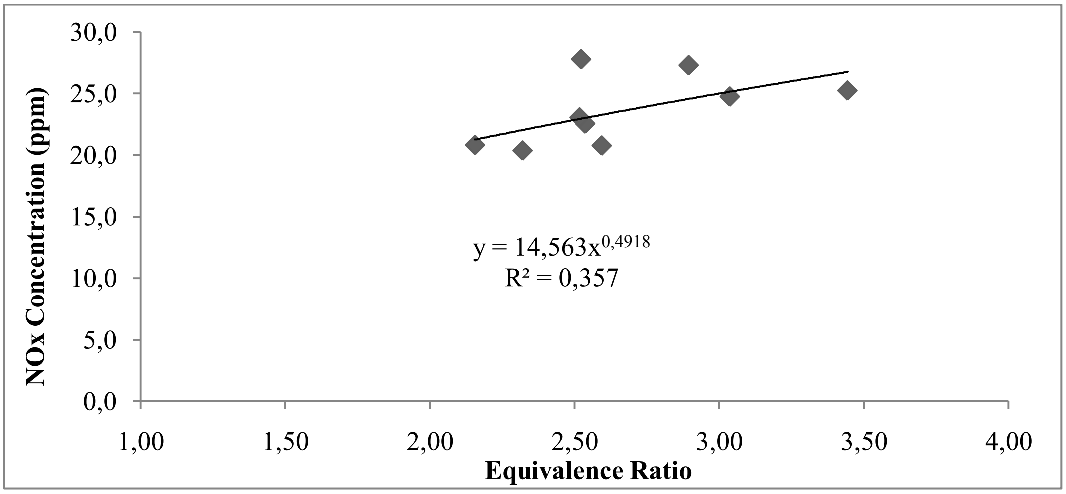

Figure 4.11 - Effects of equivalence ratio on NO_x emissions from syngas combustion

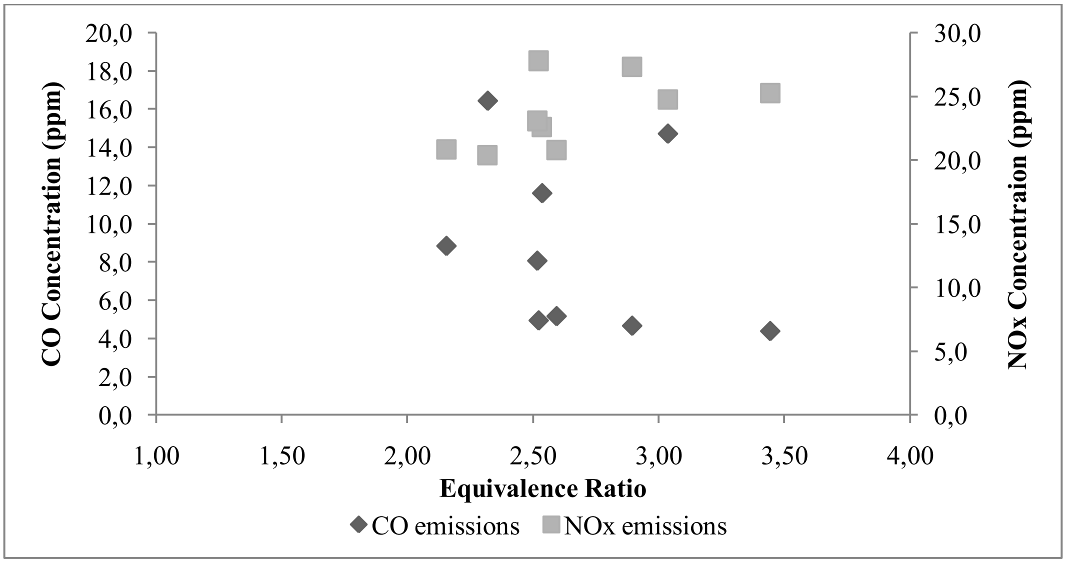

Figure 4.12 – Effects of equivalence ratio variation on both CO and NO_x emissions

4.4.2.5 Nitrogen oxide

The NO_x emissions reached an average of 23.6 ± 2.8 ppm, which was much higher than the ASHRAE standards. Similarly to previous CO emissions, NO_x emissions, displayed in Figure 4.11, 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. Normally, an opposite effect on CO and NO_x concentrations should be observed as a result of increasing excess air, as described by air pollution literature (De Nevers, 2000), but Figure 4.12 did not display such a trend. Additional experimental data points on a wider range of ER values would be needed to validate this observation. Nonetheless, these results indicated that NO_x emissions would be too high for CO_2 enrichment with direct flue gas utilisation. Some NO_x emissions were probably due to the apparent recirculation zone observable in the burner combustion chamber. Recirculation zones typically increase residence time, which promotes thermal NO_x formation (Littlejohn et al., 2007). The average flue gas temperature of 631.6°C in the chimney and the low efficiency of the furnace heat exchanger were also a cause of a higher residence time for flue gases. This meant that high temperatures in the combustion chamber of the furnace, in which syngas combustion took place, were sustained enough to produce more thermal NO_x. From these results, NO_x emissions would need to be controlled and would require a burner design improvement to reach lower NO_x levels.

4.4.2.6 Sulphur dioxide

Considering the trace amount of sulphur in sawdust wood pellets, it was assumed early on that SO_2 emissions were negligible. From the portable analyzer measurements, SO_2 emissions were undetectable or within the error margin of the instrument (± 10 ppm) at its best resolution (1 ppm). For premium quality sawdust wood pellets, SO_2 emissions were therefore insignificant at ppm resolution. 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.

4.4.2.7 Ethylene

Gas chromatography analyses for C_2H_4 emissions were very encouraging. Measurements from flue gas samples showed an average presence of 55 ppb (parts per billion) of C_2H_4, which was very close to the C_2H_4 levels measured from the ambient fresh air samples, at 43 ppb (Table 4.10).

Table 4.10 – Ethylene emissions following combustion of syngas from sawdust wood pellets gasification

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

The difference in C_2H_4 concentrations from flue gas and fresh air samples implied that syngas combustion added a mere 12 ppb in the flue gas. 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. As seen in Table 4.9, 90% of the trials showed CO emissions below 50 ppm. At this point, 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.

4.4.2.8 Oxygen and carbon dioxide

Flue gas O_2 levels were measured at an average of 9.0%, close to the estimated value of 8.4% (Table 4.11) obtained from Equation 13.

Table 4.11 – 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%

The portable analyzer provided calculated concentrations of CO_2, which resulted in an average of 11.9 %, higher than the previously calculated value of 8.7%. 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 had 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, both average values for CO_2 emissions were calculated estimations but should at least dictate the range of CO_2 emissions useable for enrichment.

4.4.3 Recommendations

The exhaust gas measurements indicated the priorities to be taken for future design modifications of the syngas burner to achieve CO_2 enrichment from syngas combustion without the addition of flue gas post-combustion control. The objective of the design improvements would be to aim at reducing NO_x emissions while maintaining the low CO and C_2H_4 emissions. The overall objective of the modifications would be to achieve very low emissions directly at the stack, which would ease flue gas utilization for CO_2 enrichment. With better flue gas quality, the absence of cleanup systems would reduce costs and less air dilution would be required before injecting into the greenhouse atmosphere.

4.4.3.1 Burner modifications

Prior to the experiments presented in this chapter, some burner modifications were attempted. While they were not conclusive and discarded from the burner used during Chapter 3 & 4 experiments, they provided additional recommendations for future burner design improvements.

A steel mesh with around 60% blockage ratio was placed halfway in the burner underneath the secondary air inlet. It was meant to improve air-fuel mixture diffusion and reduce recirculation. However, the combustion would flashback underneath the mesh, 5 to 10 minutes after ignition. Before flashback, the flame remained at the surface of the mesh while the surrounding burner material was heating and glowing red. Without any cooling system, this heat was quickly conducted to the bottom of the burner due to the thermal conductivity of the burner and the mesh material, both made of steel. Consequently, the incoming partly premix gas was then pre-heated and ignited, resulting in a flashback. Following the flashback, the flame stayed underneath the mesh and CO emissions rose considerably. To temporarily resolve the heat conductance problem, an array of copper tubes (12.7 mm diameter) was placed around the exterior of the swirl burner to dissipate some of the heat. It was expected that the heat at the top of the tubes would induce natural convection through the tubes and suck cooler air at the bottom. Still, the tubes only helped in preventing flashbacks for a few more minutes. Moreover, the high temperatures of the burner material prevented the integration of an oxygen sensor to monitor the A/F ratio in real time. These trials pointed out the necessity of replacing the burner material with high temperature metal alloys or refractory materials, which would improve the burner integrity, maintain good flame temperatures and reduce heat conductance leading to the air-fuel mixture pre-heating.

Another trial was made by placing a 38 mm thick bed of alumina spheres (3 mm diameter) as an improvement to the steel mesh, with the intent of these refractory spheres acting as a flame arrestor. For this trial, syngas combustion produced a blue, non-luminous flame with very low emissions, but which lasted less than 10 minutes. Ultimately, the burner material and the copper tubes quickly conducted heat to the bottom of the burner, most likely pre-heating the air-fuel mixture and causing flashback. The pressure drop across the bed might also have been a nuisance. The air-fuel mixture seemed to be injected in the burner with high flow and velocity. The flame cones were emerging mostly on the side of the burner and were stretching for almost 20 cm. The flow could not be reduced since it was controlled by the primary needle valve used to control the gasifier vacuum pressure and maintain proper core temperatures. Littlejohn et al. (2007) had concluded that flashback was not significantly affected by pressure but mostly by gas pre-heating and presence of hydrogen. Consequently, the porous bed seemed to be better suited for much leaner gas mixture, prone to flame blow-off, with lower flow rates that could take advantage of this design and could benefit from pre-heating (Wood and Harris, 2008).

This particular trial illustrated problems due to pressure drops and necessities of flame arrestors. Flashback arrestors are recommended for safety reasons. Refractory type materials with very low heat transfer properties, placed at the entrance of the burner combustion chamber, would help in preventing flames from propagating upstream. A flashback arrestor can also improve the initial air-fuel mixture distribution (Wood et al., 2009). To solve the issues caused by high pressure drops, the alumina spheres could be replaced by small saddles of alumina, which could minimize the pressure drop according to Wood et al. (2009). However, additional maintenance would be needed as some remaining syngas tars would condensate on the flame arrestor, which, in time, would clog the burner inlet.

From the literature, the low-swirl burner from Littlejohn et al. (2010), described in section 4.2.4, would be a very appropriate design to improve the GEK syngas combustion. The burner injector, consisting of swirl blades surrounding a center channel, improves the flame diffusion and stability, while providing a more homogeneous distribution of the air-fuel mixture. This design ensures an optimal air-fuel mixing, which is necessary to achieve near complete combustion and lower CO, VOCs and PAH emissions. It also effectively prevents recirculation zones in the combustion chamber, thus reducing thermal NO_x formation. The burner could be further tested with the operational condition of the GEK to assess its application for CO_2 enrichment.

The double layer mesh catalyser suggested by Li et al. (2009) could be an addition to test in conjunction with the low-swirl burner if NO_x and CO emissions were still an issue. A first layer of catalyser material could replace the center channel screen of the low-swirl burner. The second mesh would be placed downstream to further reduce emissions. With these mesh, thorough attention should be given to the blockage ratio in order to minimize pressure drops.

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. This extended residence time for flue gas is prone to generate thermal NO_x. Therefore, a better heat exchanger would improve heat recovery for use in the greenhouse while potentially reducing NO_x emissions.

From the experimental results, it was calculated that the primary air inlet supplied enough air to pre-mix with the syngas and provide adequate ER between 1.5 and 2.5, which fell in the optimal range mentioned by Quaak et al. (1999). To better compare the currently obtained results with future experiments, the range of ER should therefore be kept between 1.0 and 4.0. Additionally, 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.

4.4.3.2 Instrumentation

Future avenues of research on this topic should assess fine particulate emissions to ensure that they respect ASHRAE standards. This information would further improve the safety of CO_2 enrichment from syngas combustion. Such analysis for exhaust gas is achieved isokinetically, which consists of sampling gas at the same velocity as the source flue gas velocity (Eller et al., 1984; Reed et al., 1988; De Nevers, 2000). Isokinetic sampling is used for particulates larger than 10 µm to ensure representative particle size distribution (Reed et al., 1988).

Emissions of unburnt hydrocarbons (UHC) or VOCs should also be measured and reduced accordingly. Reduction of these compounds seems to be related to the reduction of CO. Indeed, high flame temperature and optimal oxidation of the fuel by pre-mixing air-fuel promotes reduction of both CO and VOC (Van Loo and Koppejan, 2008). It could then be assumed that due to the low concentrations of CO observed in this research project, VOC concentrations were relatively low as well. Still, the orange color of the flame indicated that a certain amount of soot was produced in the flue gas, contributing to UHC emissions. Therefore, future measurements of total VOC, or UHC, emissions along with actual syngas composition would confirm the level from which they should be reduced.

The burner instrumentation would benefit from digital flow meters and pressure gauge to datalog continuously the flows injected to the burner. Digital measurements could monitor real time flow variations and investigate relationships between the behaviour of the gasifier reactor and the syngas combustion. Real time digital measurements could also be integrated in an automated control for the syngas combustion and ensure a steady pre-determined air-fuel mixture flow to the burner dependent on the trial. Exact flow measurements at the chimney and at the air inlet of the gasifier reactor would improve the accuracy of the mass balance analysis. The addition of a complete syngas analysis would improve the accuracy of the syngas mass flow to the burner. Additionally, following the modifications in the burner design with refractory material, preventing air-fuel pre-heating and a stable flame, it should be safer to use an oxygen sensor without the risk of damaging it. Considering that the equivalence ratio for syngas combustion, presented in this research project, consisted of estimations based on literature, these instrumentation improvements would provide better accuracy to ER values.

4.5 Conclusion

The objective of this research project was to monitor the performance of a syngas burner in terms of exhaust gas composition and to identify potential improvements for the burner design. The steel swirl burner was operated with an average equivalence ratio of 2.6, which produced an average CO concentration of 8.8 ppm. About 60% of the trials were below the ASHRAE standards, while 90% were below 20 ppm. The NO_x emissions would need to be reduced in future research, since the average concentration was 23.6 ppm. The SO_x emissions were negligible at ppm levels. The ethylene emissions were also found to be negligible and below the critical concentration of 50 ppb for CO_2 enrichment. The theoretical exhaust gas CO_2 concentrations were below the calculated concentrations obtained from the portable analyzer. This difference indicated that the actual syngas composition could be different than the estimated composition used in the calculations and that the actual CO_2 enrichment potential of GEK gasifier was probably higher.

These results are promising since we were able to reach low concentrations for some important exhaust gas compounds, even before implementing modifications to burner design. These burner improvements would aim at reducing NO_x emissions and further improving the syngas combustion efficiency, by integrating the low swirl design, the use of mesh catalysers, better refractory material and a better heat exchanger. Continuing research on this topic should look at emissions of particulate matter and VOCs. By trying to reach near complete combustion of syngas, we are closer to making CO_2 enrichment from biomass feasible, but we are also contributing in improving biomass gasification technologies as clean and efficient heating systems.

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Chapter 5: General Conclusion

Sustainable development and energy efficiency are important driving forces of current technological innovations. Biomass energy has the advantage of being considered carbon neutral and being a renewable energy source for which the technology is readily available. Greenhouse producers are using biomass heating to reduce the thermal energy costs and the environmental footprint of their operation and could further reduce their greenhouse gas emissions by using the exhaust gas carbon dioxide for enrichment and improving crop yield.

The main goal of this Master thesis project was to identify and explore research avenues for CO_2 enrichment using a biomass heating systems. A review of current literature investigated different aspects of CO_2 enrichment from biomass and the potential research projects surrounding biomass gasification including: syngas combustion, optimisation of biomass heating systems efficiency, optimal CO_2 enrichment management, fertilizer production from wet scrubbers and separation of CO_2 from polymer membranes.

Biomass gasification technology was selected since it offers lower emissions and better control when compared to direct combustion. Gasification is a thermo-chemical reaction, which converts solid biomass into a gaseous fuel, known as syngas. Our research goal was to reach complete combustion of the syngas produced by the gasifier to reduce toxic exhaust gas compounds below safety levels directly at the stack and avoid the use of post-combustion cleaning systems. This research was performed using a downdraft gasifier with several experimental runs to monitor its performance. Wood pellets (hardwood sawdust) were used as the biomass fuel source. Monitoring of temperatures and pressures across the gasifier provided data to allow optimal gasification operations in terms of reactions temperatures, biomass fuel depletion rate, ash grate shaking, micro-explosions detection, char bed packing and pressure drop across the packed bed filter. The gasifier operated with an estimated average equivalence ratio (the actual air to fuel ratio relative to the stoichiometric air to fuel requirement) of

0.17, below the optimal value of 0.25, and achieved a cold gas efficiency of 59%. Results from the experiments showed that the gasifier running with wood pellets, at a rate of 7.7 kg/hr, could provide a maximum of 22.9 kW of thermal energy and could theoretically enrich a maximum of 1540 m^2 of greenhouse surface area. Further analysis indicated that biomass, following combustion or gasification, could provide more CO_2 for greenhouse enrichment than propane or natural gas per unit of energy.

Syngas combustion performance was monitored using a flare combustion system for gaseous emissions including CO, CO_2, NO_x, O_2, SO_2 and C_2H_4. The steel swirl burner was operated with an average equivalence ratio of 2.6, which produced an average CO concentration of 8.8 ppm. About 60% of the trials were below the ASHRAE standards of 11 ppm, while 90% were below 20 ppm. The average concentration of NO_x emissions was 23.6 ppm, much above the ASHRAE standards of 0.05 ppm. The SO_x emissions were below ppm levels, while C_2H_4 emissions were below the critical concentration of 50 ppb for CO_2 enrichment. The theoretical exhaust gas CO_2 concentrations were calculated as part of this thesis and were below the calculated concentrations obtained from the portable gas analyzer. This difference indicated that the actual syngas composition was different than the estimated composition used in the calculations and that the actual CO_2 enrichment potential of the gasifier could have been higher.

Considering that some of the undesirable exhaust gas compounds were kept below safety levels demonstrated that syngas combustion may present a promising renewable alternative for CO_2 enrichment. This research project has achieved the first steps in facilitating CO_2 for greenhouse enrichment from a biomass heating system, while contributing to the general knowledge on biomass gasification and syngas combustion. In preparation for actual tests inside of a greenhouse, future research avenues should look at improving the controls of the gasifier operation, modifying the burner design, comparing performance with other sources of biomass and assessing the exhaust gas for VOC and particulate matter emissions.