McGill University

Greenhouse CO_2 enrichment from biomass combustion.

Final Report Design III

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12

Contents

List of Tables:

List of Figures:

1. Introduction

1.1. Context

Greenhouse carbon dioxide (CO_2) enrichment has long been recognized by biologists and plant physiologists to enhance the growth of plants. Greenhouse producers have used this knowledge to increase their production significantly (by at least 30%) in the last 30 years (Iverson et al. 2008). Due to the unsteady and rising cost of CO_2 enrichment in greenhouses (volatile and rising prices of oil) the focus of this design project is on utilizing the readily available CO_2 from biomass combustion used for heating. In fact, many greenhouse producers in Québec are already equipped with direct combustion biomass furnaces and have at hand this valuable source of CO_2 which is currently being released into the atmosphere (released through the exhaust via chimney). This idea was studied in great detail both mathematically and physically. The physical model and testing was performed on a biomass furnace (SBI Caddy Alterna) in a greenhouse at the Macdonald Market. A pre-established design had been developed in the previous term and this setup was examined and developed further. The physical model is of relatively small size when compared to actual biomass boiler system in the industry however the same principles can be up scaled for various dimensions and is adaptable. The goal of the system is to reduce the toxic compounds such as carbon monoxide (CO), nitric oxide (NO), and sulfur dioxide (SO_2) found in the emissions to allow a safe environment for the plants and workers. The first step in reducing these compounds was the determination of the current baseline concentrations emitted by a typical biomass pellet furnace. Using a Testo analyser, we determined that the compounds were found on average concentrations ten to sixty times higher than what is prescribed by the ASHRAE standards for indoor air quality. The pre-established processes and components that had been selected from the literature the previous term were as follows: internal modifications (Air to Fuel ratio) and external modifications (catalytic converter, dilution, semi-permeable membrane separation). In the following sections all these processes and components will be examined, mathematically analyzed and most will be physically tested in a working system.

1.2 Engineering Problems and Objectives

A breakthrough in utilizing the CO_2 source available from biomass combustion could single handily reshape the greenhouse industry as a whole. It would allow a greater number of producers to make the transition to biomass furnaces due to the increased profitability of the system as a whole. The producers are presently paying hundreds of thousands of dollars a year (dependant on the size of operations) to enrich their greenhouses with CO_2 therefore exploring the utilization of the exhaust gas from direct combustion of biomass is of great interest to the greenhouse industry as a whole. The main objective of the design project was to successfully inject the purified emissions of the furnace into the greenhouse to increase plant yield while maintaining a safe environment for humans. Ultimately, the available CO_2 source is contaminated with toxins and needs to be decontaminated before being injected into the greenhouses. The constraints in terms of air quality that needs to be maintained in the greenhouse are regulated by the American society of heating, refrigerating and air conditioning engineers (ASHRAE 2009). Therefore, the objective of the exhaust cleaning system must meet the ASHRAE standards to ensure the safety and well-being of the users of the greenhouse.

1.3 Baseline concentrations of a typical biomass pellet combustion

The baseline concentrations that will be presented in the following table were determined using a TESTO 335 flue gas analyzer and the Caddy Alterna furnace burning wood pellet fuel. All original data can be found in the Design 2 Report (Greenhouse CO_2 enrichment from biomass combustion. 2011. Design 2 report. Bouchard, J. Filion, F. Glover, A. Nguyen, Q.). However a summary table will be presented. The TESTO 335 allows the determination of Oxygen (O_2) , CO, NO, nitrogen dioxide (NO_2), SO_2 and nitrogen oxide (NO_x) concentrations. The results of the test are also compared to the AHSRAE standards to give the reader a better understanding of the work that is needed in order to achieve the main goal.

Table 1: Current and Objective Concentrations of Pollutant

Emissions	**Objective Concentrations**	**Curent Concentrations** [1]
Carbon Dioxide(CO_2)	1200 mg/L	70 000 mg/L
Carbon Monoxide (CO)	**< 11 mg/L**	530-600 mg/L
Nitric Oxide (NO_x)	5 mg/L	60 mg/L
Nitrogen Monoxide (NO)	25 mg/L	55 mg/L
Nitrogen Dioxide (NO_2)	0.05 mg/L	0.5 mg/L
Sulfate Dioxide (SO_2)	0.019 mg/L	12 mg/L
Fine Particulates	40 µg/m3	N/A

2. Theory, Analysis and Specifications

In this next section, all the mathematical theory and analysis for every component of the proposed design system will be thoroughly explained. For the basic theory, please refer back to the Design 2 report (Greenhouse CO_2 enrichment from biomass combustion. 2011. Design 2 report. Bouchard, J. Filion, F. Glover, A. Nguyen, Q.). This section is of upmost importance as it will allow for proper modeling and simulation and will aid in predicting important parameters such as the temperatures at critical areas in the exhaust system. It will also allow provide the necessary information to properly plan and dimension the exhaust system for our physical model.

2.1 Exhaust Cleaning System

After the literature review done in the Design 2 Report, many techniques to clean the exhaust gases from its major contaminants, e.g. CO, CO_2, NO_x, SO_2 and fine particles, were proposed. Such purifications processes can be very effective to remove contaminants concentrations either in the form of gases or particulates in the flue gas. The prototype will include many techniques where each of them will have targeted contaminants to remove. After a multi-criteria analysis, the best purification techniques for the project were chosen as follows.

The air-to-fuel ratio optimization is an internal modification made in the furnace to push the emissions towards a desired direction. In a lean combustion, the air mixture has to be considerably more than fuel, it will result in better performance of the furnace, efficient fuel use and low exhaust emissions of carbon monoxide (CO) and carbon dioxide (CO_2). However, the excess oxygen will have a tendency to bind with nitrogen (N_2) present in the air to form nitrogen oxides (NO, NO_2 or NO_x).

Connected to the exhaust tube, the catalytic converter is the first external modification in the prototype. Commonly found in cars, catalytic converters convert toxic emissions from internal combustion into less hazardous substances. Occurring in the converter, oxidising reactions will convert carbon monoxide (CO) to carbon dioxide (CO_2) and unburned hydrocarbons (HC) to water (H_2O). The last reaction will reduce nitrogen oxides (NO_x) to atmospheric nitrogen (N_2). A drawback of catalytic converter is that they are required to operate at a high temperature in order to be efficient. Therefore the temperature profile will be analyzed to provide optimal conditions for the reactions.

In order to reduce the CO_2 concentrations in the exhaust, which are currently too high for optimal growth of plants, and to avoid accumulation of NO_x, SO_x and particulates concentrations in the system, dilution and semi-permeable membrane are conjointly used. The use of the fan in the dilution process will mix the exhaust gas with air and will help creating a pressure difference across the membrane, which is needed to allow the gases to permeate through. Polyethylene membrane will let smaller particles, in this case CO_2, to go through and will block bigger particles such as NO_x, SO_x and particulates. This system will be very carefully analyzed, modeled and tested in the following sections.

2.2 Air to Fuel Ratio

The first proposed modification of the furnace to achieve the wanted compound concentrations in the flue gas is the air to fuel ratio. In order to decrease the production carbon monoxide (CO), air must be added to the system to allow for all the hydrocarbons in the biomass to burn (Quaak 1999). The following ratio can be emitted:

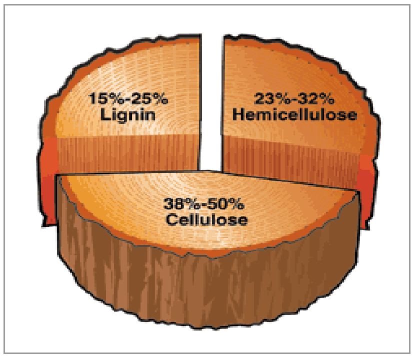
$$\lambda = \frac{air\ supply\ (real)}{Theoretical\ air\ supply\ needed} \tag{1}$$

In an ideal case, lambda (λ) should be equal to one. However most well designed and properly working furnaces have values ranging from 1.6 to 2.5. It is important to note that as λ increases, the temperature of the flue gas will decrease (Quaak 1999). Therefore, raising the air to fuel ratio can have some major disadvantages as the furnace will no longer provide enough heat and will no longer achieve its primary function. With the flue gas temperature lower, it may no longer be hot enough to allow for the proper functioning of the catalytic converter. Before blindly modifying the air to fuel ratio, it is important to determine the theoretical air supply needed which can then be compared to the actual ratio. The actual air supply is determined experimentally by allowing the furnace to run for a predetermined amount of time while measuring the amount of fuel needed for that allowed time. By determining the mass flow rate, it will be possible to determine the real air supplied.

In most cases when sizing the theoretical air needed for a combustion system, the flue gas is analysed using Orsat analysis (Howell 2009). This method determines the ~~percent~~ carbon dioxide (CO_2), carbon monoxide (CO) and oxygen (O_2) by percent volume in the flue gas. Knowing information and the chemical equations governing the combustion process, it is possible to determine the amount of air needed. This technique is applied and works very well with simple fuels such as methane or hydrocarbon fuels (Howell 2009).

However, in this case, the fuel cannot be simply represented chemically since it is in the form of wood pellets. Wood pellets are simply biomass from grass or trees which has been reduced in size but has a great increase in density. These wood pellets are a highly efficient fuel as they are composed of little ash (>0.2%) and very low moisture (≈5%) (Lefsrud 2010). Therefore there chemical composition is the same as a biomass. Biomass composition can be separated into 3 main compositions: cellulose, hemicellulose and lignin.

Figure 1:Composition of Biomass and there Percentage Value



Cellulose and hemicellulose are themselves mainly composed of glucose ($C_6H_{12}O_6$) (Lefsrud 2010). For these reasons, the assumption is made that glucose is the main source of fuel for the combustion process. To determine the theoretical air supply needed, there must be the exact amount of oxygen that will convert all of the fuel into water, carbon dioxide and heat.

$$6O_2 + C_6H_{12}O_6 \xrightarrow{Energy} 6H_2O + 6CO_2 \tag{2}$$

There are two other important processes that occur during combustion which need to be taken into account when trying to determine the air supply needed: the conversion of Nitrogen (N) from the air to Nitric Oxide (NO) and the sulfur in the fuel to Sulfur Dioxide (SO_2). These compounds are considered as they are found in much greater proportions in the flue gas than any other.

$$O_2 + N_2 \rightarrow 2NO \tag{3}$$

$$S_8 + 8O_2 \rightarrow 8SO_2 \tag{4}$$

Knowing these reactions and knowing the concentrations of carbon dioxide, nitric oxide and sulfur dioxide in the flue gas, it will possible to determine the oxygen required for all three processes by stoichiometry. Once the amount of oxygen is summed for all three processes, this will be our theoretical air supply needed for a certain amount of fuel. The heating value of the wood pellets and the energy output of the furnace are known to be of 18.5 MJ/kg and 126.6 MJ respectively, the amount of air needed per second can be determined.

However after analysing the flue gas, the concentrations of NO and SO_2 are very low compared to the CO_2 concentrations. Therefore, we assume that the contributions of oxygen are negligible and may be omitted in the calculations.

2.3 Heating and cooling the air

To achieve are objective concentrations exiting the modified exhaust system, it is important that the devices work as effectively as possible. Most of the devices efficiencies, such as the catalytic converter, are temperature dependant. Also, some other parts of the exhaust system such as the fans and the dilution membrane can be damaged by high temperatures. Because of these conditions, it is of upmost importance to mathematically model the temperature profile along the exhaust to ensure a properly working physical model.

2.3.1 Radial Heat Transfer

Before attempting to model the temperature profile, it is important to understand basic heat transfer theories. As the flue gas travels through the exhaust system, the heat contained in it will be diminished due to convection and conduction. Conduction by heat transfer is governed by Fourier's law of heat conduction (Holman 2010):

$$\dot{Q} = -kA\frac{\partial T}{\partial x} \tag{5}$$

A is the area normal to the direction of heat transfer (m^2)

$\frac{\partial T}{\partial x}$ is the temperature gradient in the direction of heat flow

k is the thermal conductivity (W/m K)

$\dot{Q}$ is the heat transfer rate (W)

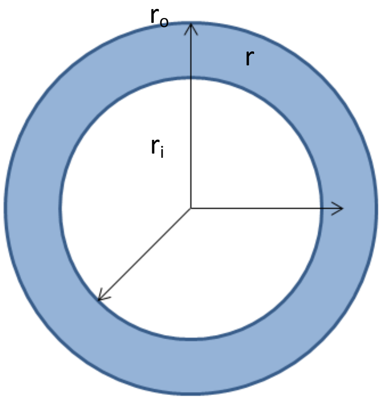
The negative sign indicates that the heat transfer occurs in the direction of decreasing temperature. The thermal conductivity is specific to the material's properties. In the case of a hollow cylinder, like the ductwork, this equation becomes (Holman 2010):

$$\dot{Q} = -k2\pi rL\frac{\partial T}{\partial x} \tag{6}$$

L is the length of the cylinder on which the heat transfer occurs (m)

r is the variable radii throughout the cylinder (m)

Figure 2: Cross-Sectional view of Exhaust System Tubing



By setting the following boundary conditions and solving the differential equation, the following is obtained (Holman 2010):

$$T = T_i \qquad at\ r = r_i$$

$$T = T_o \qquad at\ r = r_o$$

(7) $$\dot{Q} = \frac{2\pi kL(T_i - T_o)}{\ln{(r_o/r_i)}}$$

T_i is the temperature along the wall of the inner radius (m)
T_o is the temperature along the wall of the outer radius (m)

And the thermal resistance of the pipe is:

(8) $$R_{duct} = \frac{\ln{(r_o/r_i)}}{2\pi kL}$$

It is important to note for this equation to be valid, the assumption must be made that cylinders length must be much larger than its radii (Holman 2010).

Convection on the other hand is governed by Newton's law of cooling (Holman 2010).

(9) $$\dot{Q} = hA(T_s - T_f)$$

h is the convective heat transfer coefficient (W/m^2 K)

T_s is temperature at the wall surface (K)

T_f is the fluid temperature (K)

The convective resistance can be written as:

$$R_{conv} = \frac{1}{hA} \tag{10}$$

The simplest way to represent this problem is by using the electrical analog method, where the heat flow is analog to the current, the thermal resistance to the electrical resistance and the temperature difference to the electrical potential (Holman 2010). Recall that:

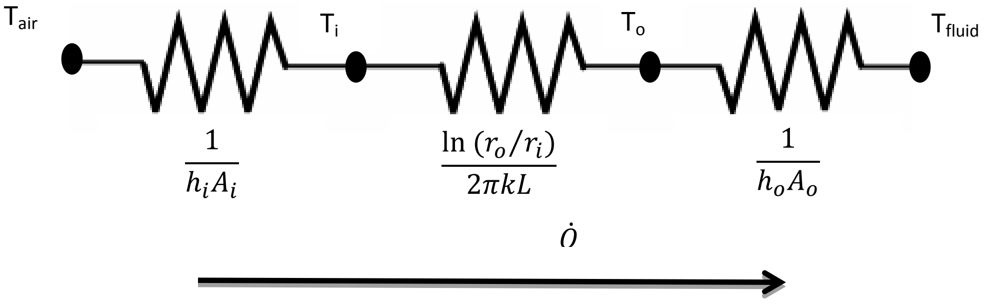
$$I = \frac{\Delta V}{R} \tag{11}$$

Therefore:

$$\dot{Q} = \frac{\Delta T}{\sum R} \tag{12}$$

This could also be represented schematically as:

Figure 3: Equivalent Overall Radial Heat Transfer through the System



With this logic:

$$\dot{Q} = \frac{T_{in} - T_{out}}{\frac{1}{h_{air}A_i} + \frac{\ln(r_o/r_i)}{2\pi k L} + \frac{1}{h_{fluid}A_o}} \tag{13}$$

In this equation T_{in} signifies the temperature at the center of the flue gas and T_{out} represents the temperature exterior to the exhaust system. With this equation, the heat transfer rate leaving the system can be determined at a certain point along the exhaust. Knowing that the thickness of the pipes is negligible when compared to the inner and outer radii, equation (19) could be rewritten as:

$$\dot{Q} = \frac{h_{air}h_{fluid}A(T_{inner}-T_{outer})}{h_{air}+h_{fluid}} \quad (14)$$

2.3.2 Heating the air

In order for the catalytic converter to function properly, the flue gas temperature must be above 200 °C (Heck et al, 2009) in order to function properly. However, the flue gas has a measured temperature of 190 °C. For our exhaust system to work properly, we must therefore increase the temperature significantly. To do so, a heating coil was introduced into the exhaust system just before the catalytic converter. For economic reasons, the coil was taken from a small heating element. The element was then machined into a coil in order for it to fit into the exhaust.

Figure 4: Coil Placed Inside Exhaust System

In order to properly determine the temperature of the air exiting the coil, a heat transfer analysis should be conducted. However, when trying to analyze this problem, the complex shape of the heating coil transforms this simple analysis into a very complicated one. In order to simplify this analysis, a thermodynamics approach is used to solve this problem as we recall the first law of thermodynamics: conservation of energy. This simply means that the energy emitted by the coil will be received by the air and the outer wall of the tube. Assuming that the flue gas receives most of the energy, we can determine the outgoing temperature. The thermodynamic approach is a valid one since our system is designed for operating at steady-state and we are only concerned about the overall energy transfer (Cengel 2006).

The energy for a control volume is governed by the following equation:

(15) $$\dot{W} + \dot{Q} + [\dot{m}(e + Pv)]_{in} = [\dot{m}(e + Pv)]_{out}$$

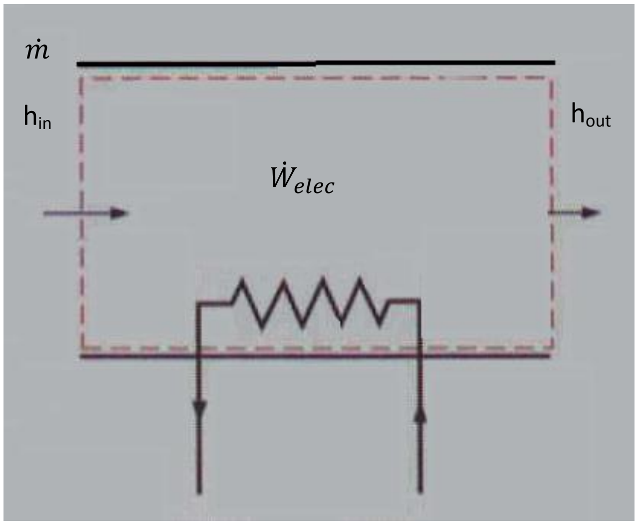
Where:
e is the sum of the internal energy (u), kinetic energy (KE) and potential energy (PE) per mass (kJ/kg)
$\dot{m}$ is the mass flow rate (kg/s)
P is the pressure (kPa)
$\dot{Q}$ is the heat Entering the control volume (kW)
v is the specific volume (m^3/kg)
$\dot{W}$ is the work being done on the system (kW)

In the case of the flue gas going through the coil, the difference in potential and kinetic energy are equal to zero and can be omitted from the equation. Also, enthalpy can be defined as (Cengel 2006):

(16) $$h = u + Pv$$

With this information, the conservation of energy equation for our control volume becomes:

Figure 5: Schematic of Control Volume



(17) $$h_{out} = \frac{\dot{W}_{elec} + \dot{m}h_{in}}{\dot{m}}$$

The electric work given to the system is specified by the manufacturer of the heating element. The mass flow rate can be determined experimentally by knowing the volumetric flow and the density of the air entering the furnace. The incoming enthalpy can also be determined by knowing the temperature entering the coil (190°C) and applying the following empirical relationship (Howell 2009):

(18) $$h = 1.006T + \omega(2500 + 1.82T)$$

Where

ω is the humidity ratio ($kg_{water}/kg_{dry\ air}$)

T is the dry bulb temperature (°C)

This relationship is valid assuming that the flue gas behaves like air. The humidity ratio is the sum of the humidity of the incoming air of the furnace which can be found by knowing the ambient conditions and by using a psychometric chart and the water content added during the combustion process which can be determine using the combustion equation (2). The temperature entering the catalytic converter can then finally be determined by rearranging equation (18):

(19) $$T = \frac{h - 2500\omega}{1.006 + 1.82\omega}$$

2.3.3 Cooling the air by Convection

Once the air is heated to increase the efficiency of the catalytic converter, it must then be cooled because of the fans and the poly membrane that cannot support extremely high temperatures. In order to do so, the flue gas will cool due to the natural convection of the air as it travels through the non-insulated duct and will cool once again due to a small heat exchanger. In order for the system to be cost-effective and simple to build, the heat exchanger will consist of the exhaust ductwork passing through a large plastic container filled with water.

To model these systems and determine the temperature exiting heat exchanger, a heat transfer analysis will be done, since the geometries are much simpler. By knowing the temperature of the flue gas leaving the heating section, and by using the general heat transfer equation (14) developed in the previous section, it will be possible to determine the heat transfer rate leaving the ductwork radially at that specific point. In order to know the temperature profile along the whole exhaust system, a numerical analysis must be done. The exhaust length must be divided into very small sections in which the amount of heat leaving the system will be determined, and a new temperature will be calculated using the following equation (Cengel 2006):

(20) $$\dot{Q} = \dot{m} c_p (T_i - T_{i+1})$$

Where

c_p is the heat capacity the of air (kJ/kg K)

T_i is the temperature of the flue gas entering the section (K)

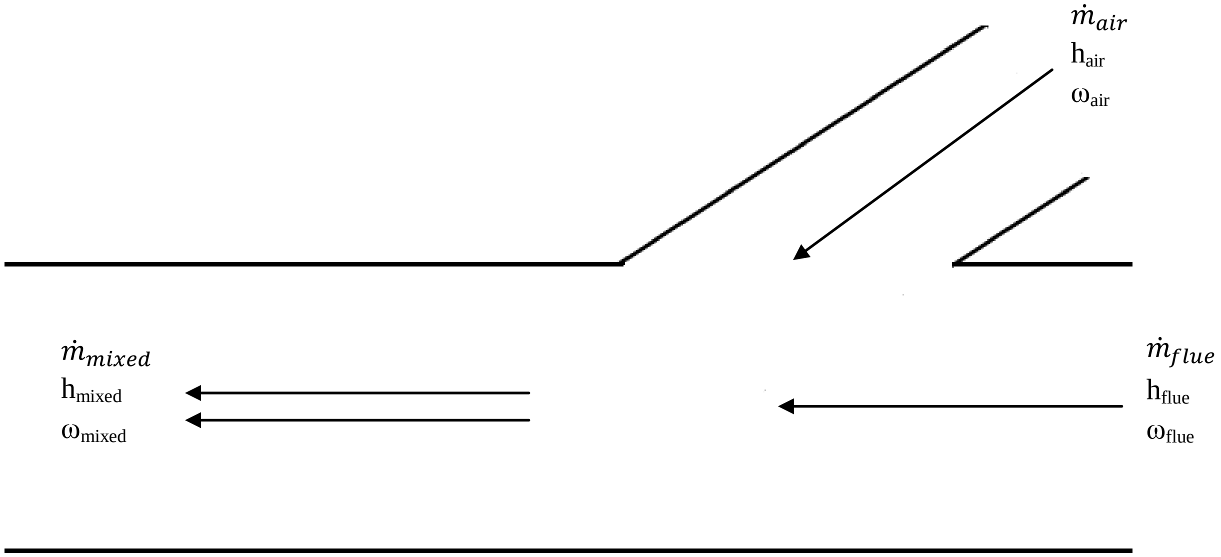
T_{i+1} is the temperature of the flue gas exiting the section (K)

With this equation, the temperature exiting the section can be determined. This process must be reiterated many times in order to cover the entire length of the exhaust. This iteration process can be done using programming software such as MatLab.

2.3.4 Cooling the Air by Dilution

The final step of the cooling is done by dilution. This is done by mixing the exhaust gas with air at ambient temperature. From the previous section, the temperature exiting the heat exchanger is known and so is the humidity ratio which did not change since the combustion stage. Therefore, using equation (18), the enthalpy can be determined. Also, by knowing the ambient conditions of the greenhouse and using a psychometric chart, the ambient enthalpy and the ambient humidity ratio can also be determined.

Figure 6: Schematic of Adiabatic Mixing Air Streams



With this information, the temperature of the newly mixed flue gas can be determined with the following sets of equations (Howell 2009):

(21) $$\dot{m}_{flue}\omega_{flue}\dot{m}_{air}\omega_{air} = \dot{m}_{mixed}\omega_{mixed}$$

(22) $$\dot{m}_{flue}h_{flue}\dot{m}_{air}h_{air} = \dot{m}_{mixed}h_{mixed}$$

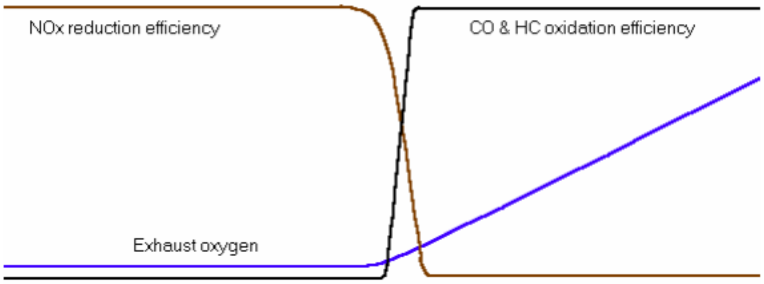
With these values now known, the final temperature can be determined using equation (19). By completing this section, it is now possible to have an approximate temperature profile if the flue gas as it travels throughout the exhaust system; this is an approximation since many assumptions were made and other parameters that where harder to be estimated, such as air infiltration, were omitted.

2.4 Catalytic Converter

Commonly found in cars, catalytic converter converts toxic emissions from internal combustion into less hazardous substances. A catalytic converter is divided into two different catalysts. Reduction catalysts cause NO_x to be reduced into O_2 and N_2. Oxidation catalysts cause hydrocarbons (HC) and CO to oxidize with any available oxygen into CO_2 and water (H_2O).

Unfortunately, oxidation will only occur when there is enough free oxygen, and reduction will only occur in a relative absence of free oxygen. In general, oxidation and reduction cannot both occur at their highest efficiency at the same time and would follow the trend on Figure 7.

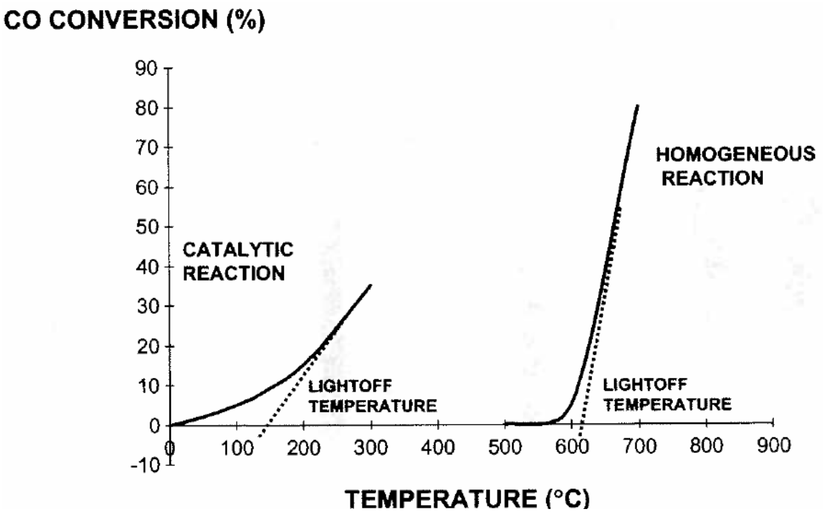
Figure 7: Relations between NOx reduction efficiency versus CO & HC oxidation efficiency at different exhaust oxygen concentration.



Both catalysts are made of a ceramic structure coated by a precious metal such as palladium, platinum or rhodium. Platinum and palladium promote the oxidation of CO and HC, whereas rhodium promotes the reduction of NO_x. (Sideris, 1998) In order to maximize surface area and minimise the quantity of precious metal used, the catalyst are usually shaped like honeycombs, either squares or triangles, in order to get more surface area. For 1995+ vehicles, advanced ~~substrates~~ honeycomb substrates achieve faster light off, lower back pressure and are smaller than first generation substrate design in the 1970s. (Heck et al, 2009)

A drawback of catalytic converter is that they are required to operate at a high temperature in order to be efficient. In fact, the activation energy for Pt catalyzed CO to CO_2 is about 20 Kcal/mole, compared to 40 Kcal/mole for non-catalyzed or thermal reaction. (Heck et al, 2009) The figure 8 shows a plot of the conversion of CO versus temperature where the catalyzed reaction as a lightoff temperature around 200°C. Thus, the temperature must be carefully controlled within the catalytic converter.

Figure 8: Conversion of CO versus temperature for catalyzed and noncatalyzed reactions (Heck et al, 2009)



2.4.1 Cold start-up

During a cold start-up, the temperature in the catalytic converter is very low. Hence, the catalyst reaction is not activated. Until the light-off temperature, contaminants such as CO or HC are not converted and 60-80% of existing HC are produced from the start-up time to the time the converter starts operating. (Sideris, 1998) There are two approaches to solve this problem: active and passive approach. The active approach relies on the addition of energy (e.g. heat) in order to raise the exhaust temperature. Systems such as electric heated converter (EHC), afterburners and fuel burners are considered active methods. Passive approach relies on the use of gas reducing exhaust system to reduce cold-start emissions. Positioning the catalytic converter closer to burner, use of secondary converters or HC absorbents are some examples.

2.4.2 Sizing of catalytic converter substrate

The cell shape and size will affect the performance and durability of the catalytic converter. For good light-off effectiveness, the substrate must have a high light-off (LOF) value. For high conversion efficiency, the substrate must have a high cell density (n), geometric surface area (GSA) and bulk heat transfer (H_S) values. For low back pressure, the substrate must have high open frontal area (OFA), large hydraulic diameter (D_h) and low resistance to flow (R_f) values. (Heck et al, 2009). The size of a substrate would depend on these factors.

The total surface area (TSA) can be defined as:

(23) $$TSA = GSA \times V$$

Where

V is the substrate volume, which is given by

(24) $$V = A \times l$$

Where

A is the cross-section area in (m) and l is the cross-sectional length of substrate in (m).

The backpressure is related to the flow velocity:

(25) $$v = \frac{V_e}{A(OFA)}$$

Where

V_e is the flow rate (m^3/s).

2.4.3 Efficiency

The catalyst in a catalytic converter has a limited lifetime so that the efficiency of the converter will deteriorates with time and use. Some contaminants such as lead, sulfur or phosphorus can inhibits the catalysts as they will contaminate the washcoat and noble metal, and reduce the active catalytic area (Sideris, 1998). Therefore, it is desirable to monitor the performance of the catalytic converter. There are three main methods of monitoring: (1) use of oxygen or air/fuel ratio (λ) sensors upstream and downstream of the converter, (2) use temperature measurements of the exhaust gases inside or outside the catalytic converter and (3) use of HC, CO or NO_x sensors.

The most obvious way to diagnose the efficiency of the catalytic converter would be the direct measurements of HC, CO and NO_x. For each type of contaminants, the conversion efficiency are computed as ratios of average concentrations before and after the catalytic converter. For example, the concentrations of the CO upstream and downstream of the converter are measured and the following ratio is formed:

(26) $$\eta = \frac{(CO)_2}{(CO)_1} \times 100$$

Where

$(CO)_1$ is the CO concentration of the exhaust gas upstream the catalytic converter

$(CO)_2$ is the CO concentration of the exhaust gas downstream the catalytic converter.

2.5 Membrane

The transport of gases through a dense polymeric membrane is usually described by the solution-diffusion mechanism. In this model the gases dissolve in the membrane material and then dissolve through it down a concentration gradient. This model is usually has three steps: (i) the adsorption or the absorption of the gases upstream (sorption step), (ii) the diffusion through the membrane and (iii) desorption or evaporation on the downstream side of the membrane. Ultimately the gradient concentration between both sides of the membrane is the driving force of the transport process (sorption, diffusion and permeation). The relationship between solubility, diffusivity, permeability, can be described by:

(27) $$P = D * S$$

Where:

P is the permeability coefficient, a measure of the flux of the membrane (cm^3 (STP) cm^{-2} s^{-1} $cmHg^{-1}$). The common unit of permeability is the barrer (10^{-10} cm (STP) cm^{-2} s^{-1} $cmHg^{-1}$)

D is the diffusivity coefficient (cm^2 s^{-1}), the mobility of molecules within the membrane

S the solubility coefficient (cm (STP) $cmHg^{-1}$), which measures the solubility of gas molecules within the membrane

For ideal gases the, the permeability is related to the gas permeation rate through the membrane (Q), the surface area of the membrane (A), the thickness of the membrane (l) and the driving force for separation, the pressure difference across the membrane (Δp):

(28) $$\frac{P}{l} = \frac{Q}{A * \Delta P}$$

The ideal selectivity (α) of one gas, A, over another gas, B, is defined as:

(29) $$\alpha = \frac{P_A}{P_B} = \frac{K_A}{K_B} * \frac{D_A}{D_B}$$

Polymeric membranes can be classified into either the rubbery or glassy category. This depends on the operating temperature relative to the glass transition temperature of the polymer. Rubbery membranes that operate above the glass transition temperature are able to rearrange in a small enough time period and are usually in thermodynamic equilibrium. Therefore the gas solubility within the polymer follows Henry's Law and is linearly proportional to the partial pressure or fugacity, f.

(30) $$C_D = K_D f$$

Where CD is the concentration of gas in the polymer matrix and is proportional through the Henry's Law constant (K_D)

However glassy membranes operate below the glass transition temperature therefore polymer rearrangement is over a very long time period which means that the membrane never reaches thermodynamic equilibrium. The polymer chains are imperfectly aligned which leads to excess free volume (microscopic voids in matrix). This increases solubility and decreases selectivity.

In our design we had chosen a low density polyethylene membrane (LDPE) which has a glass transition temperature of -120 ^oC which means the membrane is operating in a rubbery state. The melting point of the LDPE ranges from 105 ^oC and 115 ^oC and its maximum continued use temperature is approximately 80 ^oC. The thickness of the membrane is 1 mm and the total surface are of the membrane is 11.8 m^2. We also know based on the molecular weight and kinetic diameter of the molecules that the ideal selectivity's of the gases through the membranes are as follows:

Table 2: Moleculear Weight and Kinetic Diameter of gases encountered in the separation

Molecule	Molecular weight	Kinetic Diameter
CO	44	3.3
NO	28	3.76
CO_2	30	3.17
SO_2	64	2.3

(30) $\propto_{CO2/CO} = 1.38$

(31) $\propto_{CO2/NO} = 1.53$

(32) $\propto_{CO2/SO2} = 0.99$

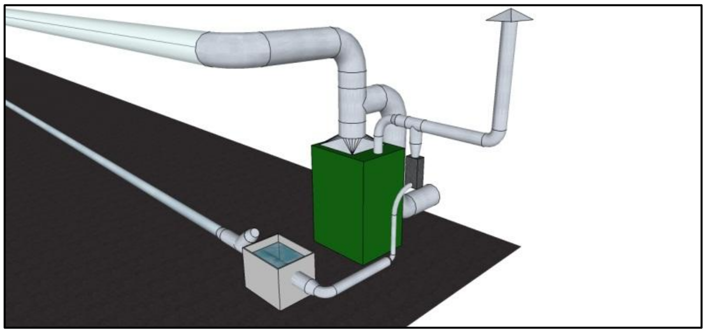
Therefore from the ideal selectivity's calculated above we know that it will selectively permeate more CO_2 in comparison to CO and NO. CO_2/SO_2 selectivity has a ratio of roughly one which is not ideal but cannot be changed since it is independent of the membranes properties. To calculate the permeation rate through the membrane many parameters need to be taken into account. The forces of pressure, temperature, concentration and electromotive forces are the ones that essentially need to be considered. These parameters are interrelated and need to be set up as a differential equation system. Mathematical simulation packages such as ASPEN Plus are capable of doing this and can determine the flow rate across the membrane. Such packages have extensive internal property data base however even with this simulation package the permeability coefficients for each gas would need to be experimentally found with a permeation experiment. This is when the use of the simple mathematical model is used. An ideal gas is flowed through a membrane with a known thickness and the permeation rate is measured. The results are plotted and the permeability coefficient is found. This experiment requires a sophisticated experimental apparatus and could be the object of an entire research project of its own. This data is unavailable since such experiments are undocumented for the gases that are of interest to us with the membrane system are designing. Past literature is void of data from the gases emitted by the exhaust from biomass combustion with a polyethylene membrane. Therefore we are counting on determining the permeation rates of the different gases through the physical model of our system. It would be highly recommended for further research purposes and advances in the realization of this project to determine the ideal membrane using a simulation package such as ASPEN Plus since it would reduce the uncertainty of the system and prove mathematically the validity of the system. It would require extensive work to determine the permeability coefficients but would result a much more reliable system with less uncertainty.

2.6 CAD Model

The next step is to design the exhaust system that will filter the flue gas from its contaminants. This model would have to be based on the size of the greenhouse at Macdonald Market, the furnace and its current exhaust and heating tubes, and the catalytic converter. The other components can be modified in respect of the flow requirements.

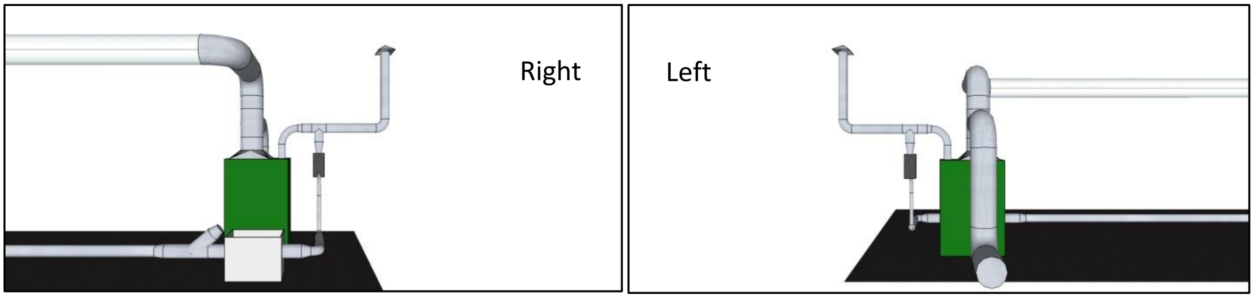
In Figure 9, the furnace and its heating tubes remain unchanged. However, the tube system going out of the chimney is slightly modified. In the system, a tee-fitting is installed right before the chimney to divert the flue gas to the catalytic converter. The catalytic converter was installed at that location so there will not be any backflow from catalytic converter, which will trigger the backpressure sensor of the furnace and shut it down. To increase the inlet temperature of the catalytic converter, the heating coil is placed before the catalytic converter.

Figure 9: Isometric view of the exhaust system at the Macdonald Market Greenhouse



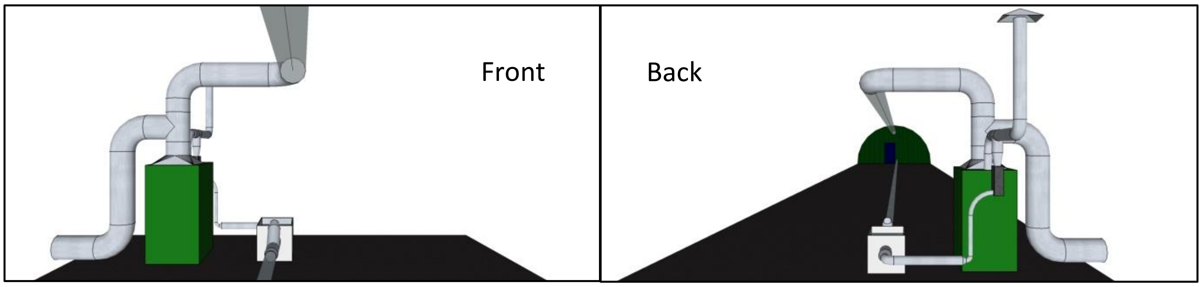
Downstream of the catalytic converter, the tube will go through the heat exchanger as seen in Figure 10. In this case, a water tank with cold water serves as the heat exchanger. The diameter of the tube can also be increased to have a higher surface area, thus a higher convection rate. After the heat exchanger, one fan will be pulling flue gas from the tee-connection. Another fan, used for dilution, will be pushing ambient air in the system at the Y-junction. It is essential to keep an airtight environment in the whole system because air would be drawn inside little cracks from the fittings instead of the flue gas.

Figure 10: Right and Left view of the exhaust system at the Macdonald Market Greenhouse



Finally, the exhaust tube is connected to the semi-permeable membrane, which goes up to the front door. The excess gas would be dumped outside. Actual pictures of the exhaust system are available in the annex.

Figure 11: Front and Back view of the exhaust system at the Macdonald Market Greenhouse



2.7 Air Changes for Optimal CO_2 Range

The optimal CO_2 concentration in a greenhouse ranges from 1000 to 1500 mg/L in order to achieve maximum plant yield. The appropriate CO_2 injection rate from the furnace must be determined in order to have the CO_2 concentration in the appropriate range. To do so the ventilation in greenhouses must be carefully discussed. The main objectives of greenhouse ventilation are to control temperatures in the summer and humidity levels in the winter. However the ventilation is subdivided into three categories; summer, winter and spring/fall.

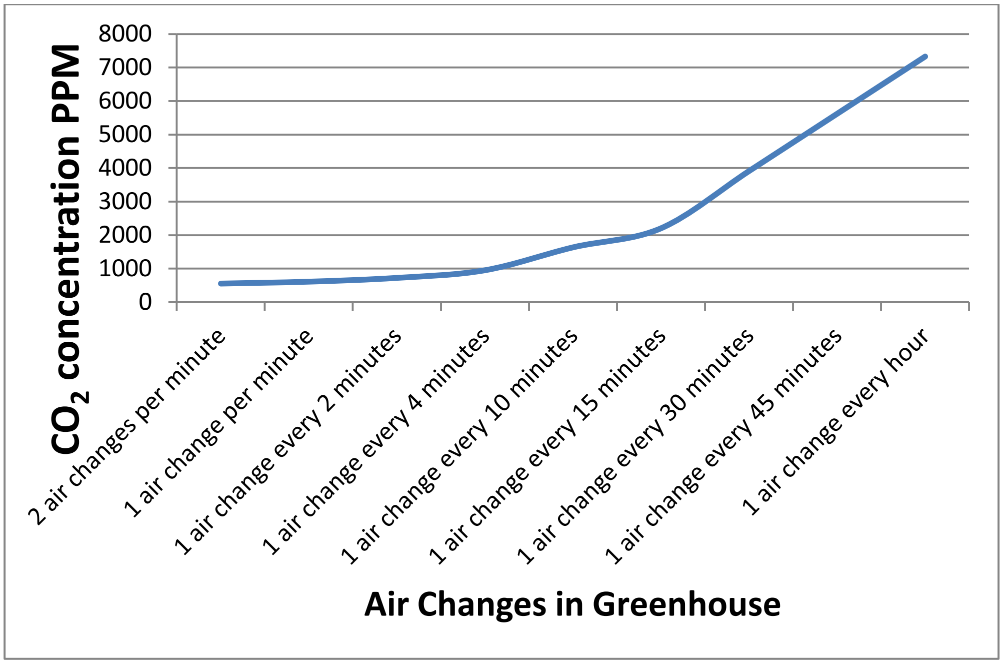
For winter ventilation the main factor that influences the rate of ventilation is the quantity of moist air within the greenhouse. If it is not removed, high humidity and excessive condensation will occur. High moisture content conditions promote diseases within the plants and inhibit the soil from drying and must be avoided. When setting the climate conditions for the greenhouse, a relative humidity of 100% must be avoided in order to prevent condensation ~~to occur~~, which is responsible for disease transmittance between plants (Hanan 1998). Over 90% humidity also leads to leaf mould, fruit and stem rot. Since the plants transpire, water is constantly being added to the environment. When temperature decrease, such as in the evening, the dew point will most likely be reached and condensation will occur. Condensation also occurs when warm, moist air from inside the greenhouse comes in contact with a cold surface such as glass, fibreglass, plastic or structural members (Nelson 1998). For example, condensation occurs if air in a greenhouse at 70° F and 70% relative humidity comes in contact with a surface that is 60° F or colder (see **Figure A.1** in appendix). Air exchange is the most effective method of lowering relative humidity. Nonetheless, 70 to 80% relative humidity must be achieved for plant health. When the ventilation rate increases in winter so do the heating costs therefore it is necessary to find the optimal rate that will keep the humidity below the damaging levels and the heating costs low. Ventilation requirements for the greenhouse in winter are generally in the order of two to three air changes per hour. Ventilation rates of less than two air change per hour should be avoided at all costs since ventilation also assures a good air quality in the greenhouse (Buffington et al. 1993)

In summer the main purpose of ventilation is to prevent the temperatures inside the greenhouse from rising too high above the outside air temperature. The minimum ventilation rate for summer is one air change per minute. This minimum ventilation rate is generally accepted in the greenhouse industry. However ventilation rates range from one air change every three minutes to 3 changes per minute. As the ventilation rate increases the temperature difference between the inside and outside air is decreased however this leads to a higher cost of fans and operating costs (see **Figure A.2** in appendix). No matter how many air changes are performed ever minute the temperature will never be the same inside and out. To achieve this other cooling methods than ventilation need to be used (i.e. evaporation pad)

In spring and fall the ventilation rate is somewhere between the rates required for summer temperature control and those required for winter humidity control. This is because there are cool and cloudy days while other days can be warm and sunny.

For the greenhouse at the Macdonald market with the Caddy Alterna funace we are faced with the following situation. Firstly when the furnace is running on a hot summer day at 1 air change per minute the CO_2 concentration is at 614 mg/L. This is under the desired conditions but is still significantly greater than the atmospheric concentration of 490 mg/L. When the furnace is running on a cold winter day at 1 air change every hour the CO_2 concentration in the greenhouse climbs up to 7327 mg/L. This is way above the desired CO_2 levels. This means that the furnace should be run at a lesser intensity. Therefore a CO_2 sensor would need to be placed in the greenhouse that controls the amount of exhaust directed into the greenhouse so that it doesn't exceed the maximum concentration of 5000 mg/L of CO_2. With the furnace running at maximum intensity the optimal air change rate is 1 air change per 10 minute (1638 mg/L). (See calculations in **Section 1.2 of Annexe**). We must remember that we assume that all the CO_2 produced by the furnace ends up in the greenhouse which is very unlikely.

Figure 12: CO_2 concentration as a function of air changes in greenhouse



3. Prototype

A mathematical analysis of the model was the first step in the prototyping of the exhaust cleaning system. However this model had many limitations due to the complexity of the system and the limited predictability of very context specific processes such as the efficiency of the catalytic converters reaction and the membrane diffusion. This is the major reason why a physical model needed to be constructed and tested in the Macdonald Market experimental greenhouse. The system was assembled with a limited budget and the fundamental goal was to quantify the reductions of toxic compounds that each component of the system could offer. This exercise proves to be a step forward in the direction of developing this technology and gathering preliminary data. Not all the ideal conditions were respected for an optimal functioning system however this is attributed to the budget restrictions. The following sections will explore the mathematical analysis of the system, provide detailed plans of the physical model and provide the experimental reductions that each component could provide.

4. Modeling and Testing

4.1 Modeling Results

In this section, the results of the different models will be presented, please refer to the appendix.

The air to fuel ratio was first determined. It was quickly realised that the actual and real air to fuel ratio was estimated to be higher than the supposed theoretical ratio.

Table 3: Comparison of Actual and Theoretical Air to Fuel Ratios

Actual A/F ratio	Theoretical A/F
5.73	3.73

Because the actual value is already higher than the theoretical proposed value, we have decided to omit this modification since this analysis clearly demonstrates that enough air is already present during the combustion process and there would be no benefit of adding any more air to the system.

Using the theory previously established, the temperature was mathematically determined at various points along the exhaust.

Table 4: Temperature along Critical points of the Exhaust System

Location	Temperature (^{o}C)
Before Catalytic Converter	191
After Catalytic Converter	273
Before Heat Exchanger	164
After Heat Exchanger	97
After Dilution	27

As indicated in the above table, with the use of the coil the temperature should raise too approximately 273^{o}C which allows the flue gas to be in the working range of the catalytic converter. It is important to note that the temperature also drops to 27^{o}C due to the cooling of the heat exchanger and the dilution. This is important as the temperature drops well below the manufacture specifications of the maximum temperature of the fans and the polyethylene membrane which are in the 100 ^{o}C to 130^{o}C range. With the help of this model, it is now safe for the devices to begin the actual testing of the prototype.

4.2 Test Results

Table 5: Test results of physical model

	CO_2 (g/L)	CO (mg/L)	NO (mg/L)	NO_x (mg/L)	NO_2 (mg/L)
Before Catalytic Converter	54	609	39,1	41,1	2,1
After Catalytic Converter	58	~ 0	44,7	46,9	2,2
Difference in Catalytic Converter	+ 7%	− ~100%	+ 14%	+ 14%	+ 5%
Beginning Membrane	21	~ 0	12,7	13,4	0,6
End Membrane	19	~ 0	12,7	13,3	0,7
Difference in Membrane	− 10%	~ 0%	~ 0%	~ 0.1%	+0 −16%

As we can see from the previous table, the catalytic converter achieved a near 100% CO reduction. The CO sensor has an error range of 10 mg/L which is why we cannot say it is 100% efficient. We can also note a 7% increase in CO_2 through the converter due to the reactions in th converter. The increase in the NO, NO_x and NO_2 compounds is also attributed to the catalytic converter reactions although this is undesirable. As for the membrane, we notice that the permeation of the NO, NO_x and NO_2 is negligible and we can notice that the CO_2 permeation rate is 10%.

4.3 Discussion

For future work on this project many improvements also need to be made based on our findings from the physical model. Now that we have experimental data that proves that the catalytic converter efficiently reduces the CO concentrations sizing of the converter becomes important. It needs to be sized as not to restrict the air flow through the system. This would allow for the entirety of the exhaust gases to pass through the cleaning system. At the moment only part of the gases are passing through it since the catalytic converter offers a resistance to the flow. Now that we have eliminated the CO component of the exhaust gases, which was the major difficulty, it now becomes an option to look at an alternative that would allow for a better utilization of the CO_2 stream. In fact our membrane separation that is part of our design only allows for a fraction of the CO_2 to be permeated into the greenhouse. At the moment 90% of the CO_2 produced by the combustion is being released back into the atmosphere. Therefore we believe that the use of a water scrubber that would allow the removal of the particulates, NO_x and SO_x would be a better option than the membrane. Once the flue gas has passed through the water scrubber if the efficiency is adequate it could be directed directly into the greenhouse and all the CO_2 could be utilized to its full potential. This however remains to be tested and further work is required on designing the said water scrubber.

5. Optimization

In order to optimize the system we constructed many modifications would need to be considered. Firstly in order to have an optimal reaction in the catalytic converter the flue gas needs to enter at 1000^{o}C therefore the heating coil would need to be able to achieve this baseline temperature. The coil that was built in the physical model could only achieve a flue gas temperature of 334^{o}C but was assembled using a stove top coil and its cost was under 20$. However it is noteworthy to mention that the efficiency of the catalytic converter was close to 100% even with the reduced inlet temperature. Another major improvement would be the location of the fan that pulls the exhaust gases through the cleaning system. Optimally the fan would be placed before the catalytic converter and would blow the air through. However this fan would need to be highly resistant to temperatures and these fans are far more expensive than lesser temperature resistant fans. Our fan was certified for 266^{o}C which allowed it only to be placed after the cooling of the gases was done. These modifications would not drastically improve the system and we strongly encourage the exploration of the recommendations made in the discussion section of the report since these modifications could yield a more efficient system that has the potential to be commercialized.

6. Conclusion

To summarize our design III final project we are pleased with the major step forward that was accomplished in the realization of the objective. The conclusive experimental data that was obtained from the testing of the physical model allows the continuation of the project. In fact the successful removal of the CO through the catalytic converter is a first in terms of cleaning the gases emitted from biomass combustion. This is an area of research that has not been explored yet and the potential for patentability and commercialization is quite reasonable. The project will continue throughout the summer since budgets have been released to allow Mr. Yves Roy to work on our recommendations presented in this report. This of course still under the supervision of Dr. Mark Lesfrud which we thank once again to have allowed us to be part of this innovative project. We are very pleased with the work that has been accomplished and are aware of the work and challenges that still lie ahead before a marketable system can be produced.

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Appendix

Greenhouse Ventilation

Figure A.1: Inside relative humidity that would result as a function of the different winter ventilation rates for 60° F and 70° F (Buffington et al. 1993)

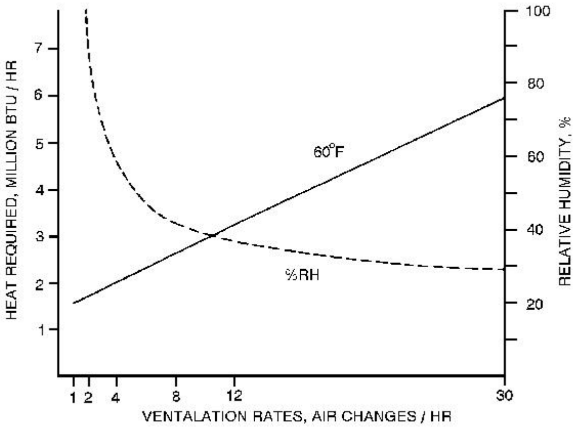
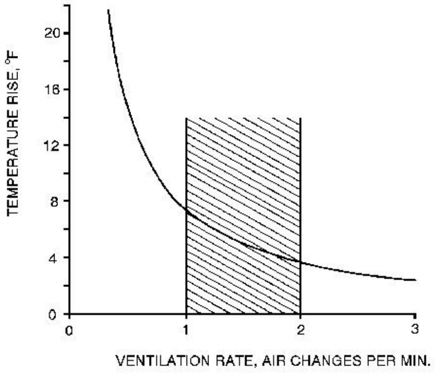


Figure A.2: The resulting temperature increases (inside temperature minus outside temperature) on a clear summer day for the greenhouse (Buffington et al. 1993)



Determining Ventilation Volume Rates:

Diameter of greenhouse = 18.5 ft

Length of greenhouse = 97 ft

$$Total\ Greenhouse\ Volume = \frac{\pi\left(\frac{d}{2}\right)^2}{2} * length$$

$$= 13037\ ft^3 \ \ = 369.17\ m^3$$

$$Maximum\ ventilation\ rate\ in\ summer = 13037\,\frac{ft^3}{\text{min}\ (1\ air\ change\ per\ minute)}$$

$$= 369.17\ m^3$$

$Minimum\ ventilation\ rate\ in\ winter = \frac{13037\frac{ft^3}{hr}}{2*60} = 434.57\,\frac{ft^3}{\text{min=12.30 m}^3}$ *(2 air changes per hour)*

Determining CO_2 injection rate:

Volumetric flow rate from exhaust = 0.001 m^3/s

Measured CO_2 concentration in exhaust = 70 000 mg/L

Optimal CO_2 concentration in greenhouse = 1500 mg/L

Table A.1 : Determining CO_2 injection rate

air changes	air changes per min	Sec before air change	V Exhaust CO2 (m^3)	
2 air changes per minute	2.0000	30.0000	0.0210	
1 air change per minute	1.0000	60.0000	0.0420	
1 air change every 2 minutes	0.5000	120.0000	0.0840	
1 air change every 4 minutes	0.2500	240.0000	0.1680	
1 air change every 10 minutes	0.1000	600.0000	0.4201	
1 air change every 15 minutes	0.0667	900.0000	0.6301	
1 air change every 30 minutes	0.0333	1800.0000	1.2602	
1 air change every 45 minutes	0.0222	2700.0000	1.8902	
1 air change every hour	0.0167	3600.0000	2.5203	
V of prexisting CO2 (m^3)	**Total V CO2 (m^3)**	**V of Greenhouse (m^3)**	**% CO2**	**mg/L CO2**
0.1846	0.2056	369.17	0.0557	557
0.1846	0.2266	369.17	0.0614	614
0.1846	0.2686	369.17	0.0728	728
0.1846	0.3526	369.17	0.0955	955
0.1846	0.6046	369.17	0.1638	1638
0.1846	0.8147	369.17	0.2207	2207
0.1846	1.4447	369.17	0.3913	3913
0.1846	2.0748	369.17	0.5620	5620
0.1846	2.7049	369.17	0.7327	7327

Air/Fuel Ratio

Theoretical

Important Parameters:

Molar Masses:

O_2 = 31.998 g/mol

$C_6H_{12}O_6$ = 180.156 g/mol

H_2O = 18.015 g/mol

Compositions:

% Oxygen in Air = 21 %

% Glucose in Biomass ≈ 70%

Table A.2: Composition of Biomass

Lignin	Cellulose	Hemicellulose
[15-20]%	[38–50] %	[23-32]%

The modeling of the theoretical air to fuel ratio first begins using equation (2)

(2) $$6O_2 + C_6H_{12}O_6 \xrightarrow{Energy} 6H_2O + 6CO_2$$

Using the appropriate molar masses, the theoretical air/fuel ratio is determined to be:

$$\frac{A}{F} = \frac{6\,mol * \frac{31.998g}{mol} * \frac{1}{0.2}}{1\,mol * \frac{180.156g}{mol} * \frac{1}{0.7}} = 3.73\ \frac{kg_{air}}{kg_{fuel}}$$

Actual

The actual air to fuel ratio can also be determined. Using the experimentally determined values:

Incoming air velocity =1.7 m/s

Inlet area = 0.0059 m^2

Density of air = 1.2 kg/m^3 (Crowe 2009) @ 20^{o}C

Furnace Consumption ≈ 5 bags of pellets 12 hours

1 bag of pellets = 18.14 kg

$$\dot{m} = 1.7\,m/s * 0.0059m^2 * 1.2\ kg/m^3 = 0.012\ kg/s$$

$$\frac{A}{F} = \frac{0.012\ kg/s * 12\,h * 3600\,s/h}{5 * 18.14\,kg} = 5.73$$

Equation (1) can now be calculated

$$\lambda = \frac{5.73}{3.73} = 1.54$$

Temperature Profile Calculations

Heating

Important Parameters:

T_{db} = 24 ^oC (Langhans 1998)

$T_{flue\ gas}$ = 191 ^oC (Experimental)

RH = 70 % (Langhans 1998)

$\dot{W}$ = 1200 W (Specified by manufacture)

$h_{forced\ convection}$ = 100 W/m^{2}K (Howell 2009)

Length = 0.305 m

Radii = 0.051 m

$h_{natural\ convection}$ = 10 W/m^{2}K (Howell 2009)

First the humidity must be determined from the psychometric chart and the biomass equation. Using the psychometric chart the humidity ratio of the incoming air is determined to be:

$$\omega = 0.013\ kg_{water}/kg_{dry\ air}$$

$$Air\ required = 6\,mol * 31.998 g/mol * \frac{1}{0.2} = 959.97\ g$$

Table A.3: Breakdown of Water content in Incoming Air

Water Content (g)	Dry Air Content (g)
12.48	947.46

$$Added\ Water = 6\,mol * 18.015\ g/mol = 108.09\ g$$

$$\omega = \frac{(108.09 + 12.48)\ g}{(947.46 + 108.09)\ g} = 0.114\ kg_w/kg_{DA}$$

It is now possible to determine the temperature entering the catalytic converter

$$h_{in} = 1.006 * 191^oC + 0.114\ kg_w/kg_{DA} * (2500 + 1.82(191^oC)) = 516.77\ kJ/kg$$

$$h_{out} = \frac{1.2kW + 0.012\ kg/s * 516.77\ kJ/kg}{0.012\ kg/s} = 616.77\ kJ/kg$$

$$T_{out} = \frac{616.77\ kJ/kg - 2500 * 0.114\ kg_w/kg_{DA}}{1.006 + 1.82 * 0.114\ kg_w/kg_{DA}} = 273.40^oC$$

Cooling

As mentioned in the report section, in order to determine the temperature profile in the cooling part of the exhaust system, a numerical analysis must be conducted using Matlab. The first code was used to determine the flue gas temperature as it was cooled due to the natural convection of the air, while the second Matlab code determines the temperature profile while being cooled due to the natural convection of water.

```
%% Design cooling of the flue Gases
% h_air = forced air convection (Howell 2009)
% h_fluid = Natural Water Convection (Howell 2009)
% r - radius
% L = length of cylinder
% Li= lenght of ith unit lenght
% i = number of iterations
% T_w = Temperature of water
% T_a1 = initial exhaust temperature
% Specific heat capacity in J/g*K
% m= mass flow rate in kg/s

h_air = 100 ; % W/m^2 K
h_fluid = 10; % W/m^2 K
r = 0.0508 ; % m
i = 500;
L= 2.26 % m
Li = L/i ; % m
T_air = 297.15 ;% K
T_A1 = 546.55; % K
V=0.01 % m^3/s



for k= 1:500
    q =[h_air*h_fluid*2*pi*r*Li*(T_A1-T_air)]/(h_air + h_fluid);
    Cp = (0.0002*T_A1+0.9296)/1000;
    m = 0.01177;
    T_A2 = T_A1 - (q/m*Cp) ;

    T_A1 = T_A2
    L= k*Li;

    hold all
    plot(L,T_A1, 'Blue');

end


title('Duct temperature drop due to natural air convection')
xlabel('Lenght along the duct in meters')
ylabel('Temperature in degrees K')


%% Design Cooling of the flue Gases
% h_air = forced air convection ASHRAE
```

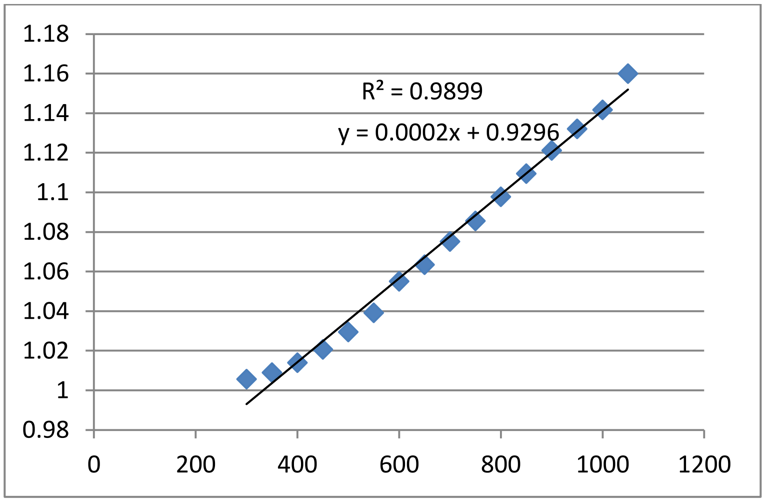
```
% h_fluid = Natural Water Convection ASHRAE
% r - radius
% L = length of cylinder
% Li= lenght of ith unit lenght
% i = number of iterations
% T_w = Temperature of water
% T_a1 = initial exhaust temperature
% Specific heat capacity in J/g*K
% rho = density in k/m^3
% m= mass flow rate in kg/s

h_air = 100 ; % W/m^2 K
h_fluid = 50; % W/m^2 K
r = 0.0762 ; % m
i = 500;
L= 0.4572 % m
Li = L/i ; % m
T_w = 293.15 ;% K
T_A1 = 437.8375 ; % K
V=0.01 % m^3/s



for k= 1:500
    q =[h_air*h_fluid*2*pi*r*Li*(T_A1-T_w)]/(h_air + h_fluid);
    Cp = (0.0002*T_A1+0.9296)/1000;
    m = 0.01177;
    T_A2 = T_A1 - (q/m*Cp) ;

    T_A1 = T_A2
    L= k*Li;

    hold all
    plot(L,T_A1, 'Blue');

end


title('Temperature Drop of flue gas along Heat Exchanger')
xlabel('Lenght along the Duct in meters')
ylabel('Temperature in degrees K')
```

In order to do these calculations, the heat capacity of the air needed to be determined. Using Excel, the relationship between the specific heat capacities at different temperature of the air was curved fitted:

Table A.4: Relationship of specific heat with respect to temperature

T (K)	Cp_{air} (kJ/kg °C)	T (K)	Cp_{air} (kJ/kg °C)
100	1.0266	550	1.0392
150	1.0099	600	1.0551
200	1.0061	650	1.0635
250	1.0053	700	1.0752
300	1.0057	750	1.0856
350	1.009	800	1.0978
400	1.014	850	1.1095
450	1.0207	900	1.1212

Figure A.3: Relationship of specific heat with respect to temperature



It is clearly demonstrated with an R^2 of 0.9899 that the specific heat capacity varies linearly in the desired temperature range.

The two Matlab scripts yield the following results.

Table A.5: Results of Matlab Program

	T_{in} (K)	T_{out} (K)
Air Exchanger	546.55	437.84
Water Exchanger	437.84	370.49

Dilution

By knowing the temperature exiting the heat exchanger we can calculate its enthalpy by using equation (21) and (22). The ambient conditions remain the same as previously mentioned and using a psychometric chart the following information is obtained:

h_{air} = 57.5 kJ/kg

ω_{air} = 0.013 kg/kg

ρ = 1.1774 kg/m^3

$\dot{V}$ =0.21 m^3/s (determined experimentally)

$\dot{m_{air}}$= 0.21 m^3/s *1.1774 kg/m^3 = 0.247 kg/s

$$\omega_{mixed} = \frac{0.012\ kg/s * 0.114\ kg/kg + 0.247\ kg/s * 0.013\ kg/kg}{(0.012\ kg/s + 0.247\ kg/s)} = 0.018\ kg/kg$$

$$h_{flue} = 1.006 * (370.49 - 273.15)^oC + 0.114\ kg/kg * (2500 + 1.828 * (370.49 - 273.15)^oC) = 403.12\ kJ/kg$$

$$h_{mixed} = \frac{0.012\ kg/s * 403.12\ kj/kg + 0.247\ kg/s * 57.5\ kJ/kg}{(0.012\ kg/s + 0.247\ kg/s)} = 73.51\ kJ/kg$$

The final temperature can now be determined:

$$T = \frac{73.51\, kJ/kg\ - 2500 * 0.018\ kg/kg}{1.006 + 1.82 * 0.018\ kg/kg} = 27.45\, ^oC$$

Sizing of catalytic converter

The size of the catalytic converter can be determined using Equation 25.

Using parameter from (Heck et al, 2009), we will determine the cross-sectional area and length of the catalysts substrate assuming a 350/5.5 squared-cell configuration (250 cell/in^2 and wall thickness of 5.5".

Geometric properties of 350/5.5 honeycomb substrate:

Wall porosity = 24%

Length = 0.14 cm

Thickness= 0.014cm

GSA = 26.4 cm^2/cm^3

OFA = 80.5%

Properties of measured flue gas measured (Page 35):

Incoming velocity =1.7 m/s
Inlet pipe area = 0.0059 m^2

$$V_e = 1.7\frac{m}{s} \times 0.0059m^2 = 0.01003\frac{m^3}{s}$$

$$A = \frac{V_e}{v * OFA} = \frac{0.01003\frac{m^3}{s}}{1.7\frac{m}{s} * 0.805} = 0.00733\ m^2$$

The length of the substrate can vary. In this situation, we will assume a length of 12 in (length of the converter used).

$$V = A \times l = 0.00733\ m^2 * 0.3048m = 0.00223\ m^3$$

$$TSA = GSA \times V = \left(26.4\frac{cm^2}{cm^3}\left(\frac{1m^2}{10^4cm^2}\right)\left(\frac{10^6cm^3}{m^3}\right)\right) * 0.00223\ m^3 = 5.88m^2$$

Pictures of Actual Prototype