CARBON SEQUESTRATION VIA AUTONOMOUS BIOCHAR PROCESSING

Preliminary feasibility study of a gasification power unit for co-producing syngas and biochar.

BREE 495 Senior Design Project: Final Design

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Executive Summary

In Canadian agricultural operations, especially now in a time of economic uncertainty, it is always important to be looking to find new and innovative ways to add value and reduce cost in every facet of farm operations. We have laid down the theoretical ground work necessary along with having fabricated a first prototype's design to take the initial steps to verify the feasibility of an autonomous machine that can harvest agricultural waste (for example corn stovers or sugar cane waste). The machine would require no energy inputs as it is powered by a gasification unit creating synthesis gas also known as "Producer Gas" that then powers the operations of the machine and also creates biochar. The biochar is rich in carbon and is used as a soil amendment which helps make the soil more productive without the need for further fertilizers in most cases. Removing agricultural waste to create energy means the loss of organic matter and vital nutrients from the soil that then need to be added typically via chemical fertilizers. By converting the biomass into biochar and entering it back into the soil we are not depriving the soil of vital nutrients. This means farmers would save on fertilizer costs, reduce environmental impacts from agriculture runoff, as typically happens with added fertilizer and a new benefit for most agricultural operations creates an opportunity for a carbon credit as the process would be carbon negative.

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Introduction:

With increasing greenhouse gases carbon credits have become popular. New and innovative technologies are being researched and developed to create carbon credits via carbon sequestration. Legislation is being reworked and policy makers are working on new ways to create and market carbon credits.(IBI, 2010) These emerging carbon markets present an opportunity to allow farmers to capitalize on an existing resource they have and have additional economical benefits. One avenue being researched is the use of biochar as a soil amendment for carbon sequestration. Much research has been done on the creation of biochar from different biomass sources.(Gaunt and Lehmann, 2008; IBI, 2010; Laird et al., 2009; Mahinpey, 2008; Major, 2010; Mathews, 2008; Nader et al., 2009; Özçimen and Ersoy-Meriçboyu, 2010; Tenenbaum, 2009) Utilizing agricultural residues a farmer could avoid the food versus fuel debate and create a possible extra revenue source via carbon credits. The use of biochar as a soil amendment is also a way to increase soil health. (IBI, 2010) In some situations where agricultural residues are in excessive quantity and need to be removed they could instead be converted into biochar. This process could reduce cost of transporting and disposing of crop residues.(Babu and Pratik, 2009) Gasifiers have been utilized in the past to create syngas to power cars and heat homes. In the 21st century this old technology is being revisited for its ability to help sequester carbon with biomass via pyrolysis process. This means sequestering carbon and syngas to be used as a biofuels to power the operations hence no outside energy source is needed making the process carbon negative.

Problem statement:

Can we fabricate a gasifier unit capable of producing a quality biochar and sufficient syngas to power an autonomous machine capable of harvesting biomass and applying the biochar into the soil?

Previous Research (Literature Review):

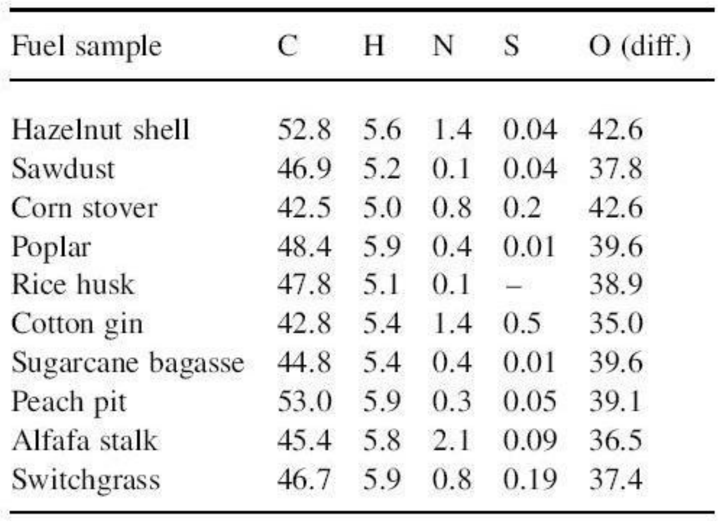
Biomass:

Biomass is the name given to all biologically produced living matter.(Babu and Pratik, 2009) Biomass fuels can include such feedstock's as wood, short-rotation woody crops, agricultural wastes (ex. Corn stovers and cobs), short-rotation herbaceous species, wood wastes, bagasse, industrial residues, waste paper, municipal solid waste, sawdust, bio-solids, grass, waste from food processing, aquatic plants and animal waste, even animal waste can be a significant biomass resource for energy production.(Demirbas, 2004a) Biomass has been said to encompasses the world's largest energy resource available.(Nader et al., 2009) Other estimates place Biomass worldwide ranking at 4th with 14% of the world's energy being produced with biomass.(Demirbas, 2004a) In developing countries it is estimated that biomass is responsible for 35% of primary energy produced.(Balat, 2008) One of humanities first energy sources was biomass and remains a very important resource in many rural and developing parts of the world where accessible and affordable energy source are scarce leaving biomass as one of the only options available.(Demirbas, 2004a) One very attractive property of biomass that is increasing its popularity over fossil fuels is the fact that is does not increase atmospheric carbon dioxide.(Balat, 2008) Biomass absorbs carbon dioxide (CO_2) during its growing life and then releases or emits it during decomposition or combustion making it carbon neutral.(Demirbas, 2004b) Biomass is largely being used in direct combustion however thermochemical processes such as Pyrolysis and gasification have been gaining interest. Thermo chemical processes transform the biomass energy into more easily handled fuels in the forms of gases (Syngass or producer gas), oils and solids (biochar). Utilizing these thermochemical processes or Thermochemical conversion (TCC) biomass is a promising means of renewable energy.(Babu and Pratik, 2009) Biomass-derived charcoal or biochar can have high carbon content that can be very stable meaning that biochar is sequestering carbon in the soil and has been recognized for this by organizations such as the United Nations Convention to Combat Desertification. (Tenenbaum, 2009)

Biomass Composition

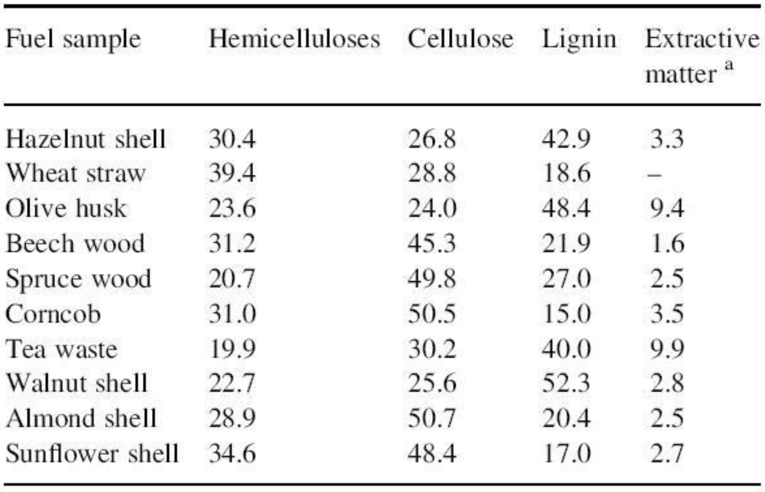
Different biomass materials have different compositions which makes research behind the makeup of biomass materials very important for biochar production. Carbohydrate compounds are the main component of biomass, with the main building blocks being carbon, hydrogen, oxygen and nitrogen. It is also important to look at the cellulose, hemicelluloses and lignin content of the biomass(Balat, 2008) which can be found in the appendix 1-4

Table 1, Ultimate analyses of typical fuel samples given in the literature (wt. % of dry fuel with ash) ref.(Demirbas, 2004a)



Fuel sample	C	H	N	S	O (diff.)
Hazelnut shell	52.8	5.6	1.4	0.04	42.6
Sawdust	46.9	5.2	0.1	0.04	37.8
Corn stover	42.5	5.0	0.8	0.2	42.6
Poplar	48.4	5.9	0.4	0.01	39.6
Rice husk	47.8	5.1	0.1	–	38.9
Cotton gin	42.8	5.4	1.4	0.5	35.0
Sugarcane bagasse	44.8	5.4	0.4	0.01	39.6
Peach pit	53.0	5.9	0.3	0.05	39.1
Alfafa stalk	45.4	5.8	2.1	0.09	36.5
Switchgrass	46.7	5.9	0.8	0.19	37.4

Table 2, Structure of selected biomass samples (wt. % daf)ref.(Demirbas, 2004a)



Fuel sample	Hemicelluloses	Cellulose	Lignin	Extractive matter [a]
Hazelnut shell	30.4	26.8	42.9	3.3
Wheat straw	39.4	28.8	18.6	–
Olive husk	23.6	24.0	48.4	9.4
Beech wood	31.2	45.3	21.9	1.6
Spruce wood	20.7	49.8	27.0	2.5
Corncob	31.0	50.5	15.0	3.5
Tea waste	19.9	30.2	40.0	9.9
Walnut shell	22.7	25.6	52.3	2.8
Almond shell	28.9	50.7	20.4	2.5
Sunflower shell	34.6	48.4	17.0	2.7

Using the characteristics of the biomass it is possible to calculate the higher heating value (HHV) of the biomass. HHV is the gross heat of combustion including the latent heat of water vapor products of combustion.(Demirbas, 2004a) typically the lignin content for herbaceous species such as bagasse, corncobs, and straw have 10% to 40% lignin by weight.(Balat, 2008) More biomass properties of various materials are available in the appendix 1-4.

Design Comparisons:

Different styles of gasifiers have been around for some time however not all gasifiers are designed or operate in the same manner below is a quick contrast of the different style gasifiers.

Tubular Batch type Pyrolysis Reactor

Biomass in a pressurized entrained flow reactor has been investigated to see the effects of pressure on Pyrolysis. These systems are batch type units that typically are very adjustable and controllable with respect to heating rates, temperatures, and pressures.(Nader et al., 2009) The down side to this system is that while one batch is being processed no new material can be handled making the use for this reactor type less suitable for a continuous flow operation.

Updraft Imbert Gasifier

The updraft gasifier was used for over 150 years with coal and WW2 style updraft gasifiers still make the majority of South Africa's gasoline. In an updraft gasifier fuel is added through air tight sealed lid that must be opened to add fuel. Air is blown from the bottom and exits the top. There is a reduction zone on the bottom followed by a combustion zone, pyrolysis zone and a drying zone. A disadvantage for biomass as a fuel for this gasifier system is the air flow path. As the air flow travels from the bottom up through the pyrolitic zone the hot reducing gases come into contact with the newer cooler biomass and the gases cool. The cooler gas then doesn't have enough heat to crack the tars, leaving tars to travel with the gas into the exit pipes and ultimately into the machinery and engines (if attached to an engines). The tar from a updraft gasifier can clog and destroy a gasifier fairly quickly making this system not recommended for biomass.(Reed and Das, 1988) In appendix 5 there is a schematic of an updraft gasifier.

Down draft Gasifier

In a downdraft gasifier there is 4 distinct zones similar to the updraft gasifier. The zones starting from highest to lowest (entry point of the fuel hopper working down to the hearth) are:

1. Drying
2. Pyrolysis
3. Oxidation
4. reduction

In an Imbert downdraft gasifier has a throated combustion zone, a stratified down draft gasifier has a uniform dimension from biomass hopper to combustion zone.(Babu and Pratik, 2009) The zones can be seen in appendix 5and 6 The air is pulled from the fuel hopper down through the biomass and combustion zone where it now contains syngas and continues to travels out of the bottom where it can be piped into a combustion engine to replace fossil fuels. A downdraft gasifier can be run under suction or under pressure, either pressure applied from the fuel hopper or suction by a blower on the gas outlet to cause suction or from the down stroke of the engine. (Reed and Das, 1988) The air flow through the downdraft gasifier and the reactions taking place in different zones can be seen in the schematic in appendix 6.

Design Selection:

We have chosen to test the feasibility of quality biochar production and sufficient syngas from the designs available from the Federal Emergency Management Agency's (FEMA) simplified wood gas generator for fueling internal combustion engines designs. The manual for building the wood gas downdraft gasifier have been made publicly available from FEMA for the use in case of a petroleum emergency. These designs are made to be easily fabricated by any small engine mechanic with basic metal fabrication skills. We will not be following the fema design instructions and dimensions, however we will use them as a guide while designing and building our prototype. In appendix 7 you can see the schematic view of the stratified, downdraft gasifier FEMA has labeled. The internal combustion engine we are designing the gasifier to run is a Briggs &Stratton Intek I//C 206 one cylinder naturally aspirated 4 stroke gasoline engine.

Using the sizing chart in appendix 13 to size the firetube for the Briggs &Stratton engine being used for the prototype we can obtain dimensions for the firetube. The engine is a 5 horse power engine therefore we need a minimum firetube diameter of 2 inches and a minimum length of 16 inches. It has been recommended to avoid bridging of the biomass (biomass forming a hollow region) to not use a firetube diameter of less than 6 inches, so our design will include a 6 inch minimum firetube diameter. It should be noted as this apparatus would be mounted on a vehicle bridging will be avoided by the constant vibration of the vehicle. (LaFontaine and Zimmerman, 1989)

Design Modifications:

For the purpose of this project we will be looking into producing high yields of biochar and producer gasses. Hence from what can be observed through the literature and research is that an optimization point between slow and fast pyrolysis has to be found. The data used to compute the approximate temperature ranges for the pyrolysis process was obtained through the research done on rapeseed by Karaosmanoglu in 1999. The reason behind looking at rapeseed is that we are interested in using corn (corn cobs or corn stovers) as our biomass and comparing appendix 10-12 we can see that rapeseed and corn have similar characteristics. What we can observe from appendix 8 is that biochar has higher yields when the temperature ranges are between 300 degrees Celsius and 500 degrees Celsius. Furthermore, looking at appendix 9 we can observed that the gaseous yields increases when temperatures range between 400 degrees Celsius to 500 degrees Celsius. Hence we are looking to use the FEMA Downdraft Gasifier at temperature between 400 degrees Celsius and 450 degrees Celsius for the scope of this project.

Autonomous vehicles

Autonomous vehicles are important because it helps to reduce the complexity and difficulty of field operations and improve efficiency avoiding overlap and skips to a minimum.

Systems as crop detection uses a forward looking laser scanner that sweeps an arc over the edge of the standing crop, this has been created because harvester are larger than before and visibility is limited. Another sensor is the light bar of graphic display, which makes the tractor drive in a straight line and parallel to the last line minimizing overlaps and skips (Blackmore and Griepentrog, 2006).

An autonomous vehicle must be capable of working without an operator. It must have and autonomous behaviour, meaning "sensible long-term behaviour, unattended, in a semi-natural environment, while carrying out a useful task". The operation of an autonomous vehicle can be divided in two parts: task, like navigate, plough, or seed, and behaviour, which is the way in which it carriers out the task. (Blackmore and Griepentrog, 2006).

Sensing system installed in the vehicle must have the ability to react to new or unknown situations.

Sensors give proximity data relative to the vehicle. The two most commonly non-contact range finders used are ultrasonic range finder and laser scanners. Ultrasonic rings are made from a number of range ultrasonic rangefinders set around the vehicle, this emits a directed ultrasonic chirp and the time taken to pick u the return echo is proportional to the distance to the reflected object. The operating range is between 20 cm and 10 meters with a 30 degree dispersion angle. Laser scanner are used to detect and intersecting surface profile from a laser plane. Laser emits a pulse rotating beam at 75 Hz through 180 degress and the distance to each point is calculated at 1 degree intervals (Blackmore and Griepentrog, 2006).

Most robotic system under development assume that all obstacles are consider to have infinite high and must be avoided (2.5D world). Sensing targets are waypoints, crop rows, or even and individual plant.

There are multiples autonomous vehicles used by researchers, one of those is ROBOTRA (Figure 1).

ROBOTRA was designed as a tilling robot at the institute of agricultural machinery in Saitama, Japan since 1993. It was developed using a commercial tractor, leaving intact its functions such as shuttle gear, a by-speed turning system and automatic depth and level control for rotary tiller. Tractor that has been retrofitted with a range of positioning systems (RTK GPS, surveying grade laser rangefinder, odometer, digital compass, and inertial measurement) and control systems to interface with the tractor to allow high levels of automation (Blackmore and Griepentrog, 2006).

ROBOTRA has a main controller where the navigation information is input. The main controller used a factory computer that allows easy modification and replacement of software programs with various I/O boards for the input and output signals.

The fact that ROBOTRA has a software that is been developed to execute different tasks as seeding and soil padding (Yosuke et al.), makes this vehicle attractive to be used in our project.

Taking advantage of it mechanicals attributes and the main controller software, we can modify it to pickup agricultural residues from the field to the gasifier.

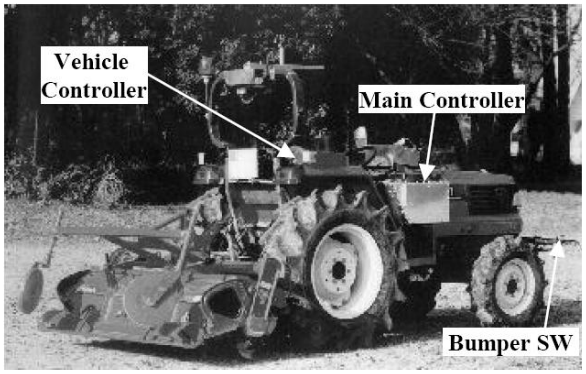


Figure 1. Robotra

Analysis:

Energy balance

For this project to be worth further investigation we must be able to produce enough energy from burning the syngas to meet the energy requirements for the field operations. To do this we must find the energy needs of the tractor to process an acre of land using only the residues from an acre of land.

The energy needed to run the autonomous tractor “Robotra” is 23.1Kwatts or 31.5 horsepower (hp), this vehicle can be fitted to be multipurpose and do more than just tillage meaning it could have a harvester head attached to pick up crop residue as well.(Matsuo et al., 2001)

We must now determine the energy we can expect from the agricultural residue. We have chosen to do this analysis for corn as it has been extensively studied.

According to research done at the University of Agriculture Faisalabad the amount of gas produced from corn gasification is 35m3 per 18 kg of corn gasified.(Ahmed, 2011)

Research done at the University of California Davis, has concluded that the gas produced from the gasification of corn has a net gas calorific value of 5464kJ/m3.(R.O. Williams, 1979) This is further substantiated by the research done by Robert C. Brown that states for an air-blown downdraft gasifier the energy content of the producer (syngas or biogas) gas is 5.5MJ/m3 or 5500 kJ/m3.(Brown, 2003a)

Now we can calculate the amount of joules per kg of corn residue.

Equation 1 (Corn Energy Density)

$$5464\frac{\mathrm{kJ}}{\mathrm{m}^3}*\frac{35\mathrm{m}^3}{18\frac{\mathrm{kg}}{\mathrm{corn}}}=\frac{191240\mathrm{kJ}}{18\frac{\mathrm{kg}}{\mathrm{corn}}}=10624.45\frac{\mathrm{kJ}}{\text{kg of corn residues}}$$

According to research at the Ohio State University we can expect 6000 lbs or residues per 100 bushel acre.(Myers, 2007)

We will use an average of 151.1 bushels of corn per acre as this is what was found to be the average since 2004. This was reported by the National Agricultural statistics Service for the United States Department of Agriculture (USDA) by Ellen Dougherty.(Dougherty, 2007)

Now we can calculate the total energy per acre of corn.

Equation 2 (Residues)

$$\frac{151.1\text{ bushels of corn}}{\text{acre}}*\frac{6000\text{ lbs of residues}}{100\text{ bushels of corn}}*\frac{0.453592\mathrm{kg}}{1\text{ lb}}=4112.27\text{kg of residues}$$

This means we can expect 4112.27kg of residues per acre of corn

We can now calculate the total amount of energy per acre:

Equation 3 (Energy per Acre)

$$4112.27\text{kg of residues} * 10624.45\frac{\text{kJ}}{\text{kg of corn residues}} = 43690.55\text{MJ}$$

If we run the Robotra tractor at 100% using ass 31.5hp we will be using 23.5kWatts or 23.5kJ/s, if we assume an average travel speed of 3 km/hr and a working width of 1.5m (two rows of corn a pass) we will have a total operation time per acre of

Equation 4 (Distance travelled)

$$\frac{10000\text{m}^2}{1.5\text{m}} = 6666.7\text{m}$$

Equation 5 (Time required to process)

$$\frac{6666.7\text{m}}{3000\frac{\text{m}}{\text{hour}}} * \frac{3600\text{seconds}}{1\text{hour}} = 8000\text{ seconds}$$

With a running time of 8000 seconds and an energy requirement of 23.5kJ/seconds, it will require 188000kJ or 188 MJ. This is far below the expected amount of energy expected from the corn residues.

Prototype Design Section:

Materials:

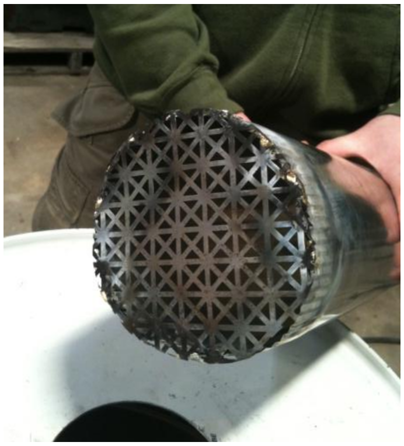
- 55 gallons metal drum
- Fire tube
    - Tin stove pipe 6in x30in
    - Wire mesh (6in circle)
    - Liquid Gasket
- Basket assembly
    - Wire mesh(17.3in by 16inches)
    - Tin sheet metal (2 x 30in by 2in strips)
- Gas Routing
    - Galvanized steel pipe 2in dia. (6in)
    - Galvanized steel pipe 1½in dia.(4in pipe)
    - Galvanized steel reduction pipe 2in to 1½in.
    - Cast Iron WYE 1½in dia.
    - Copper pipe 1 in dia.
    - Reducer from 1½in to 1in.
    - Reducer from 1in to ¼in
    - ¼in air compressor hose fittings.
    - Solid Bras cylinder insert(17.54mm long with a diameter of 13.69mm)
    - Air valve
    - Pluming tape

Building Procedure:

1. Make a 6 in diameter whole in the top of the 55 galon drum
    a. We did this with a 6in whole saw and a drill press

Figure 2 (Barrel with 6in. hole)

2. Cut out 6in diameter circle from metal mesh



3. Braise metal mesh circle to tin stove pipe

Figure 3 (tin pipe with mesh bottom)

4. Braise tin pipe into barrel, leaving 6in. exposed, seal with liquid gasket

Figure 4 (Tin Pipe in barrel with seal)

5. Roll metal mesh for basket into a 5.5in diameter and spot weld.
6. Braise metal mesh bottom cap similar to step 3 but with 5.5in diameter
7. Spot weld on two handles with 2in. of handles secured to basket.
8. Bend handles to form grips.

Figure 5 (basket assembly)

9. Using pluming tape assemble galvanized pipes together to form gas routing apparatus (see image) ensuring that the compressor attachment port is secure and not leaking.

Figure 6 (First routing setup)

Preliminary testing Phase 1:

Suction test:

We now tested the systems for suction by using the acetylene torch to create smoke to map the air flow.

Suction Test Results: Venturi:

Initially for our gas outlet design we had the 1’’ ½ inch Wye pipe attached to an apparatus of galvanized steel piping as shown in the **Error! Reference source not found.**. We had the inlet for the compressed air attached to the Wye pipe and the air ran straight into the piping. The goal of running the compressed air was to create a suction which would suck in the producer gas and mix it with the air. However, with the initial design a problem occurred, because air is an incompressible fluid. Hence, air was blowing out of the outlet and air was also blowing back into the barrel which was not the desired outcome. A new design solution needed to be taught of to be able to overcome this obstacle. The solution was found in a fluid dynamics property, a venturi tube.

Figure 7 - initial design

The venturi tube uses two principles, the laws governing fluid dynamics and conservation of energy. As the fluid goes through a change in cross sectional area from bigger to smaller its velocity increases hence it is accelerated(Mott, 1990). Furthermore while it is going through the smaller section called the "throat" the pressure of the fluid is decreased as it can be observed below in **Error! Reference source not found.**. Hence by having a pressure decrease to satisfy the conservation of energy we can have a suction effect.

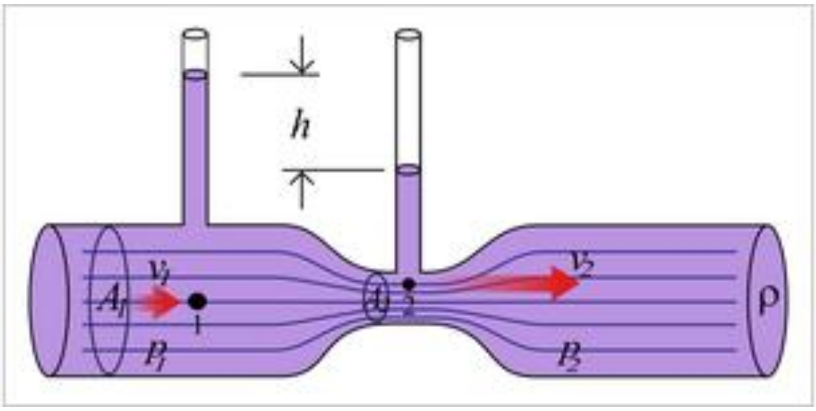


Figure 8 - venturi tube (Wikipedia, 2011)

Therefore, by using the principle behind the venturi tube we were able to build a pipe of varying diameter which was inserted into our Wye pipe to create suction. After the venturi tube was attached another suction was performed on both the venturi tube and the entire gas routing apparatus. Both suction tests with the venturi in place succeeded. **Error! Reference source not found.**, shows how the gas outlet looked at after its modifications.

Figure 9 - Final Design with venturi attached

Below you can find several images of the brass insert placed inside the copper tube to create the venturi.

Figure 10 (placement of brass Insert In Cooper Pipe)

Figure 11 (Brass outer diameter)

Figure 12 (Brass inside Diameter)

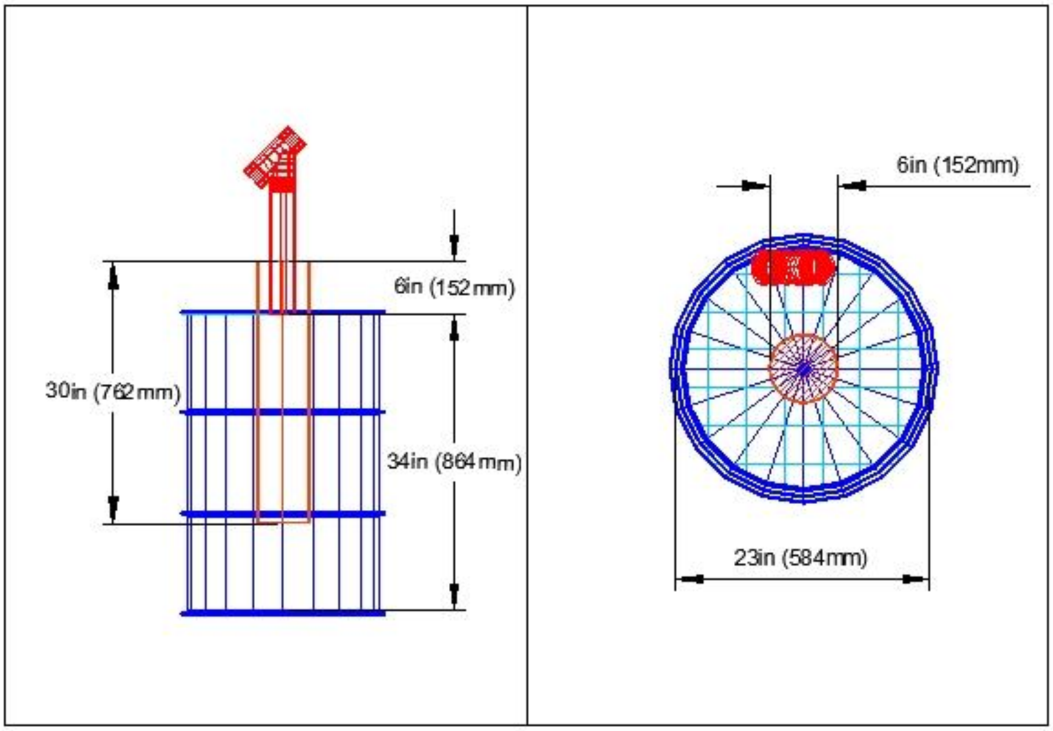
The brass cylinder was machined on the lathe to have two smooth reductions at 60 degrees to create the funnel effect in the venturi. The brass Fitting was inserted in the cooper tube and press fitted. This completed our build process of the prototype.

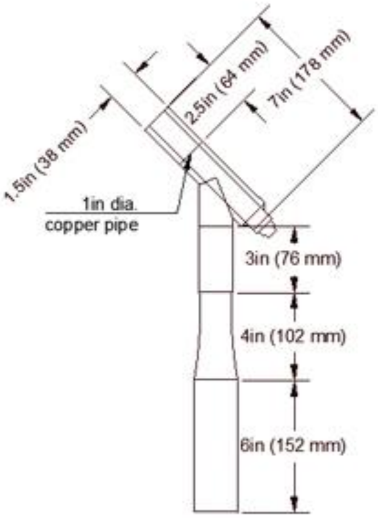
Testing of biomass fuel:

We used corn silage to for our biomass which we received from the MacDonald Farm and did an initial test to determine the moisture content, these can be found in appendix 16.   The initial moisture content (wetbulb, %) of the silage was 58.46%. The high moisture content made the biomass unusable to burn. Hereafter the biomass was left to dry for 48 hours, which then gave a new moisture content (wetbulb, %) of 56.67%. The method of drying of the biomass was open air drying at room temperature. A moisture content drop of 1.79 % was still not low enough. After 72 hours of drying, the biomass reached moisture content (wetbulb, %) of 28.24%. However, the moisture content was still too high. After 168 hours of drying the biomass reached a moisture content (wetbulb, %) 5.5%, which was a sufficient moisture content to use in the gasifier.

Schematics:

Figure 13 (AutoCAD DWG of final Prototype)





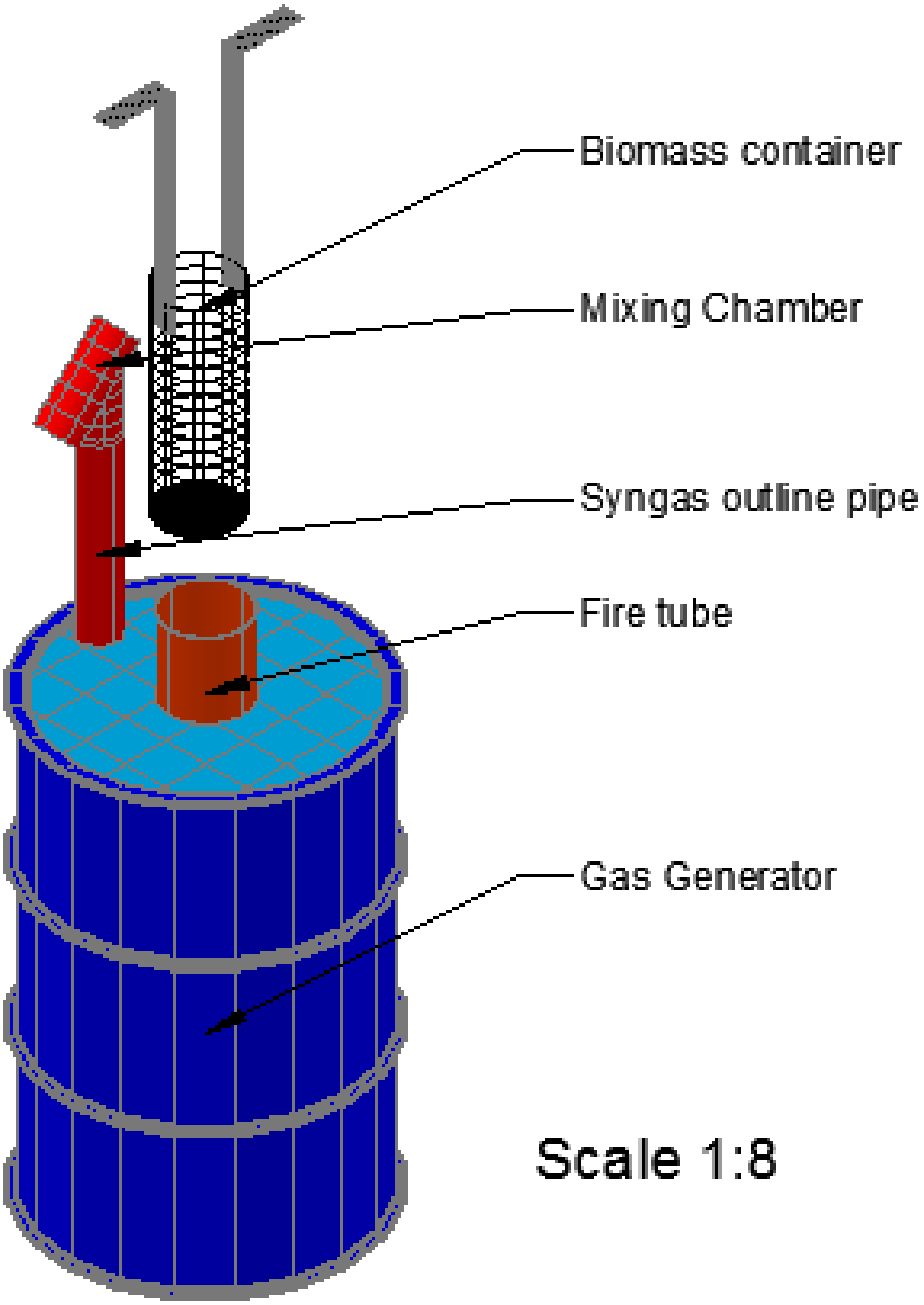


Figure 14(Final 3D Prototype Design)

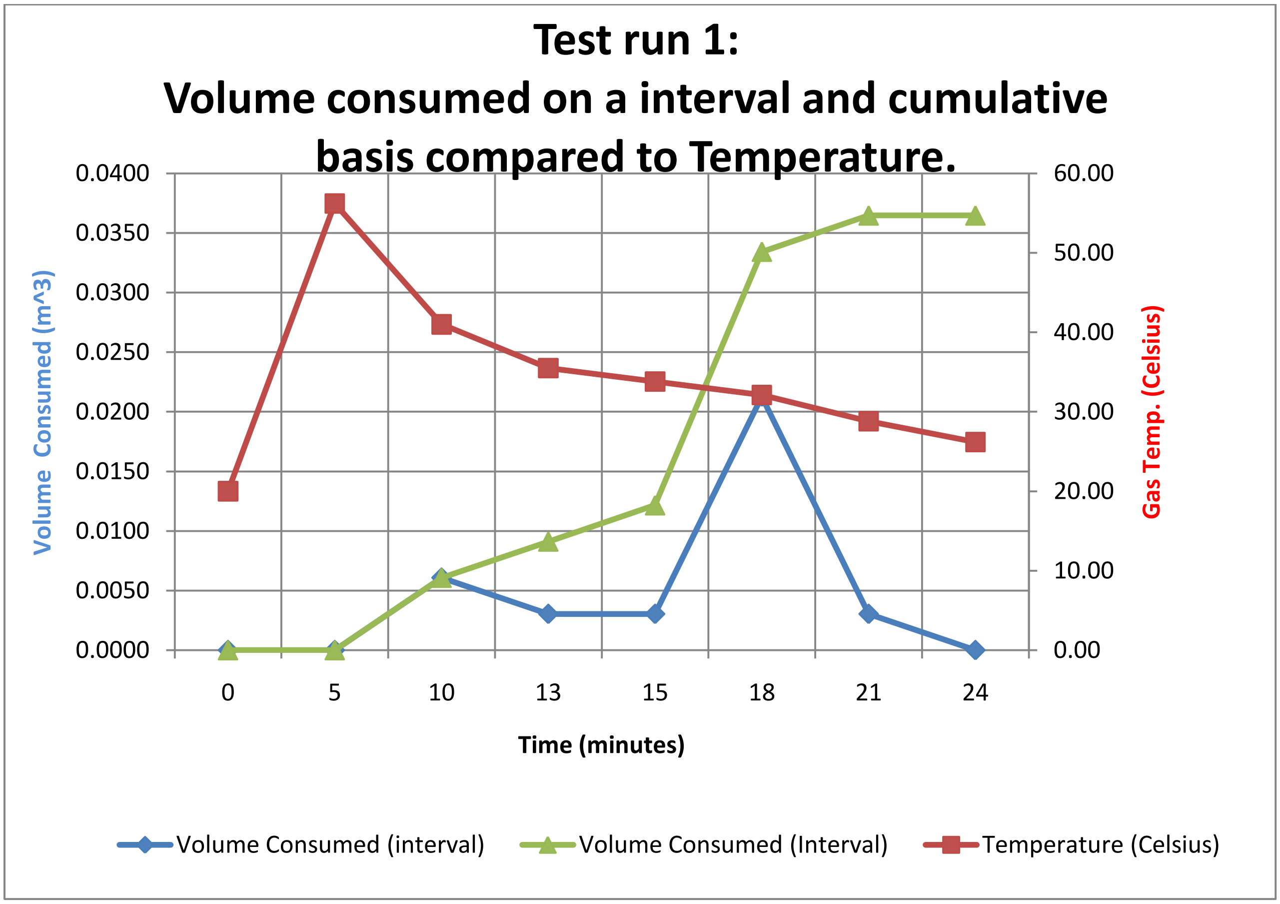
Results:

Test Data:

We had sufficient time to do two final test runs monitoring biomass consumption rates and temperature of the gas. We monitored the gas temperature 2 inches from the top of the barrel with a thermocouple. We monitored the biomass consumption rate by measuring the height of the biomass in the firetube.

The tests were done with corn silage, the test started by lighting a small amount of biomass in the basket and once a good flame had developed we placed the basket in the firetube and started the compressor which produced the downdraft. The next step is to add biomass to fill the firetube. Measurements were taken periodically.

Below is a graph of the first test data, this can also be found with a table of values in Appendix 14.

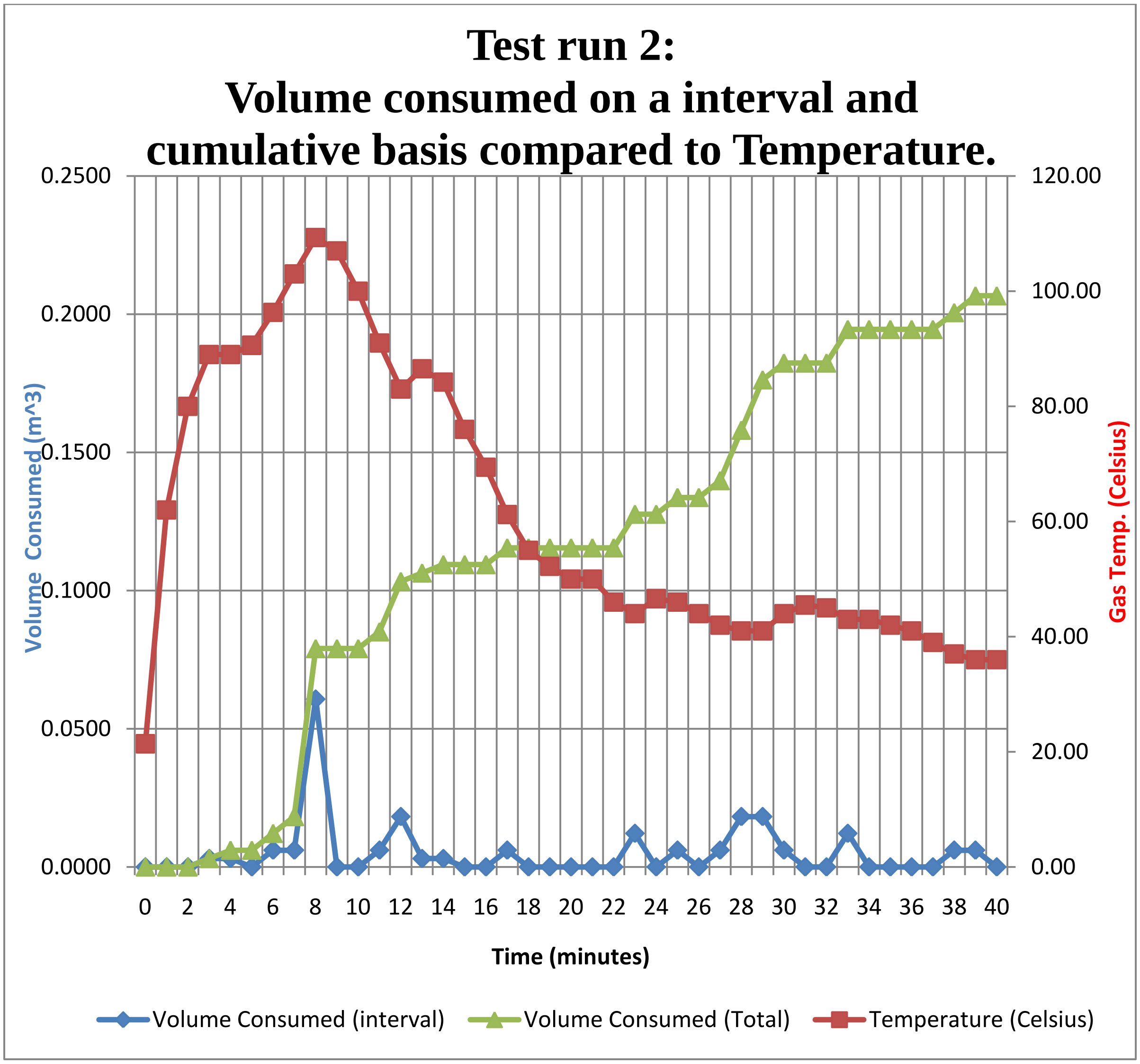


We can see that there is a large increase in consumption rate (blue line) that corresponds with the total consumption line , however a drop in temperature occurs, this is counter intuitive. What has happened is bridging has taken effect within the fire tube and then the bridging gave way and we get a sudden drop in biomass height in the firetube however very little biomass is being consumed or rather thermo chemically converted to gas.

Bridging is when the biomass forms a block in the firetube and a void is created below the bridging area.

When we say the temperature fall below 30 degrees Celsius we ended the burn. Upon removing the basket we could see that the basket had been clogged by bridging due to tar build up. This can be seen in Figure 16 - tar clogging fire tube.

The second test was started the same way as test one however we agitated the basket more frequently to prevent bridging. Below is the graphical representation of the collected data for the second test run.



The full test results can be seen in appendix 15 This test started similar to the previous test however with agitations every minute the temperature climbed higher than the peak 600C that we hit before, this time a temperature of 1100C was reached however even with agitation we ended up having bridging. On the graph a bridging event can be seen when a plateau in the green line or a zero on the blue rate line is followed by a sharp increase. This is because the biomass bridges, so no material is being consumed, then the bridging area collapses giving a steep biomass height reduction. We can see a pattern of no consumption then peak in the rate of volume consumed line on the graph. Bridging with this experimental prototype gasifier is a problem.

In both test the desired temperature range of 400-450 degrees Celsius was never reached and a flammable gas was never produced.

Optimizations:

Going forward with this design there are several points that need to be addressed, the main points of optimization to further this project are listed below.

Throat:

While running tests on the gasifier tar build ups became a major problem in our design. The tar is produced through the burning of the biomass. What was observed during the test runs of the gasifier is that the tar build up clogs the piping and the fire tube. Once blocked the gas outlet piping reduces the amount of air-gas mixture hence, not enough gas is available to run an engine. The other big problem is the tar builds up in the fire tube, which helps bridging. Bridging prevents the biomass from being consumed at proper rates. The tar build up can be observed in **Error! Reference source not found.** and **Error! Reference source not found.**.

Figure 15 - tar clogging gas outlet

Figure 16 - tar clogging fire tube

The solution to the tar problem is building what is called a throat section into the gasifier as shown in **Error! Reference source not found.**.

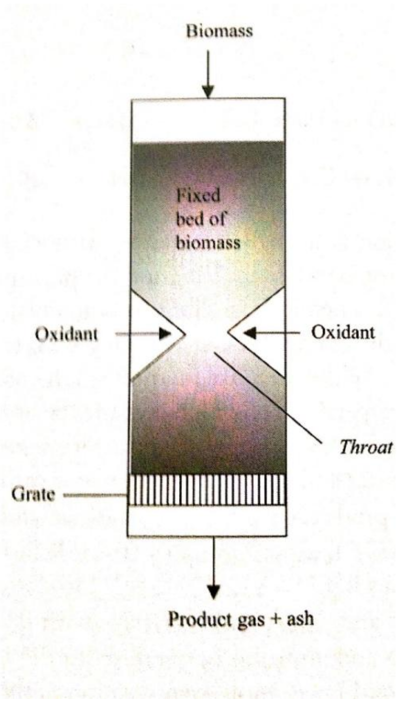


Figure 17 - Throat section

The throat is air or oxygen that is directly admitted into the section where combustion takes place. Hence the condensable gases released during pyrolysis are forced to go through a hot bed of char(Brown, 2003b). When the producer gases passes through the hot bed of char it cracks or thermally decomposes the tars. Hence, using a throat reduces the tar to an acceptable level of about 1g/m3. Hence optimizing our design would include building a throat section where air or oxygen will help decompose the tars. Furthermore, using a throat section reduced also the compaction or sintering of the ashes also known as bridging(Brown, 2003b).

Filter Unit:

As mentioned in the testing section….. According to the FEMA Design manual (LaFontaine and Zimmerman, 1989) a filter unit is needed to trap tars and particulate before it reaches the engine. Tars and particles can cause damage to the engines and greatly reduces efficiency and engine life. In the FEMA schematic in appendix 7 you can see the filter unit.

Gas Cooler:

According to the FEMA emergency wood gas generator documentation for every 10degrees above 70^0F above you lose 10% of your horse power. The expected exiting gas should be approximately 180^0F. This is caused by the low energy density of syngas (woodgas or producer gas) which needs to be cooled to increase its energy density.(LaFontaine and Zimmerman, 1989) With this decrease in efficiency it is imperative that we cool the gas before attempting to run it in an engine. Below are the calculations for a gas cooler to meet the requirements to cool the gas from 180^0F to 70^0F. These calculation are sized for the Briggs &Stratton Intek I//C 206 one cylinder naturally aspirated 4 stroke gasoline engine available in the Bioresource Engineering machine shop.

Goal: to find the ideal length for a cooling pipe made from a 1in diameter copper pipe to bring the temperature of the air – gas mixture from 180 F (82^0c = 355 k) to 70 F (21^0c = 294 k).

Assumptions:

- Air at 2atm
- Use properties of air because the output gas is a mixture of gas and air. The properties of air have higher values then that of the gas which are too small to make a difference.
- $\mu_{air} = 2.56 \times 10^{-5}$ kg/m sec(Holman, 2006)
- $k_{air} = 0.0386$ W/m ^{0}c(Holman, 2006)
- cp = 1.025 Kj/Kg ^{0}c(Holman, 2006)
- u_m=velocity of air = 12.9m/sec(Holman, 2006)

- d = diameter of pipe (1 in copper) = 2.53cm = 0.0253m

We can start by calculating the density of air ρ

$$\rho = \frac{P}{RT}$$

R = gas constant

P = pressure

T= temperature (kelvin)

$$\rho = \frac{2atm\ x\ (1.0132\ x\ 10^{5})}{287\ x\ 355}$$

Equation 6 – Density (Holman, 2006)

Then we can calculate the Prandlt number

$$\mathrm{Pr} = \frac{{}^{\mu}/_{\rho}}{{}^{K}/_{\rho\ cp}}$$

μ = dynamic viscosity in kg/m sec

K = thermal conductivity in W/m ^{0}c

Cp = specific heat coefficient in kJ/kg^{0}c

$$\mathrm{Pr} = \frac{{}^{2.57\ x\ 10^{-5}}/_{1.99}}{{}^{0.0386}/_{1.99\ x\ 1.025}} = 0.683$$

Equation 7 - Prandlt number(Holman, 2006)

Now we can calculate the Reynolds number

$$Re_d = \frac{\rho \ \times u_m \times d}{\mu}$$

u_m=velocity of air in m/sec

d = diameter of pipe

μ = dynamic viscosity in kg/m sec

$$Re_d = \frac{1.99 \ \times 12.9 \times 0.0253}{2.57 \ \times 10^{-5}} = 25271.45$$

Equation 8 - Reynolds number(Holman, 2006)

What we can see from the Reynolds number is that it is between $10^4 < 25271.45 < 5 \text{ x } 10^6$ and that our Prandlt number is between $0.5<0.683<1.5$. Therefore we can use the Dittus and Boelter equation to calculate the Nusselt number by usin g the equation:

$$Nu_d = \frac{hd}{K} = 0.023 \times {Re_d}^{0.8} \times Pr^n$$

h = heat transfer coefficient in W/m^2 ^{o}c

d = diameter of pipe

K = Thermal conductivity in W/m ^{0}c

n = 0.4 for heating or 0.3 for cooling (in our case it is for cooling)

$$Nu_d = \frac{h \times 0.0253}{0.0386} = 0.023 \times 25271.45^{0.8} \times 0.683^{0.3}$$

Equation 9 - Nusselt number(Holman, 2006)

From this we can calculate h = 104.14 W/m^2 ^{o}c

Now we calculate the heat transfer q

$$q = \dot{m}c_p(T_{b2} - T_{b1})$$

q = heat transfer in kW

$$\dot{m} = mass\ flow\ rate\ kg/sec$$

T_{b2} and T_{b1} = temperature

To calculate mass flow rate we used: (GEK, 2009)

- engine displacement =205cm^3 (Briggs and Stratton Intek engine)
- speed RPM = 3800
- 50:50 ratio of gas to air

3800 x 205 = 779000 cm^3/min (total volumetric flow rate)

Since 50:50 actual volumetric flow rate = 389500 cm^3/min

When multiplied by density (in our case of air because all the calculation are made for air) we get a mass flow rate = 0.0129 Kg/sec

$$q = 0.0129 \times 1.025 \times (-61) = -0.81\ kW$$

Equation 10 - heat transfer rate q(Holman, 2006)

As we can see from this the heat transfer is negative because of the cooling.

Now we can calculate the length needed to cool the gas from 180 F to 70 F using a q = 0.81 kW

$$\frac{q}{L} = h \times \pi \times d \times (T_w - T_b)$$

Equation 11 - heat flow per unit length(Holman, 2006)

L = length of pipe

h = heat transfer coefficient in $W/m^{2\ o}c$

d = diameter of pipe

T_w = temperature of wall (since copper pipe is thin we are going to assume temperature is same as air gas mixture = 180 F)

T_b = temperature at length L = 70 F

From this we can calculate the length of the gas cooler pipe to be equal to 1.60 meters

Firetube Design:

Our firetube design was designed to have a basket lowered in with biomass. The basket allowed for easy startup, fast system shut down and easy mode of agitation however it caused bridging. The bridging was caused due to the rough surface of the basket. As the basket was fabricated from a metal screen it had many areas where material could stick to and eventually bridge. We would recommend this basket be made of tin similar to the fire tube so as to eliminate any possible bridging sites.

Biochar Removal

Once a successful fast throughput gasifier is found it will be important to devise a way to extract the biochar during operation so as to be able to implement it into the soil. This step is critical that it be done in an air tight method because if done improperly devastating consequences will occur. If air enters at the bottom of the fire tube (refer to appendix 7.) near the grate it could cause the syngas to ignite and destroy the gasifier if not detected soon.(LaFontaine and Zimmerman, 1989). This step is beyond the scope of this project however it is critical for the global idea to be functional.

Conclusion:

From our testing we have identified several failure modes such as bridging and tar build up, these are serious problems that caused our prototype experimental gasifier unit to underperform. With this testing we have determined ways to increase the gasifier unit's performance and overcome the flaws in the current design. We were not successful in producing syngas however from the literature and calculations in this document an autonomous biochar processing platform is feasible.

Acknowledgements

The authors would like to acknowledge and thank the following individuals:

Dr. Mark Lefsrud for providing information and the initial idea to get this project started.

Scott Manktelow, for his guidance and support during the fabrication of the experimental gasifier unit.

Dr. Vijaya Raghavan, for his assistance in overcoming our suction issues.

References:

Ahmed, M. 2011. Research at UAF-Fabrication and Evaluation of a downdraught gasifier operated with biomass for sustainable agriculture.

Babu, B. V., and N. S. Pratik. 2009. Experimental studies on producer gas generation from wood waste in a downdraft biomass gasifier. *Bioresource Technology*(100):3127-3133.

Balat, M. 2008. Mechanism of Thermochemical Biomass cOnversion Processs. Part 1:Reaction Of Pyrolysis. *Energy Sources* 27:620-635.

Blackmore, B. S., and H. W. Griepentrog. 2006. *4.3 Autonomous Vehicles and Robotics*. Blackmore, B. Simon, and Hans Werner Griepentrog. 2006. Section 4.3 Autonomous Vehicles and Robotics, pp. 204-215 of Chapter 4 Mechatronics and Applications, in CIGR Handbook of Agricultural Engineering Volume VI Information Technology. Edited by CIGR--The International Commission of Agricultural Engineering; Volume Editor, Axel Munack. St. Joseph, Michigan, USA: ASABE.

Brown, R. C. 2003a. *Biorenewable Resources*. Ames.

Brown, R. C. 2003b. *Biorenewable Resources*. Engineering New Products from Agriculture. First Edition ed. Blackwell Publishing Professional, Iowa.

Demirbas, A. 2004a. Combustion characteristics of different biomass fuels. *Progress in Energy and Combustion Science* 30(2):219-230.

Demirbas, A. 2004b. Effects of temperature and particle size on bio-char yield from pyrolysis of agricultural residues. *Journal of Analytical and Applied Pyrolysis* 72(2):243-248.

Dougherty, E. 2007. 2007 Corn Crop a Record Breaker, USDA Reports.

Gaunt, J. L., and J. Lehmann. 2008. Energy Balance and Emissions Associated with Biochar Sequestration and Pyrolysis Bioenergy Production. *Environmental Science & Technology* 42(11):4152-4158.

GEK. 2009. Union. Available at: http://wiki.gekgasifier.com/w/page/6123837/Union-based%20gas%20flow%20measurement.

Holman, J. P. 2006. *Heat Transfer*. 3rd ed. McGraw Hill, New York.

IBI. 2010. How does biochar affect soil properties like pH and CEC.

Karaosmanoglu, F. 1999. Biofuel production using slow pyrolysis of straw and stalk of the rapeseed plant. *Fuel Processing Technology*(59):1-12.

Kumar, G., A. K. Panda, and R. K. Singh. 2010. Optimization of process for the production of bio-oil from eucalyptus wood. *Journal of Fuel Chemistry and Technology* 38(2):162-167.

LaFontaine, H., and F. P. Zimmerman. 1989. Construction of a Simplified Wood Gas Generator for Fueling Internal Combustion Engines in a Petroleum Emergency. 1-66. B. E. F. Inc., and O. R. N. L. E. Division, eds. Miami Florida: Martin Marietta.

Laird, A. D., R. C. Brown, J. E. Amonette, and J. Lehmann. 2009. Review of the pyrolysis platform for coproducing bio-oil abd biochar

Biofuels, Bioproducts and Biorefining 3:547-562.

Mahinpey, N. 2008. Analysis of Bio-Oil, Biogas, and Biochar from pressurized Pyrolysis of Wheat straw Using a Tubular Reactor. *Energy and Fuel* 23:2736-2742.

Major, J. 2010. Commercial scale agricultural Biochar field trial in Quebec Canada, over two years. Blue Leaf. Drummondville: B. Leaf.

Mathews, J. A. 2008. Carbon-negative biofuels. *Energy Policy* 36(3):940-945.

Matsuo, Y., O. ukumoto, Y. Irie, N. Ichisugi, H. Terao, and Y. Haga. 2001. Navigation systems and work performance of tilling robot, 2: Specifications of vehicle and controller and work performance tests. *Journal of the Japanese Society of Agricultural Machinery* 63(3):122-129.

Mott, R. L. 1990. *Applied Fluid Mechanics*. 5th ed. Prentice-Hall Inc, New Jersey.

Myers, D. K. 2007. Ohio State University.

Nader, M., M. Pulikesi, M. Thilakavathi, and R. Renata. 2009. Analysis of Bio-oil, Biogas, and Biochar from Pressurized Pyrolysis of Wheat Straw Using a Tubular Reactor. *Energy and Fuels* 23:2736-2742.

Özçimen, D., and A. Ersoy-Meriçboyu. 2010. Characterization of biochar and bio-oil samples obtained from carbonization of various biomass materials. *Renewable Energy* 35(6):1319-1324.

R.O. Williams, J. R. G. 1979. An assessment of the gasification characteristics of some agricultural and forest industry residues using a laboratory gasifier. *Resource Recovery and Conservation* 3:317-329.

Reed, T. B., and A. Das. 1988. *Handbook of Biomass Downdraft Gasifier Engine Systems*. 1 ed. Solar Energy Research Institute, Golden, Colorado.

Tenenbaum, D. J. 2009. Biochar: Carbon Mitigation from the Ground Up. In *Environmental Health Perspectives*. EHP Online.

Wikipedia. 2011. Venturi Effect. Wikipedia. Available at: http://en.wikipedia.org/wiki/Venturi_effect.

Yosuke, M., Y. Satoshi, and Y. Osamu. Development of Tilling Robot and Operation Software. In *Pp. 184-189 in Automation Technology for Off-Road Equipment, Proceedings of the July 26-27, 2002 Conference (Chicago, Illinois, USA)*.

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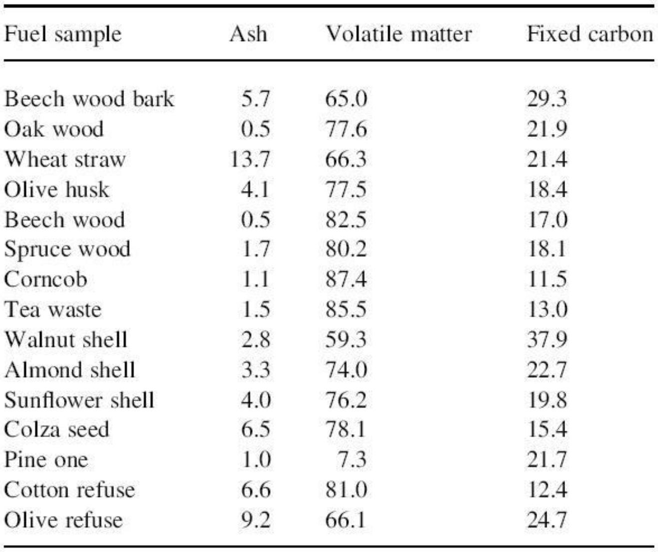
Appendices:

APPENDIX 1, Proximate analyses of the selected biomass samples

(wt.% of dry fuel)

(Demirbas, 2004a)

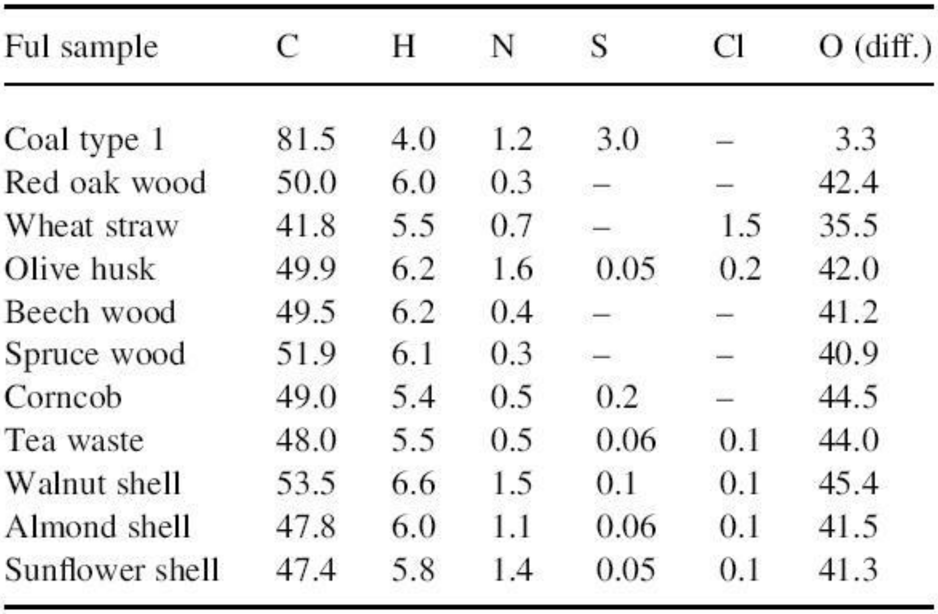


Fuel sample	Ash	Volatile matter	Fixed carbon
Beech wood bark	5.7	65.0	29.3
Oak wood	0.5	77.6	21.9
Wheat straw	13.7	66.3	21.4
Olive husk	4.1	77.5	18.4
Beech wood	0.5	82.5	17.0
Spruce wood	1.7	80.2	18.1
Corncob	1.1	87.4	11.5
Tea waste	1.5	85.5	13.0
Walnut shell	2.8	59.3	37.9
Almond shell	3.3	74.0	22.7
Sunflower shell	4.0	76.2	19.8
Colza seed	6.5	78.1	15.4
Pine one	1.0	7.3	21.7
Cotton refuse	6.6	81.0	12.4
Olive refuse	9.2	66.1	24.7

APPENDIX 2, Ultimate analyses of typical fuel samples

(Wt. % of dry fuel with ash)

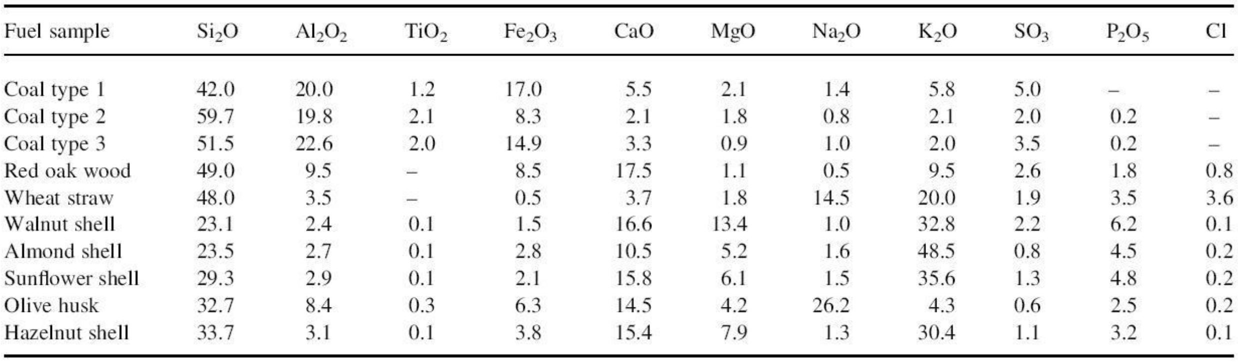
(Demirbas, 2004a)



Ful sample	C	H	N	S	Cl	O (diff.)
Coal type 1	81.5	4.0	1.2	3.0	–	3.3
Red oak wood	50.0	6.0	0.3	–	–	42.4
Wheat straw	41.8	5.5	0.7	–	1.5	35.5
Olive husk	49.9	6.2	1.6	0.05	0.2	42.0
Beech wood	49.5	6.2	0.4	–	–	41.2
Spruce wood	51.9	6.1	0.3	–	–	40.9
Corncob	49.0	5.4	0.5	0.2	–	44.5
Tea waste	48.0	5.5	0.5	0.06	0.1	44.0
Walnut shell	53.5	6.6	1.5	0.1	0.1	45.4
Almond shell	47.8	6.0	1.1	0.06	0.1	41.5
Sunflower shell	47.4	5.8	1.4	0.05	0.1	41.3

APPENDIX 3, Inorganic properties of typical fuel samples (wt% of ash)

(Demirbas, 2004a)

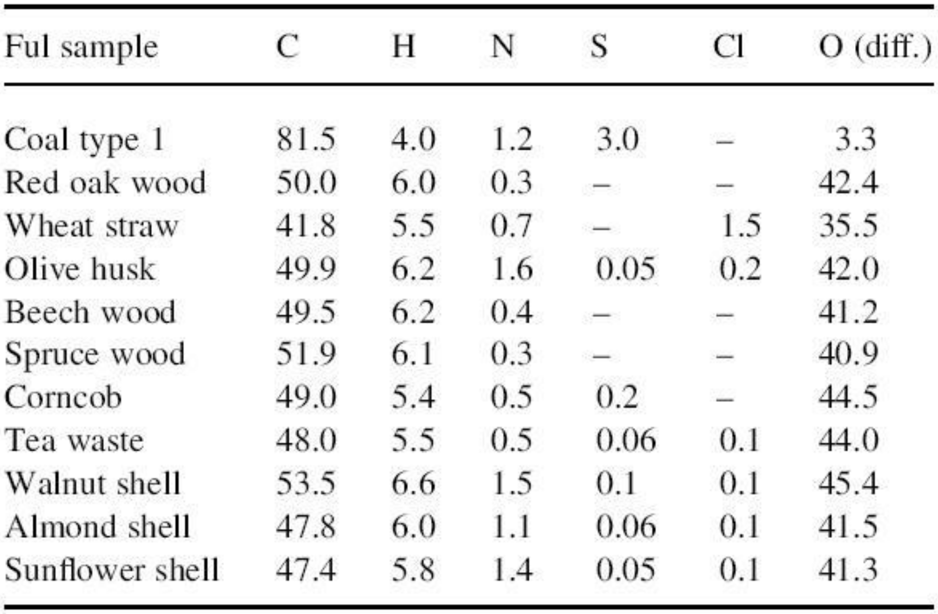


Fuel sample	Si_2O	Al_2O_2	TiO_2	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	Cl
Coal type 1	42.0	20.0	1.2	17.0	5.5	2.1	1.4	5.8	5.0	–	–
Coal type 2	59.7	19.8	2.1	8.3	2.1	1.8	0.8	2.1	2.0	0.2	–
Coal type 3	51.5	22.6	2.0	14.9	3.3	0.9	1.0	2.0	3.5	0.2	–
Red oak wood	49.0	9.5	–	8.5	17.5	1.1	0.5	9.5	2.6	1.8	0.8
Wheat straw	48.0	3.5	–	0.5	3.7	1.8	14.5	20.0	1.9	3.5	3.6
Walnut shell	23.1	2.4	0.1	1.5	16.6	13.4	1.0	32.8	2.2	6.2	0.1
Almond shell	23.5	2.7	0.1	2.8	10.5	5.2	1.6	48.5	0.8	4.5	0.2
Sunflower shell	29.3	2.9	0.1	2.1	15.8	6.1	1.5	35.6	1.3	4.8	0.2
Olive husk	32.7	8.4	0.3	6.3	14.5	4.2	26.2	4.3	0.6	2.5	0.2
Hazelnut shell	33.7	3.1	0.1	3.8	15.4	7.9	1.3	30.4	1.1	3.2	0.1

APPENDIX 4, Ultimate analyses of typical fuel samples

(Wt. % of dry fuel with ash)

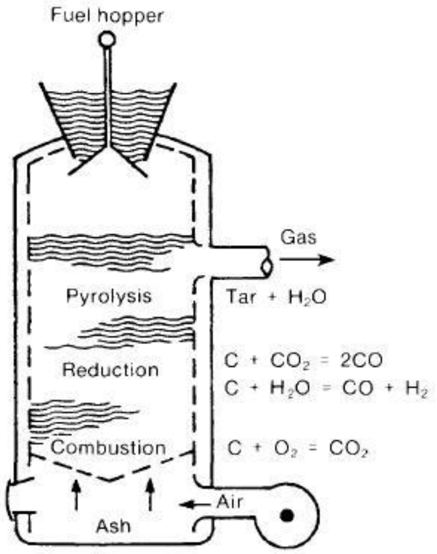
(Demirbas, 2004a)



Ful sample	C	H	N	S	Cl	O (diff.)
Coal type 1	81.5	4.0	1.2	3.0	–	3.3
Red oak wood	50.0	6.0	0.3	–	–	42.4
Wheat straw	41.8	5.5	0.7	–	1.5	35.5
Olive husk	49.9	6.2	1.6	0.05	0.2	42.0
Beech wood	49.5	6.2	0.4	–	–	41.2
Spruce wood	51.9	6.1	0.3	–	–	40.9
Corncob	49.0	5.4	0.5	0.2	–	44.5
Tea waste	48.0	5.5	0.5	0.06	0.1	44.0
Walnut shell	53.5	6.6	1.5	0.1	0.1	45.4
Almond shell	47.8	6.0	1.1	0.06	0.1	41.5
Sunflower shell	47.4	5.8	1.4	0.05	0.1	41.3

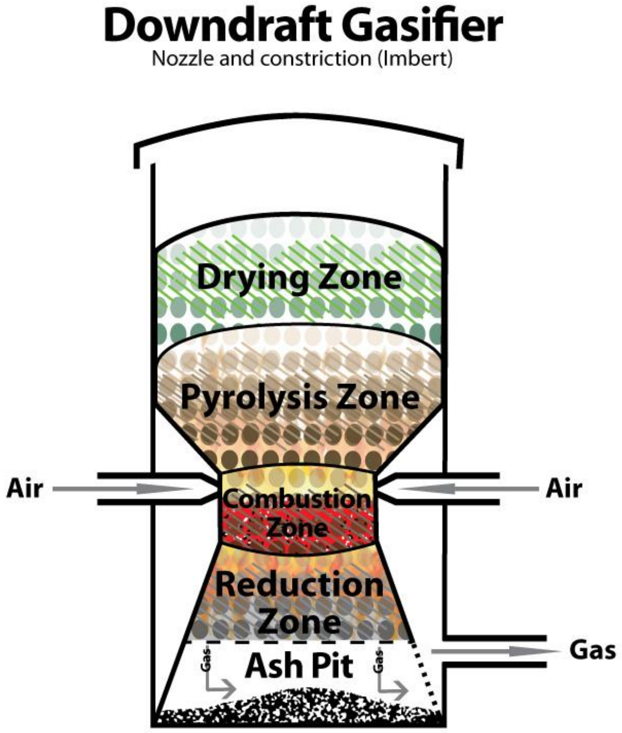
APPENDIX 5 SHEMATIC DIAGRAM OF AN UPDRAFT GASIFIER SHOWING REACTION OCCURING IN EACH ZONE

(Reed and Das, 1988)



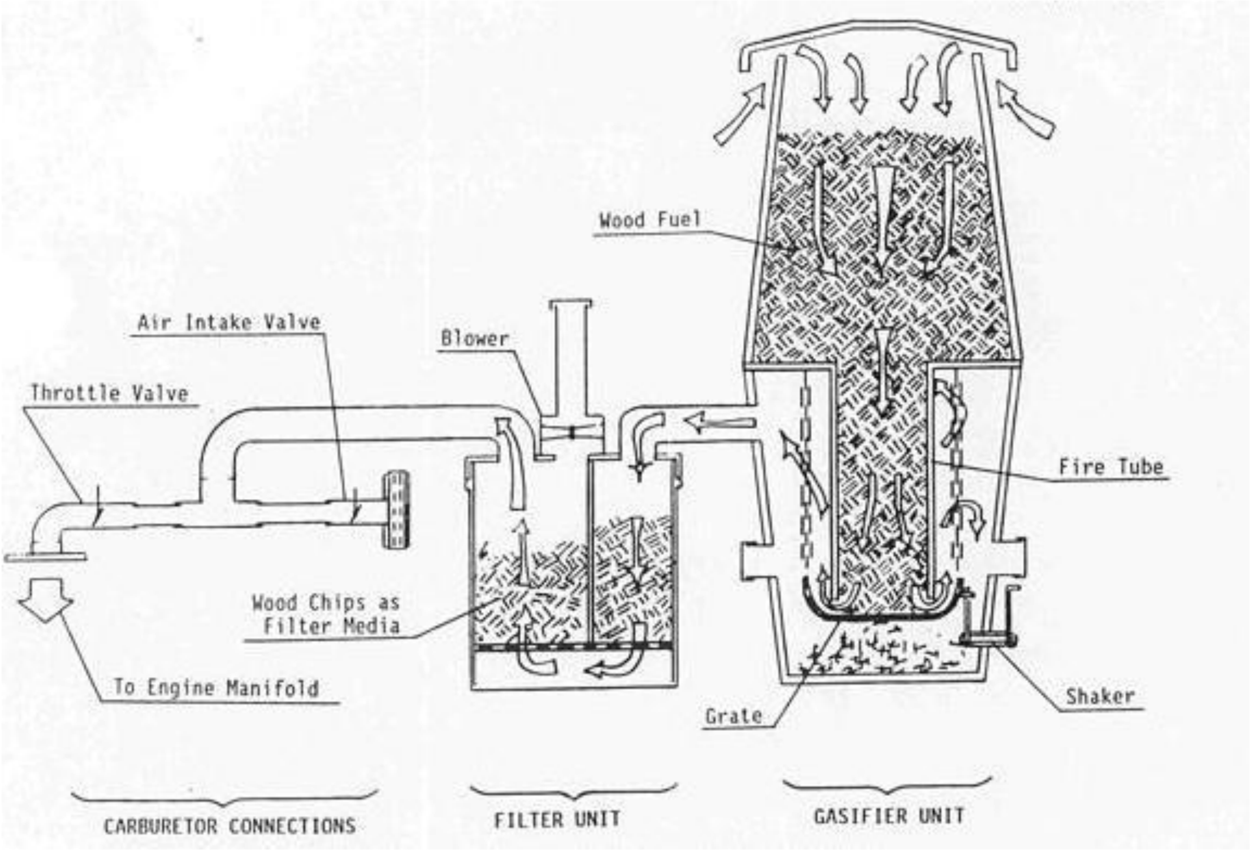
APPENDIX 6, SCHEMATIC OF DOWNDRAFT GASIFIER WITH LABELED ZONES

(Babu and Pratik, 2009)



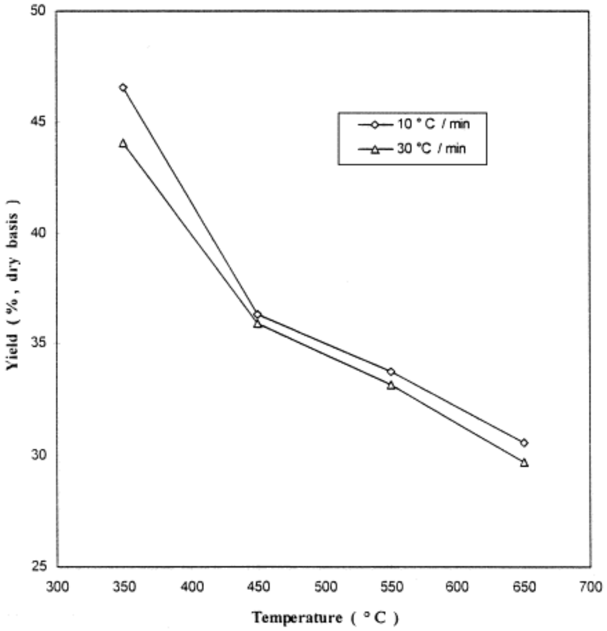
APPENDIX 7, FEMA GASIFIER SCHEMATIC

(LaFontaine and Zimmerman, 1989)



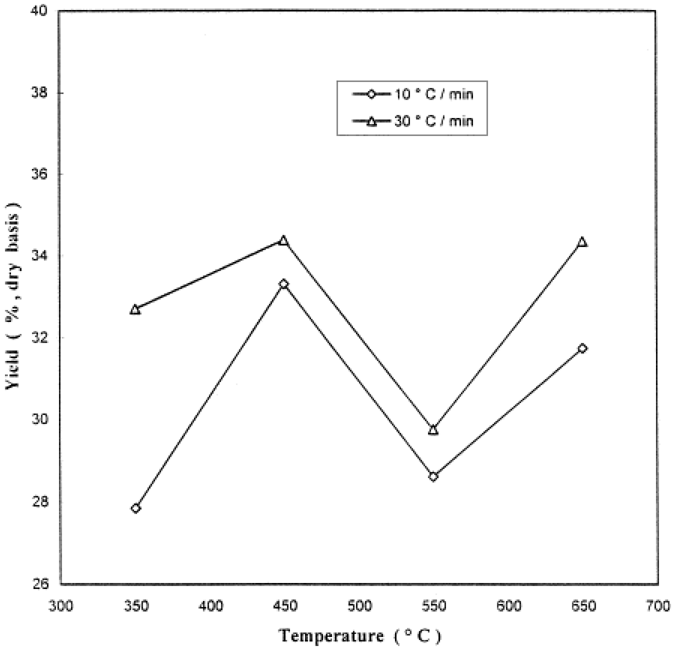
APPENDIX 8, COMPARISON OF YIELDS DEPENDING ON VARYING PYROLYSIS TEMPERATURE AND HEATING RATES USING RAPESEED AS BIOMASS.

(Karaosmanoglu, 1999)



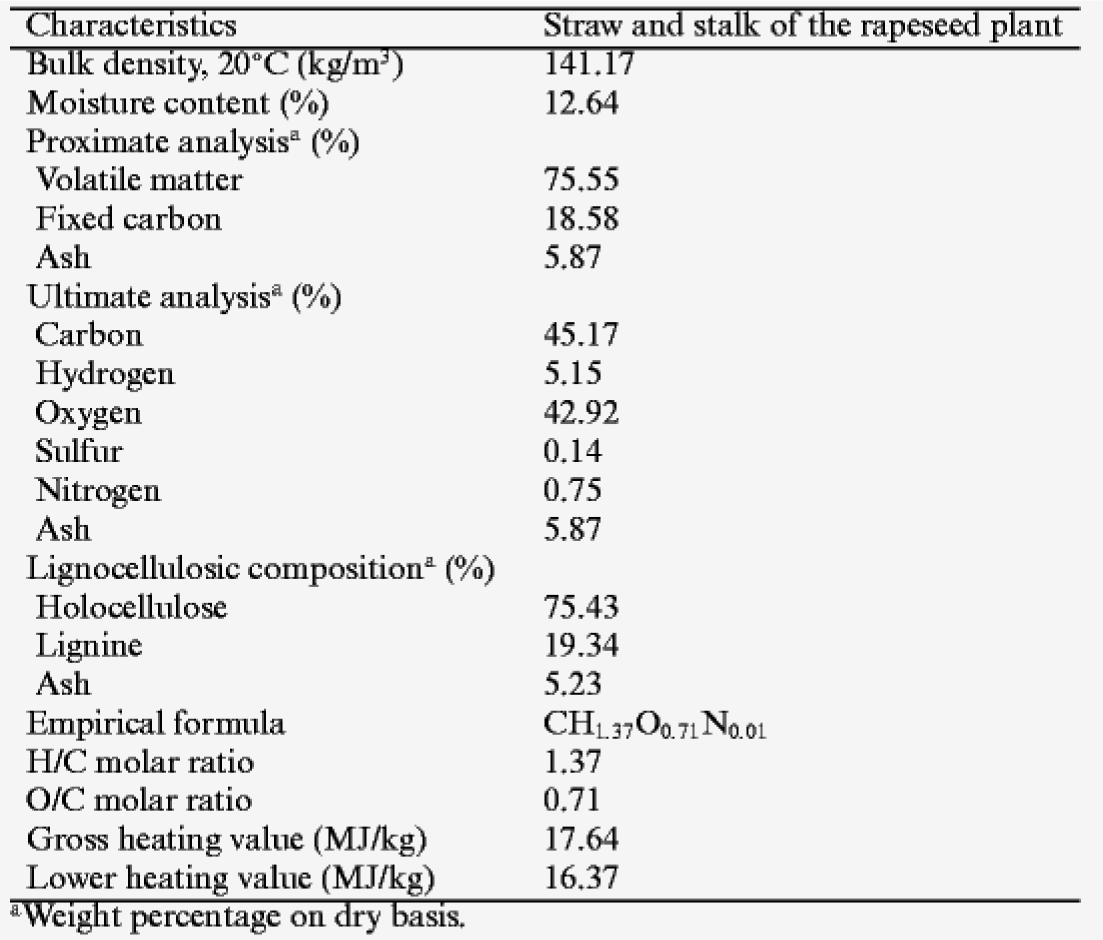
APPENDIX 9, COMPARISON OF GASEOUS PRODUCTS YIELD DEPENDENT ON VARYING PYROLYSIS TEMPERATURE AND HEATING RATES USING RAPESEED AS BIOMASS

(Karaosmanoglu, 1999)



APPENDIX 10, MAIN CHARACTERISTICS OF THE STRAW AND STALK OF RAPESEED PLANT

(Karaosmanoglu, 1999)

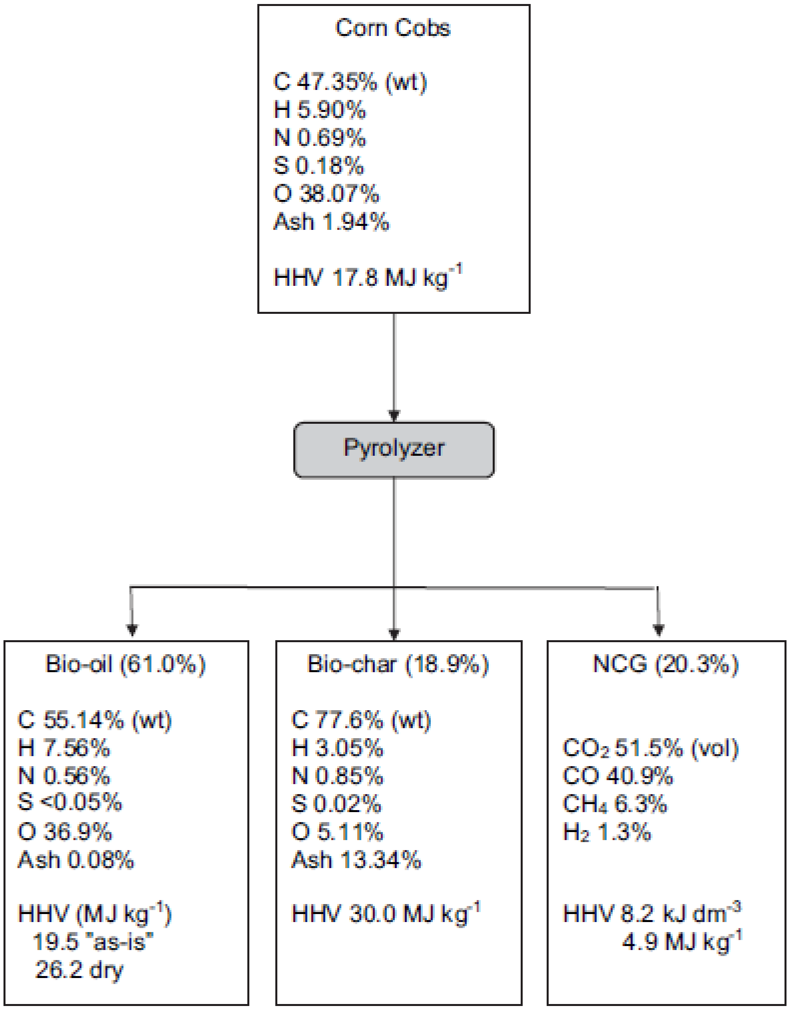


Characteristics	Straw and stalk of the rapeseed plant
Bulk density, 20°C (kg/m^3)	141.17
Moisture content (%)	12.64
Proximate analysis[a] (%)	
Volatile matter	75.55
Fixed carbon	18.58
Ash	5.87
Ultimate analysis[a] (%)	
Carbon	45.17
Hydrogen	5.15
Oxygen	42.92
Sulfur	0.14
Nitrogen	0.75
Ash	5.87
Lignocellulosic composition[a] (%)	
Holocellulose	75.43
Lignine	19.34
Ash	5.23
Empirical formula	$CH_{1.37}O_{0.71}N_{0.01}$
H/C molar ratio	1.37
O/C molar ratio	0.71
Gross heating value (MJ/kg)	17.64
Lower heating value (MJ/kg)	16.37

[a] Weight percentage on dry basis.

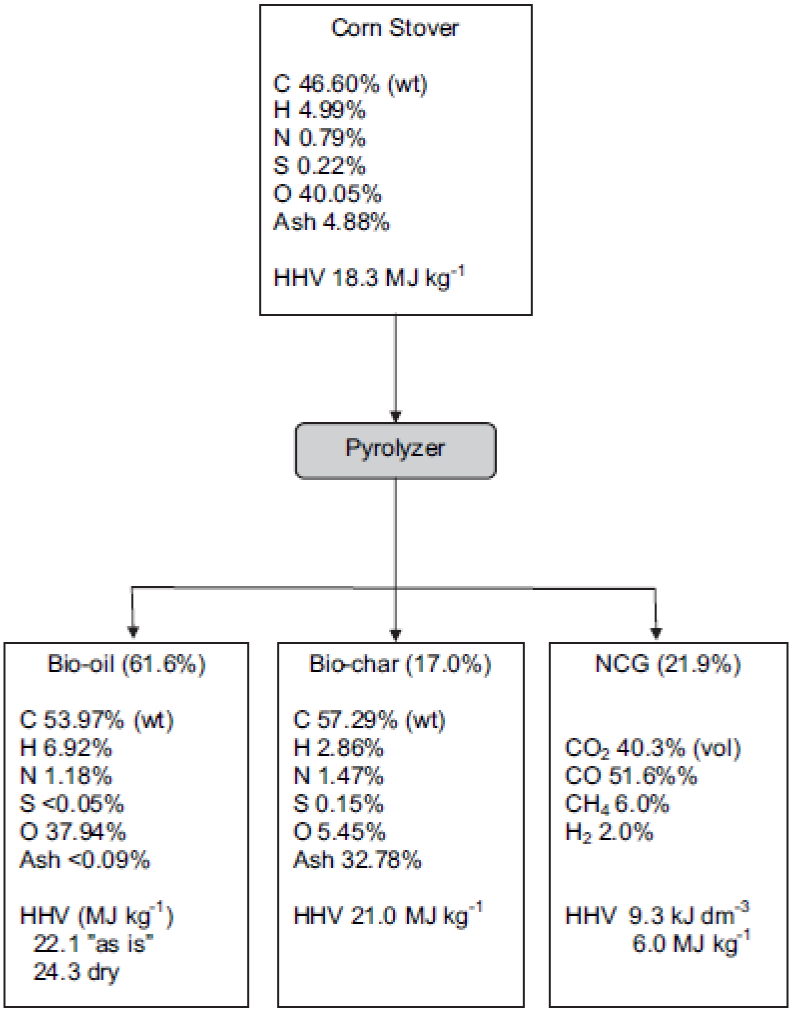
APPENDIX 11, ELEMENTAL ANALYSIS (DRY BASIS) AND HIGH HEATING VALUE(WET BASIS) OF CORN COBAND ITS PYROLYSIS PRODUCTS

(Kumar et al., 2010)



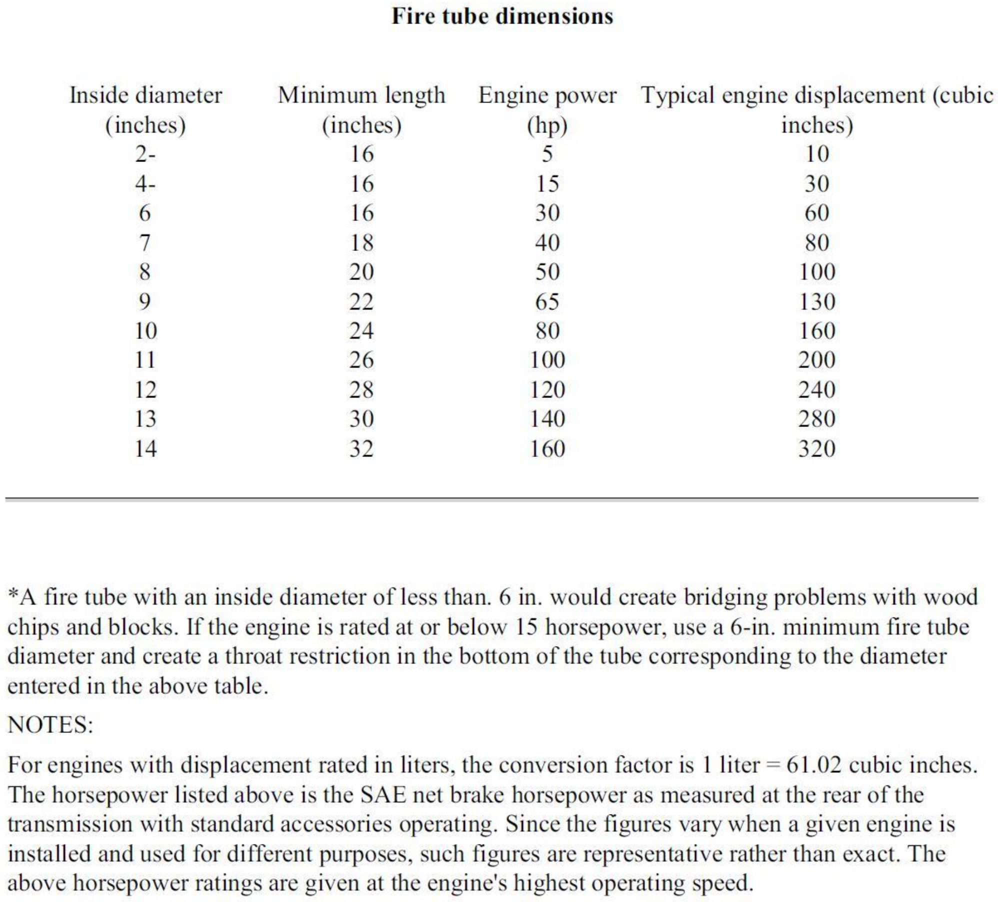
APPENDIX 12, ELEMENTAL ANALYSIS(DRY BASIS) AD HIGH HEATING VALUE (WET BASIS) OF CORN STOVERS AND ITS PYROLYSIS PRODUCTS

(Kumar et al., 2010)



APPENDIX 13, FIRE TUBE DIMENSIONS

(LaFontaine and Zimmerman, 1989)



Fire tube dimensions

Inside diameter (inches)	Minimum length (inches)	Engine power (hp)	Typical engine displacement (cubic inches)
2-	16	5	10
4-	16	15	30
6	16	30	60
7	18	40	80
8	20	50	100
9	22	65	130
10	24	80	160
11	26	100	200
12	28	120	240
13	30	140	280
14	32	160	320

*A fire tube with an inside diameter of less than. 6 in. would create bridging problems with wood chips and blocks. If the engine is rated at or below 15 horsepower, use a 6-in. minimum fire tube diameter and create a throat restriction in the bottom of the tube corresponding to the diameter entered in the above table.

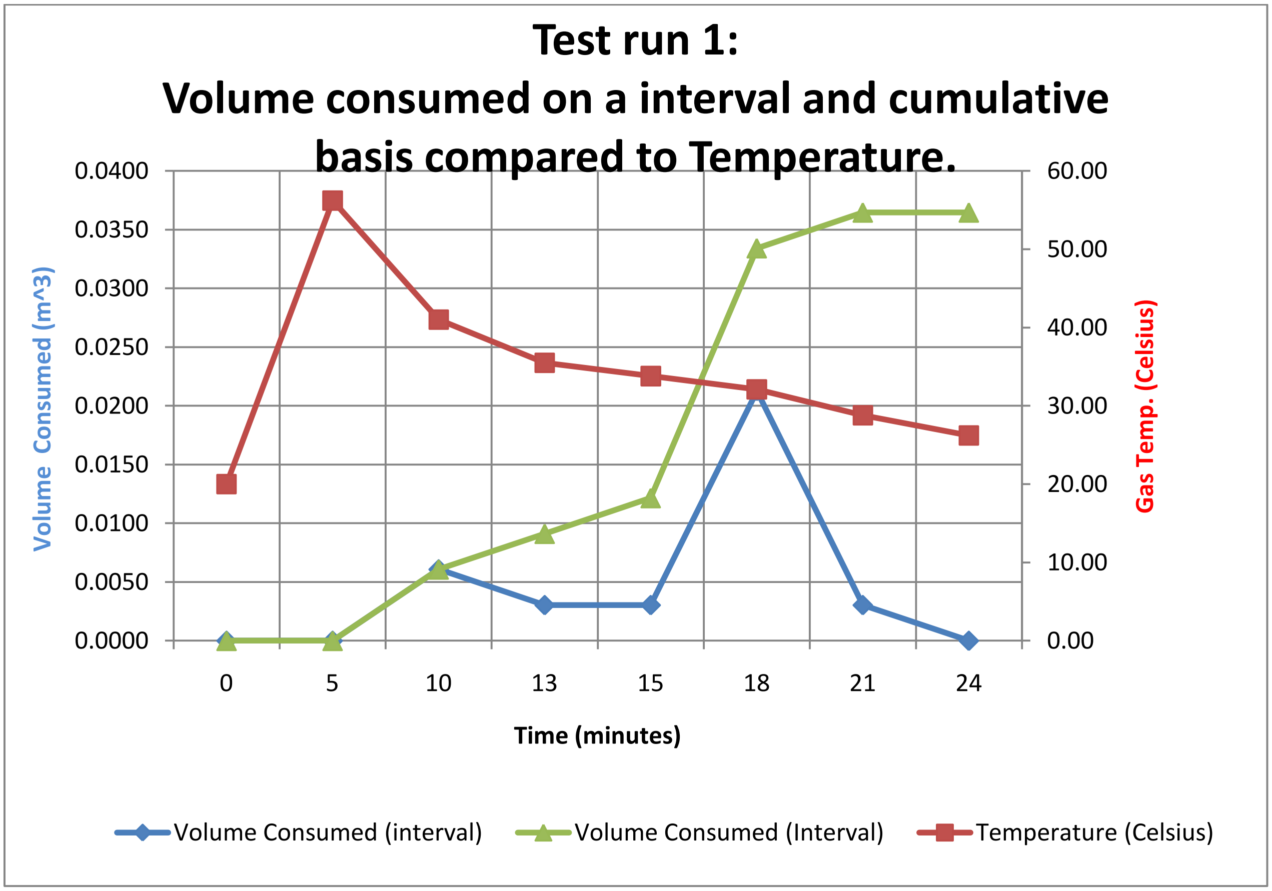
NOTES:

For engines with displacement rated in liters, the conversion factor is 1 liter = 61.02 cubic inches. The horsepower listed above is the SAE net brake horsepower as measured at the rear of the transmission with standard accessories operating. Since the figures vary when a given engine is installed and used for different purposes, such figures are representative rather than exact. The above horsepower ratings are given at the engine's highest operating speed.

Appendix 14

Test run monitoring Biomass Consumption and temperature

		Fuel Drop			
Elapsed time (minutes)	Temperature (Celsius)	inches	meters	Volume Consumed per interval(m^3)	Total Volume Consumed (m^3)
0	20.00	0.00	0.0000	0.0000	0.0000
5	56.20	0.00	0.0000	0.0000	0.0000
10	41.00	0.50	0.0127	0.0061	0.0061
13	35.50	0.25	0.0064	0.0030	0.0091
15	33.80	0.25	0.0064	0.0030	0.0122
18	32.10	1.75	0.0445	0.0213	0.0334
21	28.80	0.25	0.0064	0.0030	0.0365
24	26.20	0.00	0.0000	0.0000	0.0365
			Total	0.0365	

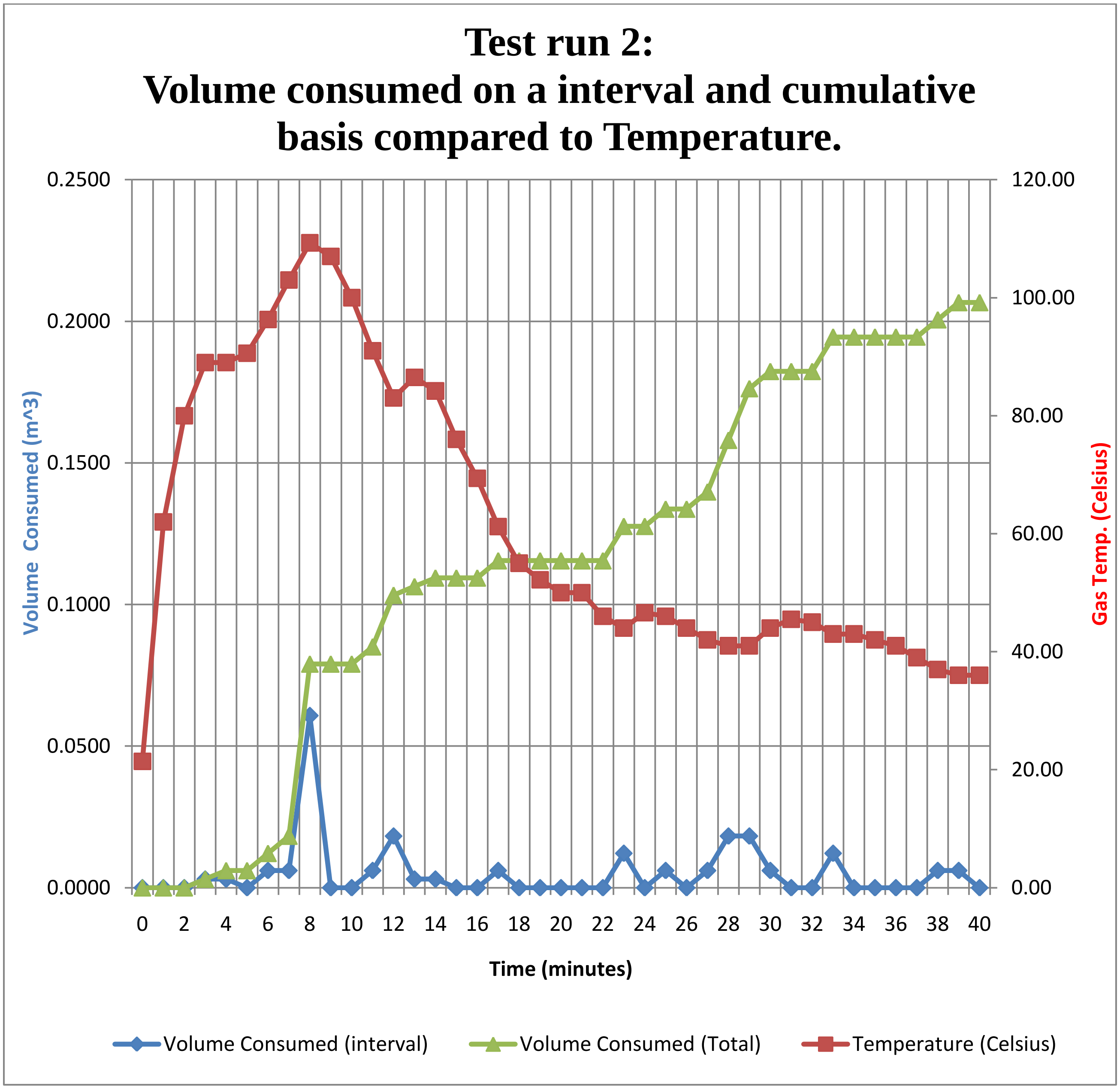


Appendix 15

2nd Test run monitoring Biomass Consumption and temperature

		Fuel Drop			
Elapsed time (minutes)	Temperature (Celsius)	inches	meters	Volume Consumed Over interval(m^3)	Total Volume Consumed
0	21.40	0.00	0.0000	0.0000	0.0000
1	62.00	0.00	0.0000	0.0000	0.0000
2	80.00	0.00	0.0000	0.0000	0.0000
3	89.00	0.25	0.0064	0.0030	0.0030
4	89.00	0.25	0.0064	0.0030	0.0061
5	90.60	0.00	0.0000	0.0000	0.0061
6	96.30	0.50	0.0127	0.0061	0.0122
7	103.00	0.50	0.0127	0.0061	0.0182
8	109.30	5	0.1270	0.0608	0.0790
9	107.00	0	0.0000	0.0000	0.0790
10	100.00	0	0.0000	0.0000	0.0790
11	91.00	0.5	0.0127	0.0061	0.0851
12	83.00	1.5	0.0381	0.0182	0.1033
13	86.50	0.25	0.0064	0.0030	0.1064
14	84.20	0.25	0.0064	0.0030	0.1094
15	76.00	0	0.0000	0.0000	0.1094
16	69.40	0	0.0000	0.0000	0.1094
17	61.20	0.5	0.0127	0.0061	0.1155
18	55.00	0	0.0000	0.0000	0.1155
19	52.20	0	0.0000	0.0000	0.1155
20	50.00	0	0.0000	0.0000	0.1155
21	50.00	0	0.0000	0.0000	0.1155
22	46.00	0	0.0000	0.0000	0.1155
23	44.00	1	0.0254	0.0122	0.1276
24	46.60	0	0.0000	0.0000	0.1276
25	46.00	0.5	0.0127	0.0061	0.1337
26	44.00	0	0.0000	0.0000	0.1337
27	42.00	0.5	0.0127	0.0061	0.1398
28	41.00	1.5	0.0381	0.0182	0.1580
29	41.00	1.5	0.0381	0.0182	0.1762
30	44.00	0.5	0.0127	0.0061	0.1823
31	45.50	0	0.0000	0.0000	0.1823
32	45.00	0	0.0000	0.0000	0.1823
33	43.00	1	0.0254	0.0122	0.1945
34	43.00	0	0.0000	0.0000	0.1945

35	42.00	0	0.0000	0.0000	0.1945
36	41.00	0	0.0000	0.0000	0.1945
37	39.00	0	0.0000	0.0000	0.1945
38	37.00	0.5	0.0127	0.0061	0.2006
39	36.00	0.5	0.0127	0.0061	0.2066
40	36.00	0	0.0000	0.0000	0.2066
			Total	0.2066	


Test run 2:
Volume consumed on a interval and cumulative basis compared to Temperature.

Appendix 16

Drying Calculations

Moisture content determination steps

1. Take a Sample of silage
2. Weigh the sample
3. Dry the sample in an oven at 105^0C for 24 hours.
4. Weigh the sample
5. We can now calculate the Moisture Content (m.c.)
    a. From these values we can calculate m.c. wetbulb (wb) and m.c. Drybulb (db)
        i. $m.c.(wb,\%) = \frac{(wet\ mass - dry\ mass)}{wet\ mass} * 100$
        ii. $m.c.(db,\%) = \frac{(wet\ mass - dry\ mass)}{dry\ mass} * 100$

Moisture content data:

We received silage from the MacDonald Farm and did an initial test to determine the moisture content. The results are listed below:

Oven dried sample

Initial mass (lb)	Final mass (0.33)	m.c.(db,%)	m.c.(wb,%)
0.65	0.27	140.7407	58.461538

We then did the above calculations for the sillage before each burn to determine the moisture content to see if moisture content held a significant influence on the gasifier performance.

2 days drying

Trial	Initial mass (lb)	Final mass (0.33)	m.c.(db,%)	m.c.(wb,%)
1	0.63	0.27	133.3333	57.142857
2	0.61	0.27	125.9259	55.737705
3	0.63	0.27	133.3333	57.142857
Average	0.623333333	0.27	130.8642	56.674473

3 days drying

Trial	Initial mass (lb)	Final mass (0.33)	m.c.(db,%)	m.c.(wb,%)
1	0.39	0.27	44.44444	30.769231
2	0.38	0.27	40.74074	28.947368
3	0.36	0.27	33.33333	25
Average	0.376666667	0.27	39.50617	28.238866

7 days drying

Trial	Initial mass (lb)	Final mass (0.33)	m.c.(db,%)	m.c.(wb,%)
1	0.27	0.27	0	0
2	0.28	0.27	3.703704	3.5714286
3	0.31	0.27	14.81481	12.903226
Average	0.286666667	0.27	6.17284	5.4915515