INCREASED ENERGY YIELD THROUGH FAST PYROLYSIS: EMPOWERING MALAWIAN VILLAGES

Diehl Mutamba
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by
Diehl Mutamba

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Department of Chemical Engineering
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Advisor: Larry Baxter
Honors Coordinator: Dean Wheeler
ABSTRACT

INCREASED ENERGY YIELD THROUGH FAST PYROLYSIS, EMPOWERING MALAWIAN VILLAGES

Diehl Mutamba

Department of Chemical Engineering, BYU

Bachelors of Sciences with Honors

This project (the “Project”) explores the use of fast pyrolysis to produce fuel in subsistence farming communities. These types of communities are common in Africa and many other impoverished areas of the world. The specific application for the Project is Malawian villages in southeast Africa, but it also has broader application. Currently, most people living in Malawian villages harvest firewood from the forests, which is a major contributor to deforestation. They convert some of the forest wood to charcoal with about 10-15% efficiency. This charcoal can be used or sold to other villages. The Project will rely on fast pyrolysis to enable herbaceous fuels to replace forest wood usage. This not only helps to avoid deforestation, but it also increases energy yield and provides a way for nutrient reintroduction back to the earth. In addition, firewood and charcoal produce smoke and carbon monoxide (CO) that compromise the...
villagers’ health. The Project helps to avoid those problems. Also, the Project will improve sustainability and improve the local economy.

I presented the results of the Project at the Utah Conference of Undergraduate Research (UCUR: February 9, 2018), at the Brigham Young University’s President Leadership Council (PLC: October 27, 2017), at the AIChE’s Rocky Mountain Student Regional Conference (March 21-23, 2018) poster competition, and at the BYU’s Kennedy Center Advisory Board meeting (October 14, 2016). The presentations have been well received. I was approached, after my presentation to the President’s Leadership Council, by one of the donors who expressed greater interest to donate for more student participation in similar projects. The team also received a third-place award after the poster presentation at the Rocky Mountain Regional Conference.

The following is a record of the work and experimentation involved to complete the Project, including an apparatus design that can be replicated by Malawian villagers and others living in impoverished, subsistence farming environments. Although the apparatus design can be further improved and likely simplified, the current final design is what has been tested and proven to work.
ACKNOWLEDGEMENTS

The Project would not be possible without the help from my project advisor Dr. Larry Baxter, from faculty reader Dr. Andrew Fry, and from the Honors Coordinator Dr. Dean Wheeler. I am also very grateful for the help received from Hannah Knight and Lars Capener, who are referred to throughout the paper as “the team”. They worked alongside me during the experimentations and designing. I am also grateful for the funding received through the Honors program, which purchased material for building the apparatus and financed analyses of the samples.
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Introduction

This paper is a culmination of the work and research done to design an apparatus for fast pyrolysis that can be used for energy in Malawi villages and other underdeveloped areas around the world. The Project research is relevant in these particular Malawian villages, as well as globally in similar settings, because it will help improve the energy yield of available fuel sources as compared to biomass carbonization. It will also decrease deforestation, decrease health effects from using wood, and improve village economies.

The fast pyrolysis process also produces pyrolysis oil that can be used as a fuel or sold. However, the pyrolysis oil must be modified before it can be used as transportation biofuel or similar high-quality applications. Important to the Malawian villages, Pyrolysis also produces charcoal that can be substituted for wood charcoal or can be used to reintroduce carbon nutrients back in the soil. The Project addresses whether the fast-pyrolysis process could be implemented specifically in Malawi, how pyrolysis oil can be used for the benefit of the people, and whether this solution can be extended to other subsistence farming cultures.

Long-term, this process could provide business opportunities in the villages. The average per capita GDP in Malawi is less than $300/year. The actual cash generated in rural areas like these Malawian villages is far less. Therefore, even a small amount of product that can be converted to cash in rural areas has the potential for a large increase in the standard of living. The process, if implemented, will help empower the villages and will help educate and encourage similar sustainable projects in many other villages.
Although much more can be done to improve the process and the apparatus design, this paper presents proof of technology and knowledge that works.

**Background**

The need for alternative energy solutions such as renewables is perhaps not the most pressing concern for a lot of Sub-Saharan African villages. It is nevertheless an important concern. As the world’s population continues to increase, there is a rising need to find alternative energy sources to substitute the current dependence on fossil fuel. In the context of helping to resolve the ongoing struggle for sustainable energy sources, the Project presents an alternative and sustainable energy source from biomass achieved through fast pyrolysis. Using fast pyrolysis, an energy-rich pyrolysis oil is extracted. Although the production of pyrolysis oil is the primary goal, the process also produces charcoal as a byproduct. I surmise that biomass energy technologies, although currently only in the early stages of development, have the potential to play a big role in the world’s energy index and eventually will contribute much to global energy needs.

The motivation behind the Project came from a personal, life-changing study abroad experience in Malawi during the summer of 2016. I consider this experience life-changing because it changed my perspective of the world. I now can better see the world as one connected place, separated only by distance, oceans and accessibility to information.

Malawi is a landlocked country in southeast Africa. It is one of the smallest countries in Africa and has one of the least developed economies which relies primarily on agriculture. Most Malawian people live in rural areas and rely on forest wood which often is turned into charcoal for cooking, cleaning, heating and other energy needs. The use of
biomass instead of forest wood for energy needs, however, has the potential to dramatically improve both the rural economy and environment where these rural villages are located.

The goal of the Project is to share knowledge about a replicable fast pyrolysis technology we designed for extracting pyrolysis oil from any form of biomass. The knowledge gained through experimentation and testing related to the Project can change lives in Malawi and many other subsistence farming communities. The new technology will be added to the knowledge previously shared with the villagers about making charcoal through carbonization. Fast pyrolysis essentially adds another product, pyrolysis oil, which comes with the carbon nutrient-abundant char. The village people of Malawi have much by way of potential energy resources. Unfortunately, they lack access to information on how to use biomass waste to create an energy source through fast pyrolysis technology. Fast pyrolysis produces both char for charcoal and energy rich pyrolysis oil, which is what makes it a better process than carbonization.

**Fast Pyrolysis**

The following diagram details the simplicity of a fast pyrolysis process, i.e, starting with biomass such as cornstover and then the resulting byproducts: (i) pyrolysis oil (desired); (ii) non-condensable gas; and (iii) char. The list following the diagram shows the characteristics of a fast pyrolysis process and byproducts. It indicates the characteristics of the pyrolysis oil which make it more useful than charcoal.
**Pyrolysis Oil Characteristics**

- Renewable energy process/ Thermochemical Technology
- Rapid heating of organic materials in the absence of oxygen
- Temperature range (400 °C - 650 °C)
- BioGas Condensing (40 °C)
- Scalable and Transportable
- Product: (bio-char and bio-oil)
- Pyrolysis oil has a smoky smell (sometimes comparable to smell of barbecue or smoke)
- Oxygenated and acidic

**Summer 2016**

In the summer of 2016, as part of a group of BYU students, I was privileged to travel to Malawi and work with farmers in two villages on a carbonization project. While in
Malawi, I helped instruct farmers from the two villages how to make charcoal briquettes out of biomass waste. The farmers quickly learned the principles behind carbonization of biomass to make charcoal and would later teach neighboring villages. The impact of our visit was not only directly felt by those who we taught, but also by surrounding villages. People in these villages, and other people whom they teach, will now be able to save money and time by using available biomass waste that can be converted to charcoal for cooking their meals. Without that knowledge, the typical practice in these villages would be to travel long distances to collect forest wood with the resulting negative impacts.

The biomass we worked specifically with was cornstover. Cornstover consists of cobs, stalks and leaves that are left after corn is harvested. Although corn kernels can be used in developed countries to produce ethanol, in places like Malawi corn kernels are used only for eating. In those areas, however, cornstover can be used to make charcoal for cooking and other rudimentary energy needs. The figure below shows one of the charcoal batches made out of cornstover in summer of 2016.

Figure 2: Photograph of charcoal briquettes made in Malawi from cornstover
Deforestation

Deforestation means the loss of forest due either to natural disaster or the deliberate cutting down of trees by human populations. Deforestation causes all kinds of problems. For example, trees help mitigate the greenhouse effect of CO₂ that is released from fossil fuel burning. If the trees have been removed, of course, they cannot provide this function. Also, natural habitat in general is severely affected by deforestation. Animals lose their natural homes in forest environments and are forced by deforestation to search for other places to live and feed. When habitat and feeding grounds become unavailable as natural forest environments are destroyed, species that cannot relocate tend to start dying off. This, in turn, causes a devastating impact on the natural area as a whole. Animal and plant diversity is lost, and the natural habitat begins to diminish and fail. The devastation resulting from deforestation often is irreversible.

Trees are essential to promote the natural process of CO₂ absorption and oxygen-release through photosynthesis. Hence, deforestation is a serious threat to nature and human existence. As trees are cut down and burned, CO₂ is produced, increasing greenhouse gas effect. Therefore, some degree of sustainably is needed so that photosynthesis is maintained. A sustainable system is achievable with adequate production of trees for every biomass used up. Simply put, as trees are taken down, more trees must be planted for sustainability.

Another practice that helps control deforestation is the proper harvesting of trees. This practice is done with in sustainable manner whereby dying trees are removed but then
replaced by planting others. This method is successful because it means trees that are dying and diseased can be replaced with much healthier trees.

The following images illustrate the methods currently used in Malawi to transport wood taken from forest trees. Although the distances travelled to find and cut down trees may vary, it is safe to assume that the work and time demanded for this task is substantial. It is work that requires travel time and significant human labor.

**Figure 3: Forest wood illegally cut down**
Project Objective

The goal of the Project was fourfold: (i) conduct a prototype fast-pyrolysis experiment that demonstrates that cornstover can be used to create high-yield pyrolysis oil; (ii) show this experiment to be replicable in the actual environments of villages of Malawi; (iii) develop a prototype apparatus for use in Malawian villages that local villagers can understand, build themselves from local supplies, and use; and (iv) share an appropriate level of knowledge about the fast-pyrolysis process with local villagers so that they can use it in a safe and beneficial manner. A literature review indicates that the energy potential under laboratory tests will yield 60-70% in energy content through fast pyrolysis,
representing the probable upper limit. The team explored ways of achieving this result on site under actual Malawian village conditions.

The Project also demonstrates that fast pyrolysis produces more than the charcoal that results from carbonization of cornstover (which yields only 10-15% of the initial feedstock energy in the form of briquette heat content). Although fast pyrolysis theoretically yields as much as 60-70% energy rich pyrolysis oil, which has a much higher energy density than charcoal, the current design provided about 25%. Heat exchange plays a huge part in this deficiency (more details found under the problems encountered section).

**Advantages of Biomass**

There is continued work to determine ways of utilizing the energy from renewable resources such as biomass. One known practice is the carbonization of biomass to form charcoal for cooking and other minimal tasks. Such a practice is currently applied in less-developed places around the world.

Herbaceous biomass has several different advantages. To start, deforestation is a serious problem in Malawi. Use of other resources beside forest trees helps to mitigate problems resulting from trees getting chopped down for wood and cooking. Biomass is renewable and thus can provide a sustainable source of energy.

Fast pyrolysis produces bio-oil in addition to charcoal from biomass, with no decrease in charcoal yield. The resulting product from fast pyrolysis is easier to transport

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and market, and in a much more convenient and cleaner form. That is one aspect that makes the Project important. Another element that makes the project relevant is the potential to help address deforestation. Although cornstover is the only biomass experimented with, other biomass waste could also be used and could result in different compositions. Use of other biomass forms will help reduce the need to cut down trees.

**Literature Review**

Fast pyrolysis is the thermochemical process by which biomass lignocellulose decomposes through rapid heating at moderate temperatures. Fast pyrolysis is only possible by heating biomass in an oxygen-free environment. For fast pyrolysis to occur, the heating source must produce heat for temperatures ranging from 400 °C to 650 °C. Heating slowly or with too high of a temperature will decrease liquid yield.

The process converts biomass into (a) light gases that remain gases at low temperatures, such as CO₂, H₂O, CO, and CH₄, (b) tars that are in the gas phase at the temperatures of the process but that condense to form liquids as the gases cool, (c) char, which remains in the solid phase, and (d) relatively little soot if done properly.

“As the temperature increases, the oxygen contents decrease and the hydrogen to carbon ratio decreases” (Soltes 55). This is the case, largely because of the fact that oxygen participates in the burning. Due to the nature of composition dependency to temperature, you get lower tar production at temperatures above 500 °C according to the text, “Pyrolysis Oils from Biomass” by Soltes.
Pyrolysis works differently than carbonization. In the charcoal (carbonization) process, oxygen is needed to initially carbonize the biomass, which would then later be converted to charcoal with use of a binding agent. In pyrolysis, heating of biomass must be done in the absence of oxygen. Therefore, the biomass must be sealed and heated through a container that is deprived of air. Once the rapid heating happens, biogas escapes the sealed container through an opening. The escaping biogas is a mixture of light gases and tar. What remains in the pyrolyzer container (internal chamber) is typically all char. Occasionally, you get un-pyrolyzed biomass, which is usually due to inadequate heating from the external chamber.

A few research articles mention the production of bio oil using lab equipment. Fast pyrolysis has been tested using more sophisticated instrumentation than is accessible in a village for the thermochemical decomposition of biomass to get char, biogas and tar as byproducts. Accessibility to material played an important role in the material selection for the design. The project goal was to design a simple apparatus to demonstrate the extraction of bio oil from biomass waste. Though fast pyrolysis is not a new process, the apparatus was intended to be an innovative and specific to a village environment.

**Design Concepts/ Iterations**

The design of a simple apparatus that can be produced in a village is essential to the success of the Project. The team designed and tested a few different systems to arrive at a practical design that is detailed later. First, it is important to explain the necessary elements which permit fast pyrolysis to occur and upon which the apparatus design must be based.
Depending on the temperature, the decomposition of lignocellulose from biomass produces different compositions of the pyrolysis oil, non-condensable gas and char. A small amount of tar, or heavier dark oil, can also be collected. Further experimenting with different temperatures could provide an analysis of what temperature ranges give the optimal pyrolysis oil, tar and char composition. The team designed and tested several systems that could actually work. That is where a lot of the research came into play. Much time was spent designing and redesigning the apparatus to address several issues including water entering the container used to collect the condensed bio oil, which affects composition yield.

Overall, the apparatus has two parts, the pyrolyzer and the condenser section. They are detailed in the Experimental Procedure/Methods section. That is important because the apparatus could be designed differently but to achieve the objective of the project, the apparatus must be able to pyrolyze biomass and there must be a way for condensing the biogas product from the pyrolyzer.

**Experimental Procedure/Methods**

**Design**

The following describes how a fast pyrolysis apparatus functions in ideal circumstances. Simply put, heat is applied in an external chamber and pyrolysis happens in the internal chamber. Biogas then escapes from the internal chamber and is later condensed with cooling water. The remainder of the uncondensed biogas is recycled back through the flame. Let’s consider a detailed step by step of the process.
The first section, the far-left section in the figure above, is the pyrolyzer. It is the main part of the process where the pyrolysis happens. There are two key parts to this first section, the internal and external chambers. The internal chamber is deprived of oxygen which allows for pyrolysis to happen.

The external chamber is used as the heating source for the internal chamber, providing heat of up to 400 to 650 °C. A fire to create heat requires the following three necessary elements: fuel, ignition source and oxygen. Therefore, the external chamber has holes punctured throughout the body of the container to allow and facilitate the flow of oxygen.

For the given design, the fuel source used in the external chamber was extra cornstover which was the same as the process feedstock. As the fuel burned out in the external chamber, the team continuously fed extra cornstover to continue the flames. For
reasons of safety and to prevent burns, the team used available long copper tubes as a prod that helped with pressing the biomass down in the external chamber to maintain heating. The copper tubing helped prevent extended exposure to the skin right above the flames as the cornstover fuel was added. (For a discussion on safety practices and the hazards involved, please check the safety section.)

Because of limited resources available in Malawian villages, the simplest design is a batch setup instead of a more efficient continuous-feed apparatus. In that case, the internal container contains the cornstover that is to be pyrolyzed for that batch. With adequate flames and the right temperature levels, with temperatures ranging between 400 to 650 °C, the biomass in the internal chamber should not require more than 30 minutes to an hour to be fully pyrolyzed. Determining the optimal temperature to yield pyrolysis oil with the least amount of moisture content is an area in need of further experimental considerations. The focus of the Project was to design a simple apparatus for pyrolysis oil extraction.

The two sections following the pyrolyzer in Figure 5, the box container and the cylindrical container, are interconnected in purpose and serve as the biogas condenser. As the biogas leave the pyrolyzer, it travels through the copper tubing. The first container, which is square in the image above, is where the majority of the heat exchange between the biogas and the water happen. Any uncondensed biogas can be fed back to the fuel source. This would serve to help the flames continue to burn. Unfortunately, that part of the design has not been tested and must be explored in order to optimize the apparatus design.
A key aspect of a successful process is for heat transfer to happen during the condensing section. Copper tubing, with a thermal conductivity of 385.0 W/m-K, was chosen because it serves as great material for heat transfer. Using the copper tubing with a high thermal conductivity facilitates the heat exchange between the cold water and the biogas being condensed. The hot biogas transfers heat to the water, thereby allowing the biogas to condense and results with pyrolysis oil. The pyrolysis oil is then collected as indicated in the figure above (i.e., collected oil).

As the water in the first container heats up from heat transferred from the biogas, the hot water is expected to rise to the surface. This expected interaction would create a rotation of water flowing from the first container to the second container, which has cold water. The idea there is, since hot water rises, the hot water would flow to the surface forcing the hot water into the second container. As the second container is filled with hot water, the cold water from the second container would be pushed down and back through the bottom connected tube, thereby pushing the cold water back into the first container. Although this works in theory, it did not necessarily work out that way in practice. The team ran into a couple problems with this part of the apparatus, which also requires further improvement based on additional experimentation. See details about the condenser problem in the following section.

**Problems Encountered**

This section highlights some of the main problems the team faced during development of the apparatus. The section will also highlight any foreseeable problems that a village looking to implement the project will likely face.
The first and biggest problem was in physically bending and coiling the copper tube for the condensing section. The reason for coiling the copper tube is to allow for as much surface area in the water as possible for heat transfer to condense the vapor. The limited machinery and inexperience by the team with coiling copper tubes made the first attempt a failure. Rather than spend additional time on this effort, however, the team elected to continue on with simplifying the overall process, leaving until later developing a better method to coil copper tubing. For the purpose of producing pyrolysis oil, the team attempted a different condensing design. The initial attempt to design something similar to the drawing above can be seen in the picture below.

A closer look of the coiled copper tube shows the imperfect job done with bending it. There are numerous kinks on the tube. The kinks create many different pressure drop points. Pressure drops throughout the tubing interrupt the flow of the biogas. In fact, when the team tested the design with the pictured coiled tube, the pressure from the internal chamber of the pyrolyser was also not adequate (given the kinks) to push the biogas out. This also was due to not having adequate flames at the right temperature to pyrolyze the
biomass. Therefore, the flow of the biogas through the tube did not have enough pressure to get through the coiled tube.

The next big problem became how to get the fire in the external chamber going quickly enough to cause pyrolysis to happen. To fix that, the internal container required faster heating from the flames of the external container. More air-flow was required to help flames to grow. Therefore, a balloon pump as a was used blower. See picture below.

Using a balloon pump to get the flames hotter, however, proved to be a bad idea because the plastic pumps ultimately succumbed to the heat and the tips melted. Therefore, use of a more robust device to fan air through the external chamber would be more effective.

If a material-bending machine is not available to local villagers for easy bending of copper tubing, other methods could be used, including methods explained in many YouTube videos. One approach is filling a copper tube with soil and then bending it by wrapping around a cylindrical object. Another approach is called hydroforming which involves filling the tubes with water to facilitate bending. These are approaches that could be experimented more in depth for future testing. Local Malawi villagers likely will have additional methods for bending copper tubing based on their own unique experiences and resources.

**Simple Design:**

The design above did not work perfectly due to pressure drops created from the kinks and the lack of heat from the external chamber. Because of time limits, however, the team ended up designing a different condenser section which did not rely on copper coils.
While experimenting outside in cold temperatures during the Utah winter, it proved easy for the condensable gas to form into oil. Thanks to the big temperature difference between the coal air and the biogas, it became possible to get the biogas to condense to pyrolysis oil, even without the added heat exchange that otherwise is made available by the use of coiled copper tubing. Because the climate in Malawi is temperate, however, further testing and design modification will be required.

With a reliable form of condensing system, most of the condensable gas will form into liquid and not escape as happens with the non-condensable gas. The condensing portion of the system design caused the most difficulty as the team worked to improve and simplify the entire design. The following is a simple design that the team tested. Using material accessible in Malawian villages dictated the design.

Assuming balmy conditions, the simple design below worked only when there was adequate temperature difference allowing for a good heat transfer. In this case, that occurred only when continuously pouring water on the tube. This proved to be too manually-intensive, however, and a different design was developed.

![Figure 7: Manual Intensive Apparatus Design](image)
The latest design uses a simple tube connection coming out of the internal chamber and is connected by an elbow to another copper tube arranged vertically that goes straight down. Most of the vertical tube is jacketed by a container and gets filled with water and serves as a heat exchanger. The latest design was tested April 10, 2018.

A few observations from the April 10th testing are as follows. The team experimented with bubbling the biogas as a form of condensing the pyrolysis oil. Bubbling works as the biogas gets condensed through bubbling of the biogas in subcooled liquid, preferably pyrolysis oil that was previously collected. Using previously collected pyrolysis oil eliminates the need for extra liquid separation after the pyrolysis oil is condensed.

While testing with the bubbling method, the biogas condensed much better than expected. In the process, however, some of the biogas was lost. One hypothesis for that is that the residence time of the biogas in the pyrolysis oil was not long enough. Residence time is defined as the amount of time something spends in a controlled volume or environment. Pyrolysis oil that was previously collected served as the controlled volume. In the case of the bubbling set up, the biogas bubbling through and escaping the pyrolysis oil did not spend adequate time in the pyrolysis oil for the heat exchange to happen. There is also the possibility that there was not enough previously collected pyrolysis oil to help condense all of the escaping condensable gas. Another probable reason is that the pyrolysis oil reached an equilibrium temperature with the saturated gas and condensation could not happen thereafter due to lack of temperature difference between the gas and the pyrolysis oil.
The other hypothesis is that the escaping gas may have only been non-condensable biogas. It is not obvious or possible for the naked eye to distinguish between the condensable and non-condensable gas. Therefore, it could have only been the non-condensable gas escaping and not the other, or both. All of the hypothesis should be considered in future experimentation.

![Figure 8: Simplest design as of April 20, 2018](image)

Some parts of the apparatus had to be welded and brazed. Specific instructions were given to avoid explosions while using the acetylene tank and the torch. The following are the particular parts connecting the different tubes used for the apparatus.

**Table 1: List of materials used**

<table>
<thead>
<tr>
<th>Materials</th>
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<tbody>
<tr>
<td>90 degree elbow</td>
</tr>
<tr>
<td>Half inch fit</td>
</tr>
<tr>
<td>Coupling</td>
</tr>
<tr>
<td>Half inch copper T</td>
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</tbody>
</table>
Materials

The team had the opportunity to work in the Mechanical Engineering lab on campus and is grateful for the equipment that was available. While in the lab, all the safety rules were followed, especially wearing eye protection. Table 1 lists the different machines that were used in the building of the apparatus.

Many of the tools available on campus are not accessible in a village. Prior experience at villages in Malawi, however, proved that the lack of tools was not as limiting of a factor as might be assumed. This is because people of the villages are quite innovative in using local tools and resources in lieu of the more sophisticated tools and materials available in the U.S.

Table 2: Mechanical Engineer Lab Machines Used During Building

<table>
<thead>
<tr>
<th>Machine</th>
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<tbody>
<tr>
<td>Drill Press</td>
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<tr>
<td>Manual Punch</td>
</tr>
<tr>
<td>End Mill</td>
</tr>
<tr>
<td>Lathe</td>
</tr>
<tr>
<td>Oxy Acetylene Torch</td>
</tr>
<tr>
<td>Spot Welder</td>
</tr>
<tr>
<td>Media Blaster</td>
</tr>
<tr>
<td>Press Break</td>
</tr>
</tbody>
</table>

At a minimum, this report serves as proof of concept to the villages in Malawi. With that in mind, they will be free to tweak the prototype design as they please, even with
limited tools and machines. The following are images of the different tools we used at the mechanical engineering lab.

![Figure 9: BYU ME Lab Equipment (1)](image1)

![Figure 10: BYU ME Lab Equipment (2)](image2)

![Figure 11: BYU ME Lab Equipment (3)](image3)

![Figure 12: BYU ME Lab Equipment (14)](image4)
Results and Discussion

Sample Analyses:
The sample of produced pyrolysis oil from the April 10\textsuperscript{th} experiment (pictured below) was taken to Timpview Laboratory in Orem for analysis. The full report from the lab is included in the appendix.
The following village oil analysis are the data analyzed from the sample taken to Timpview Laboratories and other literature analysis. The pie graphs titled village oil are analysis of the oil sample from the April 10\textsuperscript{th} experiment. The pie chart labeled Lab oil are analysis of data that came from experimentation detailed in the Mullen literature.\footnote{Mullen, C.A., et al., Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. Biomass and Bioenergy, 2010.}

Below are observations relative to the lab and village oil elemental compositions. This is on a dry basis. The Village oil was made using the experimental apparatus shown above. Lab oil results was made by heating up cornstover in a laboratory.\footnote{Mullen, C.A., et al., Bio-oil and bio-char production from corn cobs and stover by fast pyrolysis. Biomass and Bioenergy, 2010.}

The key learning from the two comparisons show that:

- Lab and village oils are almost comparable in composition
- Carbon is most abundant element
• There is an equal amount of oxygen when comparing between the lab and village oil.

**Figure 17:** Lab Oil Composition

**Figure 18:** Village Oil Composition

**Figure 19:** % Energy Yields

**Figure 20:** % Mass Yields
The following are conclusions from comparing heating values of village oil, lab oil, char and Non-condensable gases (NGC). Again, some of these values come from literature\textsuperscript{4} and results received from Timpview Lab.

- Pyrolysis oil is the largest product by mass
- Pyrolysis oil is the most energy dense
- Pyrolysis oil is easier to work with than either char or gasses once produced
- Pyrolysis oil has the highest heating value of any product
- The village oil had a heating value slightly greater than that of the lab oil
- The values are all on a dry but with ash basis

Next steps:

Although the apparatus works and can produce pyrolysis oil, there is still work to be done to improve the yield. One of the areas to further consider is figuring out how to get a desired composition based on precise temperature alterations. This will help to develop the optimal temperature and residence time that yields the best results. The picture on the right is optimal pyrolysis compositions achieved in a lab (See Mullen\textsuperscript{5} paper). The following gives a brief list for the next steps to take:

- Improve the apparatus with a complete condensing design
- Increase our % yield—currently we get about 25 mass % yield compared to a theoretical max of 62%
- Designing a better condensing apparatus
- Simplifying and up-scaling our design

Areas of application:

There is a need for continued development of technologies utilizing biomass and other renewable energy sources. The project shows the possibility of extracting high energy content pyrolysis oil that could have many benefiting impacts in village environments. There is still work to be done to improve the quality of pyrolysis oil after it is collected. There is great potential for use of fast pyrolysis oil. Different literatures and studies indicate that fast pyrolysis oil have either been tested or used in the following areas:

- Heat and Power (Commercially Proven)

• Automotive Fuels
• Bio Refineries
• Potential of being the alternative to fossil fuel
• Petrochemical production
• Meat browning
• Boiler fuel
• Diesel engines
• Food flavoring

**Safety**

This section is of utmost importance because as the team worked on building and testing the apparatus, there were serious hazards to be aware of. This section highlights the different safety matters that the team needed to be aware of.

To start, any fire requires a plan to extinguish it in case of an uncontrolled situation. For that to happen, one of the main three elements needed for a fire has to be eliminated or has to be controlled. Because a heating source is needed for experimenting, the team had to have a setup that allowed a controlled fire environment. It is important to work in an inherently safe environment. What allowed for a controllable environment, in case of an unexpected fire, was conducting the experiment in an open environment. In our case, the team experimented outside.
Conducting the experiment outside helped diminish smoke hazards. In a confined environment without ventilation, the smoke could have been lethal. Therefore, if the experiment is conducted inside, having ventilation will be necessary.

Another level of protection to prevent burns was heavy-duty gloves that conduct heat very slowly. This gave the team capacity to handle the containers with appropriate time to move them out of the flames before starting to feel any heat through the gloves. No containers were held too long while they were hot. They must only be handled with proper personal protective equipment (PPE).

Additional PPE included eye protection. Thanks to the abundant availability of eye protection in the Unit Lab Operations room on campus and the available goggles in the storage lab used, there was available eye protection for use while burning.

Conclusions
Pyrolysis oil has the potential for application in various areas, most of which are still under research. The following characteristics are what makes pyrolysis oil useful in the assumed application in Malawi: transportable, storable, useful in making chemicals, and its high heating value in comparison to charcoal which is also a byproduct. Also important, fast pyrolysis is a process with economic, environmental and health benefits. One simple economic advantage is that it saves the people of the village time and money spent travelling long distances to gather or acquire forest wood for cooking. With respect to the environment, the use of biomass waste such as cornstover reduces deforestation concerns. Lastly, using char, resulting from the pyrolyzed biomass that remain in the internal chamber
after pyrolysis, reduces and at times eliminates smoke health hazards that result from forest wood charcoal. Although there is more that can be done to improve the apparatus, it is fair to say that the current design is an adequate and operable design. It has been successfully tested. It can be replicated in Malawi with materials available in village settings.

There is certainly more that future research can do to further this work. An example as mentioned, would be to test the compositions resulting from pyrolyzing at different temperatures. There are several potential areas of application for pyrolysis oil but there is also much that must be done to the oil to improve its quality and usability. This has been an exciting and worthwhile project to work on.
Appendix

Figure 22: Malawi Village (Carbonization project summer 2016)

Figure 23: Charcoal Briquettes being used to cook (2 pictures)
**Figure 24:** Initial Design Drawing

**Figure 25:** Barrel and brick kiln used for carbonization of cornstover (Summer 2016)
**Figure 26: Sample Analysis from Timpview Analytical Laboratories**
**Figure 31:** Design with copper coil

**Figure 32:** Char from internal container (pyrolyzer)

**Figure 33:** Experimenting outside the Clyde building

**Figure 34:** Copper tube brazing to tin can
**Figure 35:** Mask used for smoke protection

**Figure 36:** Bellow used to keep fire going

**Figure 37:** Gloves used to handle hot material
Figure 38: Poster competition 3rd place award (2018 AICHE REGIONAL CONFERENCE)
Figure 39: UCUR Presentation (SUU 2018)

Figure 40: Presentation at the Honors Thesis Poster Session

Figure 41: 2018 AIChE Regional Conference
Figure 42: Village chief demonstrating how to cook nsima

Figure 43: Demonstrating how to make the briquettes (Summer 2016)
Figure 44: Copper Tube Prods

Figure 45: Coiled Copper Tube

Figure 46: Small Paint Can (Internal Chamber)

Figure 47: Heating Source

Figure 48: Pyrolyzer and Heating Source

Figure 49: Larger Paint Can (External)
Figure 50: Lighter used to get the fire going

Figure 51: Plastic balloon pumps (for blowing air)

Figure 52: Jar used to collect pyrolysis oil

Figure 53: Design considered (I)
Figure 58: Design considered (VI)

Figure 59: Design considered (VII)

Figure 60: Design considered (VIII)

Figure 61: Design considered (IX)
References

Ceranic, M. “Experimental Investigation of Corn Cob Pyrolysis.” JOURNAL OF RENEWABLE AND SUSTAINABLE ENERGY 8, 2016,


