

Improvement of Kiln Design and Combustion/Carbonization Timing to
Produce Charcoal from Agricultural Waste in Developing Countries

by

Jason A. Martinez

Submitted to the Department of Mechanical Engineering in Partial Fulfillment of the
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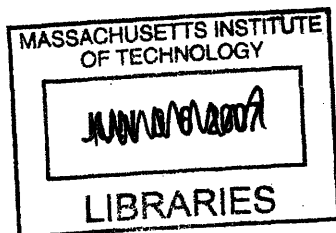
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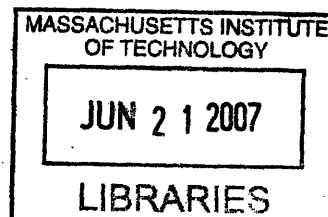
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ABSTRACT

Current economic conditions in third world countries like Haiti are so poor that the majority of the population has no access to energy sources that people in the first world take for granted. In Haiti the last two percent of the forests are being cut down to provide energy for basic cooking to survive. In response to the situation, MIT professors and students are designing a multi-step process for making charcoal briquettes from local agricultural waste products, or biomass.

The process involves the combustion and carbonization of biomass at sustained high temperature in an air-tight metal barrel kiln to produce char. The char produced from haiti's main agricultural waste product, bagasse, must be powderized, mixed with a binder, compressed into briquettes, and finally baked. The purpose of the thesis was to improve on key areas of the charcoal making process. The goals were to: conduct and investigation into alternative kiln layouts; address safety concerns with water boiling, briquette baking, and bottom venting; design of a method for uniform and complete briquette baking using heat from the carbonizing kiln; and gain a better understanding of the importance combustion timing and sealing. Design for affordable, low level manufacturing would be an important requirement as well.

The results of the thesis were: an analysis of possible kiln designs based on the supplies typically available in developing countries; improvements to safety by using wire tethers on kiln hardware to allow kiln operators to keep a safe distance; a proposed new design for a briquette baking box with multiple briquette banks; and combustion timing and kiln insulation techniques to maximize char output.

Thesis Supervisor: Dr. David Wallace
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TABLE OF CONTENTS

1.0 Introduction.....	4
2.0 Background.....	4
2.1 Haiti.....	5
2.2 Carbonization of Biomass.....	5
2.3 Briquette Production.....	6
3.0 Kiln Design.....	6
3.1 Drum Configurations for Complete Combustion.....	7
3.2 Briquette Baking.....	12
3.3 Safety.....	15
4.0 Combustion and Carbonization.....	18
4.1 Combustion Venting Timing.....	18
4.2 Carbonization Timing.....	18
4.3 Testing.....	19
5.0 Conclusions and Recommendations for Future Improvement	23
6.0 References.....	25

1.0 Introduction

The goal of the thesis is to improve the process parameters for a low-tech agricultural waste-based charcoal production system through empirical experimentation. This process is intended for use in developing countries where biomass fuels, such as wood, wood charcoal and dung, are typically used.

The charcoal production system is a two part process that uses various forms of agricultural waste (such as corn stalks and sugarcane bagasse) as inputs, and yields charcoal briquettes that can be used to provide cooking heat. The first step is combustion and carbonization. In this step the organic matter, or biomass, is reduced to carbon via an endothermic pyrolysis reaction in a kiln made from a 55-gallon metal drum. The second step is making briquettes. In this step the carbon, in powder form, and a binding agent made from the root of the cassava plant are mixed and pressed into charcoal briquettes [Vechakul, 2005]. The briquette-making step utilizes lost thermal energy from the combustion and carbonization step to boil water for making the cassava binder, and to dry and bake the pressed briquettes to improve durability. This charcoal production system is a source of renewable energy that might have a high impact in developing countries where the use of wood and wood charcoal is leading to significant deforestation problems, and the use of dung and wood causes respiratory illness [Sanders, 2001].

In order to effectively implement this new charcoal production system, its design and production process needs to be reliable. For this reason research and design were completed to improve the proposed charcoal system in three areas: a) completeness and consistency of carbonization; b) uniformity and completeness of briquette baking; and c) safety during the manufacturing process. Mechanical design investigation was conducted into each of these areas, and solutions proposed. Additionally, experimentation to discover the effects of timing, venting and sealing parameters on completeness and consistency of carbonization was conducted. The improvement process adhered to the functional requirements of simplicity and low cost for developing countries.

2.0 Background

To understand the motivation for optimizing the charcoal making process, some knowledge of economic conditions in developing countries is required. A developing country is defined by the UN as a country with a low Human Development Index. For these countries, the use of affordable renewable energy sources can be very important in rural and underdeveloped areas. Biomass conversion processes are very attractive because they can utilize agricultural waste that is already present in the developing country's region. The three most common methods of biomass conversion are anaerobic digestion, alcoholic fermentation, and pyrolysis [Lewis & Ablow, 1980]. Pyrolysis is the simplest process to introduce in developing countries because it does not require special organisms to convert the biomass, only requiring thermal energy to initiate the reaction. An appreciable portion of the pyrolysis products are in the form of solid carbon char which can be used directly for combustion to produce heat for cooking. Carbon char is also easy to store because it is a solid and is unaffected by moderate changes in ambient temperature and humidity.

2.1 Haiti

The pilot country for this charcoal making process is Haiti. Haiti is the target for introduction of this process because of its environmental and economic situation. It is the poorest country in the Western hemisphere and one of the very poorest in the world (1). The GDP of Haiti (population 8.5 million) in 2005 was \$440 whereas the GNP of the Dominican Republic (population 9.2 million), with whom Haiti shares the island of

Hispaniola, was \$6,600 for 2005. Furthermore Haiti's GDP was decreasing between the years of 2001 and 2004 and has now only begun to increase again [US Dept. of State, 2006]. As a result of the poor economic state, Haiti has been unable to develop its infrastructure or purchase expensive energy sources. Much of the population does not have access to mass distributed energy sources such as electricity or natural gas to which first world countries are accustomed. Because it is drastically cheaper, Haitians have been using domestic wood sources either directly, or to create charcoal, for cooking heat. Despite carbonization of wood in earthen kilns being used for thousands of years, the process is inefficient and the forest wood used is not easily renewed. In Haiti, the demand for agricultural land and a heat source for cooking has resulted in 98% deforestation which has in turn led to desertification and erosion [Smith & Frayne, 2003]. Desertification makes it increasingly difficult to produce agricultural crops because of a lack of nutrients in the soil due to destruction of the natural eco-system. Without adequate vegetative root structures to keep the top soil bound severe erosion occurs during tropical storms in the area, leading to thousands of deaths.

The proposed charcoal production system aims to use agricultural waste from Haiti's existing sugarcane farms as a replacement for domestic forest wood in the manufacture of cooking charcoal. Additionally this process hopes to boost the local economy by providing jobs. People would be employed to produce charcoal from agricultural waste for an immediate small community of a dozen or so households. By stopping deforestation and increasing the demand for sugar cane bagasse, this process may lead to growth in the area of agricultural production, raising the overall GDP of the country. If successful in Haiti this model can then be used in other developing countries using the local agricultural waste products.

2.2 Carbonization of Biomass

Carbonization is a chemical decomposition process otherwise known as anhydrous, or water free, pyrolysis. In this endothermic process thermal energy is added to dried biomass in an oxygen free environment. When enough thermal energy has been added to raise the biomass' temperature above approximately 150 C, volatiles within the material begin to vaporize. If the thermal energy added raises the biomass temperature to between approximately 300 C and 500 C the cellulose (C₆H₁₀O₅) and other predominantly hydrocarbon molecules separate into H₂ and H₂O vapor, leaving behind basic carbon. Cellulose is composed of 44.4% Carbon, 6.2% Hydrogen, and 49.4% Oxygen by weight [Lewis & Ablow, 1980]. Thus the products of carbonization are non polluting, non hazardous gasses. An experimentally determined equation for the percent yield of char was found by Roberts et al. in application to cellulose carbonization and is given by

$$Y = -2.4 \ln (\tau) + C \quad (1)$$

Where percent char yield, Y , is shown to be a function of heating rate, τ , in degrees C/min and an experimentally determined constant, C [Roberts, 1978]. C is for pyrolysis of pure cellulose.

The carbon produced, known as char, remains in a solid state and can later be combusted in an oxygen rich environment where it oxidizes into CO₂, releasing thermal energy to be used for cooking.

High-tech industrial pyrolysis techniques use various methods to capture the vapor and liquid products of pyrolysis. However without financial means, or access to modern manufacturing methods, the capture of these products is not currently feasible in developing countries like Haiti. Thus the pyrolysis process for developing countries is focused on maximizing the production of solid carbon char while using a process that is as simple and robust as possible, requiring a minimum of capital investment. In the metal drum carbonization system heat is added to the biomass by igniting and combusting a portion of the organic material. The heat released from the combustion raises the temperature high enough for carbonization of the remaining biomass. Once the desired temperature is reached, the metal drum must be sealed to prevent oxygen exposure. Preventing oxidation halts combustion and only carbonization occurs until all of the cellulose has been converted to basic carbon, hydrogen gas and water vapor, or until too much thermal energy is lost to complete the carbonization reaction. The timing of events in this method is crucial. Enough biomass must be combusted provide heat for carbonization, however over combusting decreases the final carbon yield. The carbonizing biomass must also not be re-exposed to oxygen too soon. Should oxygen exposure occur before carbonization is complete, and the temperature is still high enough, the carbon and remaining biomass can re-ignite and consume the product.

2.3 Briquette Production

Once the char is produced from the pyrolysis process it must be turned into briquettes to be usable as cooking charcoal. Char produced from some forms of biomass like corn cobs and wood can be used directly as charcoal. However char produced from sugar cane and corn stalks must be mixed with a binder to form rigid briquettes. The binder is produced from cassava, a root vegetable. The root is skinned, grated, and squeezed to extract its starchy juice. It is then mixed with boiling water to produce an adequate binder for the char powder [Vechakul, 2005]. The briquettes are then compressed and sun dried, but remain fragile. To solve this problem the briquettes can be re-baked in a box using the heat in the kiln. Re-baking the briquettes makes them much harder and more durable.

3.0 Kiln Design

The redesign of the combustion and carbonization kiln apparatus was motivated by the three main goals of increasing consistency of carbon yields, achieving uniform re-baking of briquettes, and increasing the safety of the kiln during combustion and carbonization, when it can reach temperatures up to 600 C. Functional requirements for the kiln were that it be cheap, made from readily available materials, simple to operate, and portable enough to move to farm sites where agricultural waste is already accumulated. Furthermore it was desired to use the kiln structure not only for combustion and carbonization, but also for the carbon char to a powder, boiling water for the cassava binder, and re-baking the pressed charcoal briquettes. This required incorporating

multiple design requirements from each of the aforementioned tasks into the design of a single kiln.

3.1 Drum Configurations for Complete Carbonization

3.1.1 Kiln Material Selection

In order to ensure complete carbonization and maximum carbon char yield, it is desirable to use a kiln whose mechanical properties are designed to complement the needs of the combustion and carbonization processes. Because of the high temperatures involved in combustion and carbonization the available materials deemed appropriate for the kiln construction were metal, brick, and soil. Each of these materials offers its own benefits and costs as shown in **Table 1**. Earthen kilns are the cheapest to construct because soil in open areas is plentiful and free, also making portability almost infinite as because one may be constructed almost anywhere. Soil is a good thermal insulator. However earthen kilns can be hard to construct, venting control is difficult, and char contamination is an issue. Brick kilns also insulate well, are cheap to build and the size, shape and venting can be controlled easier than with a plain earthen kiln. However brick kilns are not very portable and sealing and contamination are problems if earth is used as a floor and gasket material. Bricks can also be relatively expensive. Metal can be used to construct a strong, portable kiln that keeps the char free from contaminants. Metal kilns can also incorporate the powderizing of the char since their entire structure can be moved while still sealed. However, metal kilns require additional insulation to be as well insulated as well as earth and brick, and modifications for use as a kiln can be more complicated.

Table 1. Tradeoff Matrix for Kiln Material Selection.

	<u>Affordability</u>	<u>Portability</u>	<u>Insulation</u>	<u>Ease of Construction</u>	<u>Resistance to Contamination</u>	<u>Venting Control</u>
Earth	High	High	High	Moderate	Low	Low
Brick	Low	Low	High	Moderate	Moderate	Moderate
Steel	Moderate	High	Low	High	High	High

From the many options for kiln structure, an industrial 55-gallon metal drum was chosen based on its portable size, its convenient shape for rolling/spinning, its cost and its relative ease of acquisition. Insulation issues and high initial cost are drawbacks that can be overcome by design and by efficiency, respectively.

3.1.2 Orientation, Venting, and Sealing

Because the charcoal production system uses combustion to provide thermal energy for carbonization, the kiln has special venting requirements. During combustion the hot gases produced are less dense than the ambient air causing them to rise, and create an upward flow of air. Adequate venting is required in any kiln to ensure uniform air flow through

the material within the kiln. Top vents allow the hot volatile gases to escape, while bottom vents allow for the uptake of oxygen rich air to supply the combustion process. Good air flow through out the material in the kiln produces uniform combustion and thus uniform heat generation.

Traditional steel drum kilns used for a combustion and carbonization process have been oriented either vertically or horizontally. In the vertical orientation, as shown in **Figure 1**, vent holes are located on the bottom, **Figure 2**, of the kiln and one large opening is at the top allowing for vertical airflow during combustion. However in the horizontal orientation, only one vent located radially, about 45 degrees down from the top, is typically used. The horizontal orientation makes use of wind to create a swirling effect within the barrel so that air enters in the vertical direction, circles the inside of the kiln and exits upwards. A sample horizontally configured kiln is shown in **Figure 3**, although it is only used for powderizing, not combustion or carbonization.



Figure 1. Top vent in a vertically oriented carbonizing kiln barrel.



Figure 2. Bottom vents in a vertically oriented carbonizing kiln barrel

These vents are a design problem because while they must provide uniform flow they must also be able to be completely sealed in order to initiate and maintain the hot carbonization phase. They must also be sealed for the cold powderizing phase where the barrel is turned to crush the char into powder. Sealing these vents can be challenging in both hot and cold phases depending on the location of the vent and the orientation of the opening. Often, the most effective method of sealing kiln vents during static processes is to use loose soil to cover the openings. However sealing the kiln while it is moving presents a problem.

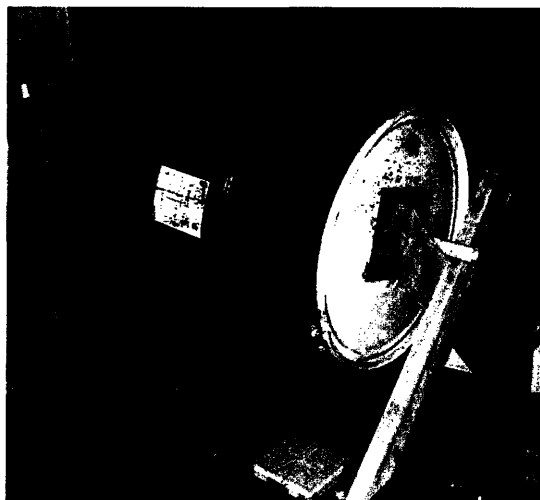


Figure 3. Horizontally Oriented Carbonizing Kiln Barrel (get new picture)

The goal of the first kiln design was to incorporate the ability to rotate it during the carbonization phase to promote uniform heat distribution. The spinning function would also allow char powderization to be done inside the kiln, rather than in a separate vessel. The horizontal orientation, similar to the one shown in **Figure 3**, would allow the kiln barrel to be spun during combustion, carbonization and afterward to crush the char into powder. The raised platform enabled spinning in place.

Vent sealing on this design proved to be a formidable problem. Because the kiln was to be moving during the carbonization phase, loose dirt could not be used to cover the vents. This application required rigid vent covers and some other sort of gasket material. While many compliant, high temperature gaskets exist, many of them are made from exotic ceramics and fiber weaves that are far too expensive, and certainly unavailable to rural areas in developing countries. These sealing problems inhibited the advancement of this design concept a rotating kiln that churned the char.

Meanwhile, testing on stationary vertically oriented metal barrel kilns by MIT graduate student Amy Banzaert were producing a consistent char yield approaching the theoretical limit for char production through the simple type of pyrolysis. At this juncture it was decided to abandon the horizontal rotating kiln in favor of further optimizing a vertically oriented barrel kiln. A cold sealing solution is still necessary during the powderization phase. The proposed solution uses a flat plate made of thin sheet metal at either end of the barrel where the top and bottom vents are located. Each plate has two small holes near each other at the plate's center. Two strands of metal wire are run through the holes on one plate, through the center axis of the barrel and through the two holes at the opposite end. The ends of the wire that are now stuck out on each side are twisted together. As they are twisted the wire strands are put in tension, holding the plate on the ends of the barrel. The barrel can thus be rolled to crush and powderize the char without loss.

3.1.3 Insulation

In choosing to use a metal kiln over a kiln of earthen or brick construction thermal resistivity was compromised. **Table 2** shows a list of some applicable thermal conductance. As seen in the table the thermal conductance of mild steel typical of metal drums is an order of magnitude greater than that of soil or brick. Having the kiln constructed of a highly thermally conductive material is less desirable, as less heat will be retained by the kiln over time once combustion stops and carbonization begins.

Table 2. Comparison of thermal conductance for various materials used in a carbonization kiln.

<u>Thermal Conductance @ 25 C (W/m-K)</u>	
Air	0.024
Brick	1.5
Earth	1.5
Plywood	0.13
Steel	50

The solution to this compromise is to use an additional insulating layer, such as the one in **Figure 4**, to surround the kiln once it is sealed and carbonization has been initiated. Potential materials available in a developing country for use as an insulating layer might be sheet metal paneling, or another common local construction material. In experiments a plywood insulator box was used initially to protect the kiln from moderate wind speeds of 15mph (6.7 m/s). Use of the insulator yielded very consistent and complete carbonization. Its theoretical effects were calculated and showed an expected decrease in heat transfer out of the kiln. Calculations predict that the heat transfer rate using an insulation layer of plywood, as was in the experiments, was three orders of magnitude lower than without it. Each of the test runs in the graphs in **Figure 5** produced the same amount of char. Run 4 was able to do so at a much lower carbonization temperature due to the aid of insulation.



Figure 4. Plywood insulating walls.

Difference in Required Maximum Carbonization Temperatures With and Without Kiln Insulation

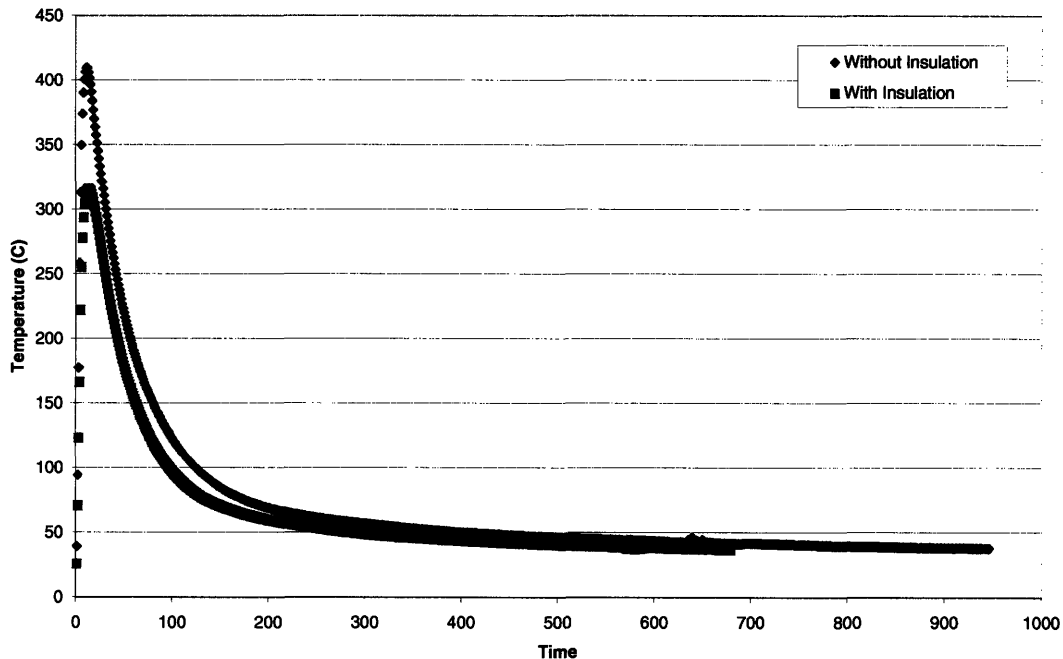


Figure 5. Difference in carbonizing temperature required to achieve the same yield, with and without insulation.

3.2 Briquette Baking

The re-baking or twice-baking of briquettes is a process by which the compressed, dried charcoal briquettes can be made harder and more durable with exposure to temperatures between 200 C and 400 C within the kiln during the carbonization phase. The process of twice-baking was shown to be effective in field testing conducted by Amy Banzaert et al. in El Salvador during March, 2006. However the results of the experiments showed non-uniform baking when using the baking box shown in **Figure 6**. The basic box is built from a sheet of wire mesh with two flaps that set over the edges of the top vent to hold the box up while it sits inside the kiln. Briquettes are loaded into the wire box in a single pile. While briquettes on the outer edges of the pile benefited from twice-baking, many on the inside did not. It was hypothesized that the outer briquettes were absorbing heat and insulating the inner briquettes, creating a temperature gradient and preventing the inner briquettes from being twice baked.



Figure 6. Briquette baking boxes made by Amy Banzaert et al. during field testing in El Salvador.

It was theorized that if each briquette had more of its surface area exposed to the surrounding hot air that they would all twice-bake more uniformly. A new briquette baking box was designed using dividers to separate the box into vertical banks. The width of each bank is equal to the nominal 2" height of a briquette and runs the length of the box as shown in **Figure 7**. The box is constructed of wire mesh which is cheap and easily accessible in most areas. Every other bank is filled with a stack of briquettes so that each briquette is exposed to hot air on two sides. An impact-loading briquette making device, like that designed by Jessica Vechakul, produces cylindrical briquettes of about 2" in height and 2" in diameter. This means that with briquettes stacked with their flat faces exposed have about 1/3 of their total 15.7 square inches of surface area exposed for free convection. The remaining surface area is exposed, but somewhat insulated by the adjacent briquettes. This design allows for straight-through flow paths of hot air around the briquettes.

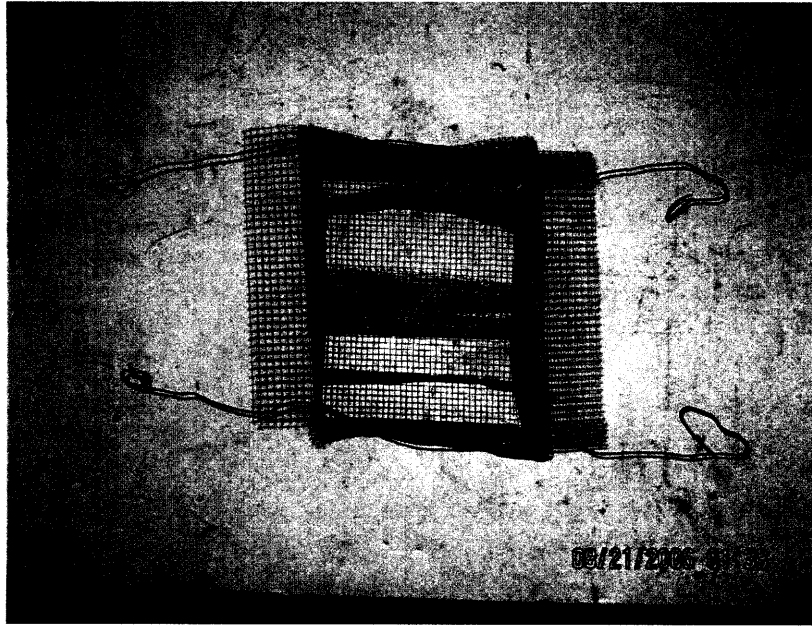


Figure 7. Wire mesh briquette baking box with vertical banks.

Data shown in **Figure 8** was collected during two sequential tests in the same kiln using K-type thermocouples. The maximum temperature gradient across the briquette box is only 12 C with the vertical banks compared to 103 C without the banks. This means that every briquette has at least 1/3 of its surface area exposed to the hot air inside the kiln, and is experiencing a convective heat transfer from both sides.

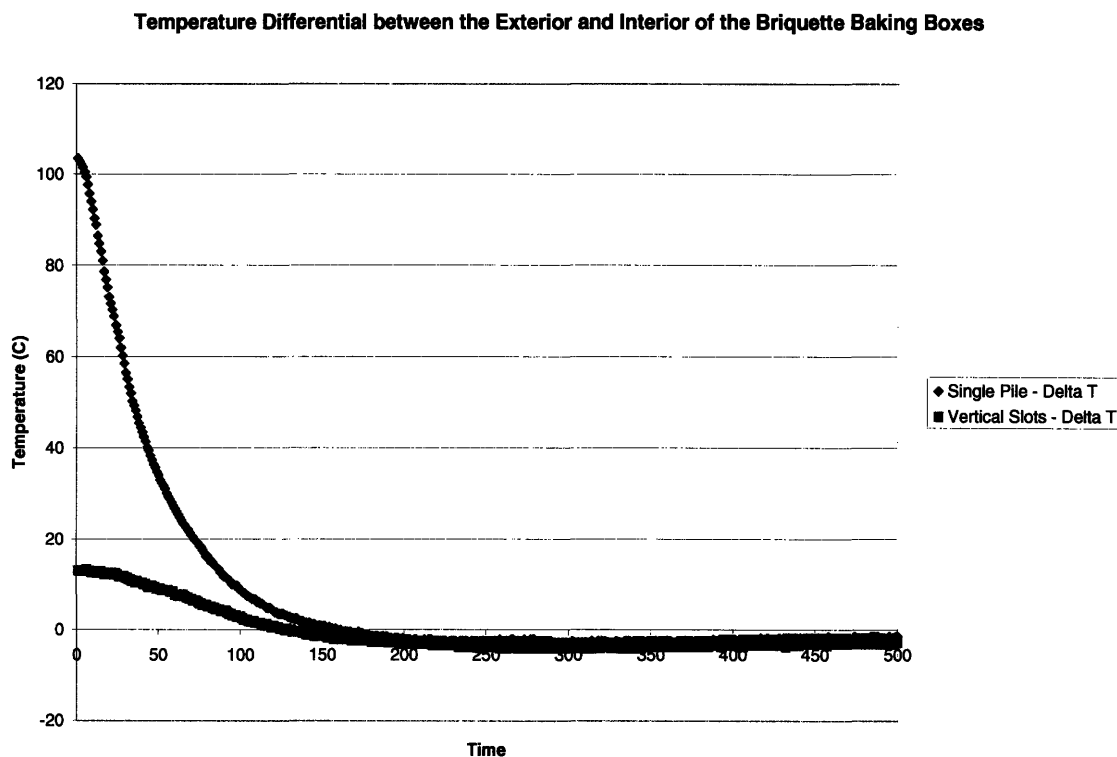


Figure 8. Graph displaying the delta-T values between the exterior and interior of two different briquette boxes.

Due to a lack of impact-loaded briquettes for experimentation, potato slices measuring 2” in diameter and 2” in thickness were used as a substitute. Visual inspection of the two batches of potatoes yielded many half baked potatoes on the bottom of the single pile briquette box, whereas the vertical bank briquette box yielded evenly baked potatoes in the inner and outer banks. The qualitative data suggests that using vertical banks with stacks of briquettes yields a higher quantity of more evenly baked briquettes than does the single pile of briquettes. An attempt was made to collect quantitative data on the depth of the bake by doing a slice test and measuring the depth obtained by a knife pressed down with a constant force. However quantitative data was unable to be gathered from this test because of the difference in toughness between the outer skin and the inner section of the potato slices. Thus while the qualitative data indicates that the vertical banks are effective, further testing must be conducted using actual briquettes.

3.3 Safety

During combustion, the temperature of the metal kiln surface can reach above 600 C, and between 300 C and 500 C during the carbonization phase. At the transition from combustion to carbonization, the kiln operators are required to interact with and move kiln components for the purposes of boiling water for cassava binder, baking briquettes, and sealing the top and bottom vents of the kiln. These events present a safety hazard for the operators and require well designed mechanisms to keep the operators adequately safe from heat exposure and burns.

The first part of the charcoal production procedure that has safety concerns is the loading of the water pot and the briquettes into the top vent for heating. Placement of the water pot into the kiln's top vent hole during the combustion phase exposes people to extremely high temperatures near 600 C. In the current method, shown in **Figure 9**, an individual places the pot, supported by a metal bar, into the vent. The action of holding the pot of water at the end of the bar resulted in a somewhat unwieldy cantilevering effect. Trials were thus conducted using two people, one on either side of a longer bar to make the lifting action easier. However poor coordination between the two people made placement of the pot into the hole more difficult. It was concluded that despite its unwieldiness one-person loading would be quicker and easier for smaller volumes of water, while large volumes would necessitate two. Construction of additional pivoting devices seemed to complicated for use in this simple carbonization system.



Figure 9. MIT alumnus, Shawn Frayne, lowering a water pot into a hot kiln during combustion.

A simple solution that increased the safety of loading the briquette baking box into the top vent of the kiln was to add wire tethers to opposite edges of the top of the box. The tethers shown in **Figure 7** allowed the box to be placed into the vent by two people without either person having to place their hands near the vent. The two ends of each wire tether were also able to be used as secondary method of securing the box to the top of the kiln. The ends of the wires can be bent around the edges of the kiln.

The second event with a safety concern is the tilting and lowering of the kiln down off of the stones or bricks that elevate it off of the ground. Past field experimentation utilized a tilt and quick kick method of removing the stones form beneath the kiln. In order to increase the safety of the stone removal, it is desirable to design a removal mechanism that allows the user to remain a few feet away from the hot kiln. To achieve this goal, two

designs were proposed. The first design tested was to elevate the kiln with long rods lying on the ground as shown in **Figure 10**. The concept was to roll the poles/sticks to one side and let the kiln drop off of them. Upon testing the pole rolling method a few problems became apparent. The kiln was unstable sitting on the poles and would shift from side to side as the poles rolled back and forth. When lowering the kiln off of the poles the kiln fell down off of the poles rather than sliding down. This event seemed dramatic and posed a potential tipping hazard.



Figure 10. Barrel kiln elevated on poles



Figure 11. Barrel kiln elevated on bricks with wire leashes

The second design utilized a wire leash on the stones, or bricks, as shown in **Figure 11**. The leashes can be made to any length, allowing the kiln to be tipped with a long rod/stick from a few feet away, and for the stone to be pulled out from the same safe distance. Testing of this method was performed by a single person. The kiln placed atop three leashed stones was tipped with a long pole held in one hand from a distance of four feet. Meanwhile the leashed stone was pulled out from beneath the kiln with the other hand, also from a distance of four feet. The kiln was then eased back to the ground using the pole. This method was very effective, very simple and easy to execute by a single person without getting too close to the hot kiln.

4.0 Combustion and Carbonization

4.1 Combustion Venting Timing

As explained in **Section 2.2**, a portion of the biomass for carbonization must be combusted to provide thermal energy to facilitate the subsequent carbonization reaction. The heat input for carbonization, the thoroughness of heat distribution in the biomass, and the amount of biomass left for carbonization can all be somewhat controlled by manipulating the venting timing during the combustion phase. The combustion phase has two parts. After ignition, the biomass in the kiln begins to combust, producing a thick yellowish smoke. This yellow smoke contains non-hydrocarbon, volatile molecules that were contained in the biomass. After some minutes the volatiles are all released and their heat perpetuates the subsequent combustion of the cellulose hydrocarbon ($C_6H_{10}O_5$) that composes the biomass. This change in combustion phase is clearly visible by the change in smoke color from thick and yellow, to clear. Once the volatiles have been purged all of the biomass should be at the minimum temp for volatile combustion. Then, when the hydrocarbons begin to combust, the temperature increases throughout the kiln, indicating an increase in thermal energy within the kiln. The operator can at this point control the size of the vents and the length of time before they are sealed and carbonization is initiated. The longer the combustion continues the more thermal energy is input to the remaining biomass. The more thermal energy input to the biomass, the more can be converted into char before the kiln cools due to convection. However, the longer combustion occurs, the more of the biomass is consumed, leaving only ash. A balance must be found to maximize both heat and biomass input at the initiation of the carbonization phase.

4.2 Carbonization Timing

Carbonization timing is for the most part uncomplicated. Once sealed, the kiln must be left sealed until it has cooled back down to ambient temperature. Upon return to ambient temperature, all of the biomass will have finished converting into char. The one problem occurs if the kiln is opened before cooling down sufficiently. If opened prematurely when the carbonizing biomass is still at a high temperature, the biomass will re-ignite in the presence of oxygen and continue to burn until the biomass and the char is consumed. At that point the kiln can either be resealed in attempt to restart the carbonization reaction, or it can be doused with water then dried out to scavenge any char.

4.3 Testing

Experimental testing was conducted in order to determine the effects of the length of combustion time, the order of kiln sealing operations and the impact of kiln insulation on char production.

4.3.1 Apparatus

The kiln apparatus was made from a 55-gallon steel drum with a removable lid. Six evenly spaced triangular holes were cut near the perimeter on the bottom surface of the barrel, and one hole was cut in the middle, as shown in **Figure 12**. These composed the kiln's bottom vents. One 14" x 10" hole was cut into the lid of the barrel, making the top vent, as shown in **Figure X**. Holes were made using a jigsaw, but in low-tech environments, a cold chisel can be used.

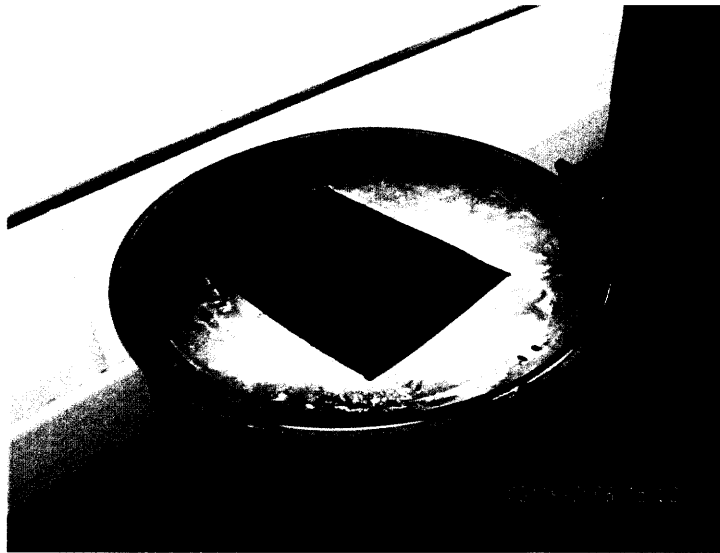


Figure 12. 55-gallon kiln barrel with top vent hole.

Outside on a flat, clear area the kiln was placed upon three evenly spaced, radially oriented bricks with wire leashes tied around them. Each brick had a four foot long leash extending outward from it with a loop at the end for a handle as shown in **Figure 11**. Additionally a six foot long steel fence pole was kept near to the kiln in order to tip the kiln to remove the bricks during the experiment. If unavailable, bricks can be substituted for large flat rocks.

A thin steel plate, 18" in diameter was used for covering the top vent opening. Additionally two five-gallon buckets containing dirt were kept nearby to use for sealing the top and bottom of the kiln. Four 2'x4' pieces of plywood were used as an insulating barrier against the wind and for keeping heat in. They were arranged as shown in **Figure 13** using twisted wire for hinges.



Figure 13. Insulation panels with wire hinges.

A 12"x8"x8" wire mesh briquette baking box was used to house briquettes for twice-baking. Two long wires were attached along the top of two opposing sides, as shown in **Figure 14**, for safe handling and mounting to the kiln. Potatoes were used to simulate compressed charcoal briquettes in the experiments.

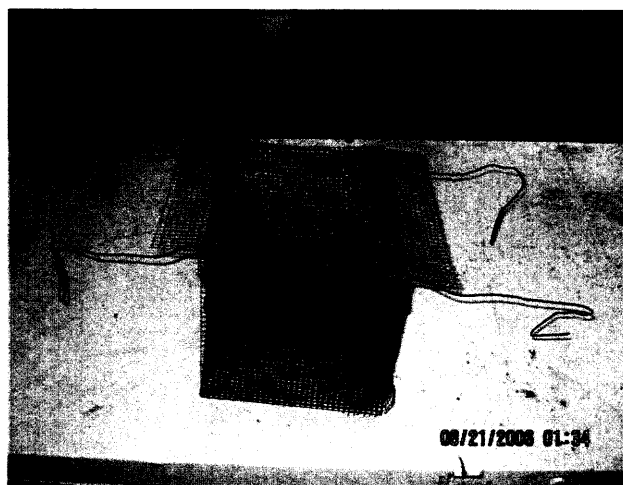


Figure 14. Briquette Baking Box with Wire Tethers

Three K-type thermocouples and data loggers were used to gather temperature data inside the middle of the baking briquettes, in the open air inside of the kiln, and in the middle of the carbonizing char at the bottom.

Dried corn stalks and leaves were used as the biomass for the experiments. Cardboard strips were used as wicks to ignite the corn stalks. Safety goggles and welder's gloves were used when conducting the experiment and/or handling hot objects.

4.0.3.2 Procedure

The experiments were conducted on a flat brick patio. Three bricks with leashes were arranged and the kiln was set upon them so that it was evenly balanced. The dried corn stalks were then massed in bags using a pull forge gauge and placed inside of the kiln through the top hole. The metal fence pole was inserted vertically into the middle of the kiln and the corn stalks were compressed around it. The pole was then removed and a lit cardboard wick was lowered into the center hole where the pole had been. The corn stalks were then allowed to ignite and combust through the yellow smoke combustion phase until the smoke changed color. It was then allowed to combust for a controlled amount of time after which the kiln was sealed.

The sealing process was done by first tipping the kiln with the fence pole and pulling out the bricks with the leashes, one at a time. Once the bottom was on the ground the briquette baking box was placed into the top vent and the top vent sealed with the cover plate. Dirt was then piled atop the kiln cover plate to create an airtight seal. Dirt was also applied to the bottom of the kiln where the rim met the ground, in order to create an airtight seal. Thermocouples were also inserted at this time and data acquisition started. Insulator boards were then placed around the outside of the kiln to block strong winds and retain heat.

The kiln was then left untouched until it reached steady state with the ambient temperature. At that time the kiln was disassembled and the char removed. The procedure was repeated varying the timing of the second phase of combustion, the sealing order, and the use of the insulation layer.

4.0.3.3 Results

Four tests were conducted to provide an idea of how changing the charcoal making process variables would affect the efficiency of the process in making the most char.

Table 3 shows a matrix of the four test runs with information on timing, conditions and changed variables. Prior test runs were conducted, but no data was collected.

Observational data regarding these four test runs were that the output from Run 1 was partially carbonized with some stalks still left in tact. Run 2 was apparently opened from carbonization too soon and the carbonizing biomass reignited, having to be put out with water, ruining the experiment but showing a valuable lesson about carbonization timing. Runs 3 and 4 yielded good product as close to the idea amount and their internal temperature trends are shown in **Figure 15** and **Figure 16**. Testing on Run 4 using an insulator allowed for shorter combustion times and lower overall internal carbonization temperatures while maintaining an output similar to that produced in Run 3. Based on the tests conducted, a general rule of one minute of smokeless combustion (after transition from yellow smoke) for every kg of biomass loaded into the kiln.

Table 3. Matrix for All Test Runs

	Run 1	Run 2	Run 3	Run 4
Initial Mass [kg]	13	12	8	8
Light	0	0	0	0
Transition		+0:08	+0:08	+0:08
Remove Bricks	+0:06	+0:05	+0:10	+0:08
Insert Briquettes	+0:00	+0:01	+0:01	+0:01
Seal Top	+0:01	+0:01	+0:01	+0:01
Seal Bottom	+0:01	+0:01	+0:01	+0:01
Place Insulation				+0:01
Open Top	+1:30	+1:30	+2:00	+2:00
Final Mass [kg]	2.8	-	1.5	1.5
% Mass Out	21.53846	FAILED	18.75	18.75
Temp [C]	22	22	24	24
Rel Humidity [%]	31	31	32	32
Wind [m/s]	5.4	5.4	6.7	6.7

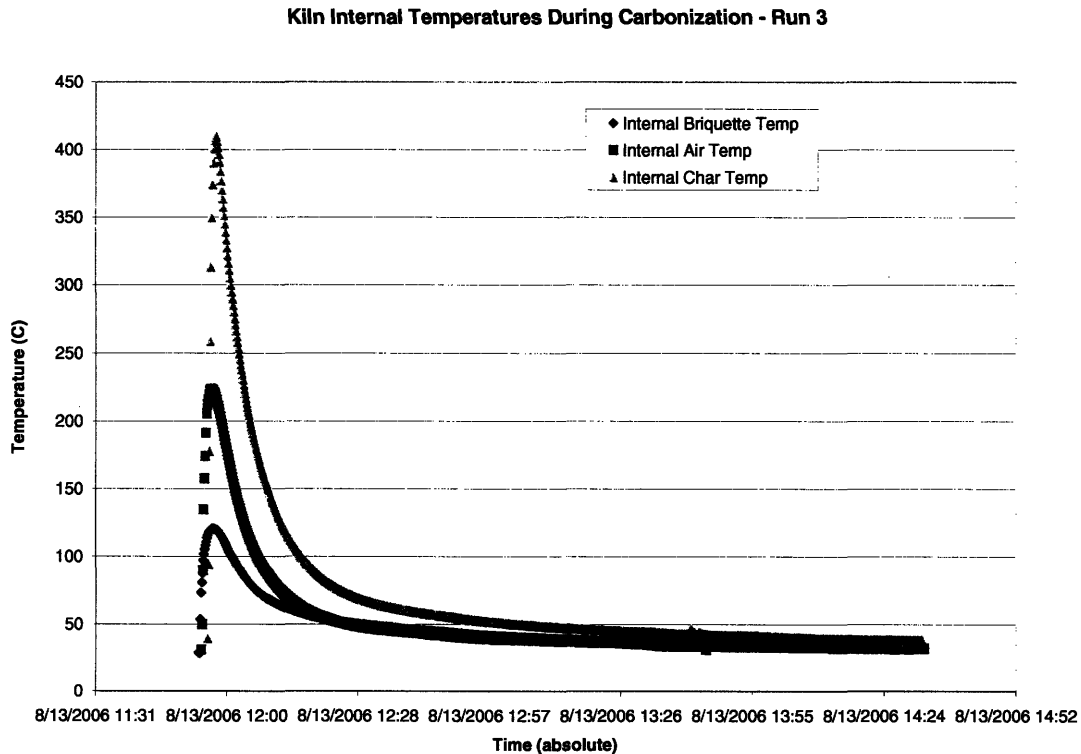


Figure 15. Kiln Internal Temperatures Measured with K-Type Thermocouples During Carbonization.

Kiln Internal Temperatures During Carbonization - Run 4

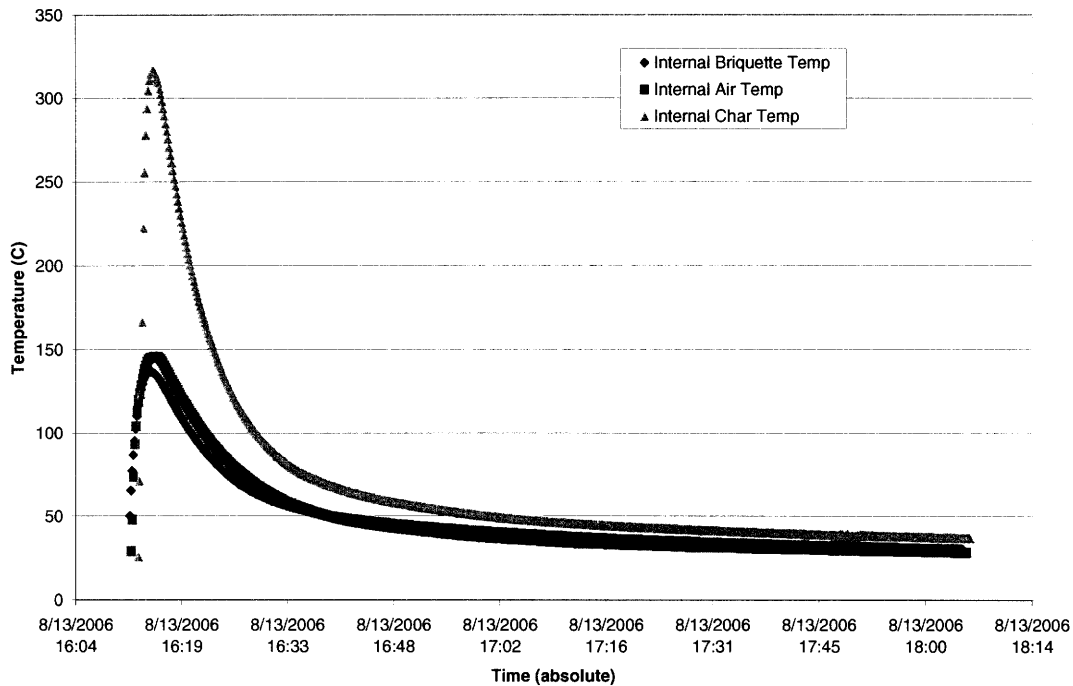


Figure 16. Kiln Internal Temperatures Measured with K-Type Thermocouples During Carbonization.

5.0 Conclusions and Recommendations for Future Improvement

The design work and experiments completed thus far yield an improved charcoal making process over the original model. The design requirements of simplistic and low cost were not compromised during this research. A vertically oriented steel drum kiln was determined to be the cheapest and most effective design for implementation in poor third world countries. Further research into sealing methods for a horizontally oriented kiln may provide a cheap alternative to a vertically oriented drum kiln. A horizontal kiln has the potential to be easier to load and easier to use for crushing the char into powder, making it useful for multiple tasks.

A moderate level of safety was able to be achieved using simple techniques, and simple cheap supplies. Wire tethers are a cheap tool to use to keep hands away from hot surfaces when removing the support bricks or rocks and for loading the briquette baking box into the kiln. The water pot loading action remains the least safe of all the practices in the charcoal making process. More design work can yield a safer and less strenuous method for loading the water pot into the combusting kiln. Design of the briquette baking box has been shown to perform according to theory. It provides an increased exposure of the briquette surfaces to hot interior kiln air. However more testing on real pressed charcoal briquettes needs to be conducted to verify that the briquettes will be made more durable.

A simple and effective insulation technique has been proven through the combustion and carbonization data. Although in many places a simple piece of metal sheeting may be wrapped around it instead of plywood as used in the experiments. In a country like a Haiti, deforestation is already an extreme problem, so wooden tools are unfavorable.

Initial testing of the combustion timing has provided a general rule for creating char from corn stalks in a drum kiln. Approximately one minute of smokeless combustion per kg of biomass provides enough thermal energy to carbonize all of the remaining biomass and still achieve nearly 20-25% efficiency in output mass from input mass. The next task to complete is to complete a rigorous test matrix testing all reasonable combustion times. Data would be taken for internal kiln temperatures and final char yield. This data could be plotted as a function of the combustion time for various materials in order to determine the optimum combustion timing for maximum char production. Then ideally testing would be repeated at different volumes to find a correlation between combustion time, type of biomass, and volume of that particular biomass used to create char. This thesis has provided a basic improvement in the areas of kiln design, safety, and briquette baking. It also offers insight into the areas of this charcoal making process, such as sealing methods and combustion timing, which can be improved upon to maximize the efficiency of its char production.

6.0 References:

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