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An Efficient and Safe Cooking Stove for Las Delicias, El Salvador

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Abstract
The primary objective of this project was to design an efficient and safe cooking stove based on the resources available in El Salvador while ensuring it could be inexpensive to produce. The stove is a cuboid, 18"×18"×12" in dimension, and weighs 75 lbs. It has a top cover to cook on, and a unique three-chamber design: a chamber for combustion, a chamber to pump hot air into the combustion chamber with a bellows, and a third chamber to add insulation material. A ventilation tube connects the inner chamber with the exterior to safely vent flue gas to the outside. The stove is made out of stainless steel, and uses sand as an insulator. The product's overall energy efficiency was calculated to be about 33%, and it requires approximately 19-20 minutes to boil 5 liters of water assuming a pot diameter of 14". The estimated manufacturing cost of producing the first 200 stoves is $51.77 per unit, without including capital equipment costs. A unit can be priced at $65, which would give the manufacturer a 25% margin while maintaining competitiveness in the market against stoves such as Turbococina and Ecocina. The stove is estimated to cost a family $15 per month to operate, which corresponds to 50% in charcoal fuel savings compared to using an open flame. The stove can be manufactured using local labor and would take on average 6 to 7 hours to construct one unit.

Disciplines
Biochemical and Biomolecular Engineering | Chemical Engineering | Engineering

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School of Engineering and Applied Science
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220 S. 33rd Street
Philadelphia, PA 19104
April 18, 2016

Dear Dr. Warren Seider, Professor Bruce Vrana, and Mr. Adam Brostow,

The enclosed report contains our proposed design for an efficient and safe cooking stove for the rural areas of El Salvador, a project proposed by Mr. Adam A. Brostow. The product can be easily and cheaply produced using resources available in El Salvador, is simple to operate, and prevents toxic flue gases from entering the household.

The stove is a cuboid, 18"×18"×12" in dimension, and weighs 75 lbs. It has a top cover to cook on, and a unique three-chamber design: a chamber for combustion, a chamber to pump hot air into the combustion chamber with a bellows, and a third chamber to add insulation material. A ventilation tube connects the inner chamber with the exterior to safely vent flue gas to the outside. The stove is made out of stainless steel, and uses sand as an insulator. The product's overall energy efficiency is 33%, and it requires approximately 19-20 minutes to boil 5 liters of water assuming a pot diameter of 14". The estimated manufacturing cost of producing the first 200 stoves is $51.77 per unit, without including capital equipment costs. The stove can be sold for $65 to make a 25% profit margin. It is estimated to cost a family $15 per month to operate, which corresponds to 50% in charcoal fuel savings compared to using an open flame. The stove can be manufactured using local labor and would take on average 6 to 7 hours to construct one unit.

The heat and mass transfer analyses were performed in Microsoft Excel, and the computer-aided design was created in SolidWorks. NextFab Labs was contracted to manufacture a prototype.

We would like thank you and the other industrial consultants for the assistance afforded to us during this project, and the Judy Soley Support for Student Groups Fund in SEAS for providing the capital to produce the first prototype.

Sincerely,

Maria Castañer	Daniel Li	Nicolas Minor

An Efficient and Safe Cooking Stove for Las Delicias, El Salvador

Maria Castañer | Daniel Li | Nicolas Minor

Advised by:
Warren D. Seider
Bruce M. Vrana

Project suggested by:
Adam A. Brostow

Department of Chemical and Biomolecular Engineering
School of Engineering and Applied Science
University of Pennsylvania
April 18, 2017

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1. Abstract

The primary objective of this project was to design an efficient and safe cooking stove based on the resources available in El Salvador while ensuring it could be inexpensive to produce. The stove is a cuboid, $18'' \times 18'' \times 12''$ in dimension, and weighs 75 lbs. It has a top cover to cook on, and a unique three-chamber design: a chamber for combustion, a chamber to pump hot air into the combustion chamber with a bellows, and a third chamber to add insulation material. A ventilation tube connects the inner chamber with the exterior to safely vent flue gas to the outside. The stove is made out of stainless steel, and uses sand as an insulator. The product's overall energy efficiency was calculated to be about 33%, and it requires approximately 19-20 minutes to boil 5 liters of water assuming a pot diameter of 14".

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2. Introduction

2.1. Project Background

El Salvador is the smallest yet most densely populated country in Central America. It is the fifth poorest country in Latin America, with more than 40% of the country's population living in poverty. The country has been greatly affected by a large number of natural disasters such as floods, droughts, earthquakes, and volcanic eruptions. El Salvador has also suffered from economic stagnation and social inequality. For more than two decades, the generation of jobs has been lower than population growth. While the 20% richest households earn 58% of the national income, the 20% poorest earns only 2.4% of the national income (Poverty in El Salvador, 2016). In El Salvador, there is a large social and economic gap between urban and rural areas. Urban areas are relatively modern and have large economic and social opportunities, while rural areas are marginalized and underdeveloped, with 56% of people living in poverty.

Las Delicias is a poor rural village located 35 km outside of San Salvador with about 3,000 inhabitants. The village suffers from low levels of employment, on average households earn $2 per day, and most of the village has no electricity. Women typically use wood or charcoal for cooking, and prepare meals in an open rack over a fire, as shown in Figure 2.1. Propane is also available in the village, but it is often used for other purposes, such as heating. Water in the region can be contaminated, so families usually boil the water to kill any pathogens before drinking.

Figure 2.1. Kitchen in Las Delicias

The current cooking techniques used in the village are highly inefficient, as most of the heat generated by the fire is lost into the surroundings. Households spend on average 9% of their monthly income on fuel for cooking, so switching to a high-efficiency stove would reduce their monthly expenses significantly. Another issue with their current cooking technique is that it fills their houses with smoke. Air pollution can cause chronic respiratory problems, especially in children. Efficient stove alternatives in the market that could help solve these problems are unaffordable or require electricity, which is unavailable in the village.

This project aims to design an efficient cooking stove to improve the lives of the people in Las Delicias. The stove is affordable by rural Salvadoran families, and pays for itself given the significant savings on charcoal consumption per meal that it can achieve. The design of the stove also eliminates indoors air pollution. It can be built using materials available in El Salvador, and assembled using techniques that require machinery available locally. This efficient stove can cook meals and boil water much faster, and help families save on monthly fuel purchase cost. Additionally, it will also create economic opportunities within the village, as the manufacturing process of the stove and the production of charcoal will require local labor, thus creating employment opportunities.

Figure 2.2. Gathering wood in Las Delicias

2.2. Objective-time Chart

Project Name	Efficient Cooking Stove for Developing Countries
Project Champions	Adam A. Brostow, Warren D. Seider, Bruce M. Vrana
Project Leaders	Maria Castañer, Daniel Li, Nicolas Minor
Specific Goals	Design an efficient cooking stove based on the resources available in El Salvador while ensuring it is safe and inexpensive to produce.
Project Scope	<u>In Scope:</u> ● Description of product concepts ● Design on SolidWorks ● Steady and transient state heat transfer models ● Profitability analysis ● Manufacturing process description ● Construction of prototype ● Testing of prototype <u>Out of Scope:</u> ● Detailed testing of prototype ● Introducing product in Las Delicias, El Salvador
Deliverables	Business opportunity assessment: ● What is the current market for cooking stoves in El Salvador? ● How do competing products compare to this product? Technical Feasibility assessment: ● Will the product increase the energy efficiency significantly? ● Will it provide adequate safety? (i.e. prevent indoors air pollution and skin burns) Manufacturing capability assessment: ● Can the product be manufactured locally and at a low cost?
Timeline	Complete design and economic analysis by April 18, 2016.

2.3. Innovation Map

The innovation map summarizes how the design of the stove will help meet the cooking requirements of families in poor rural areas in El Salvador (Seider, et al., 2017). The proposed design is simple and can be constructed using local inexpensive materials, ensuring that the stove is affordable, easy to manufacture, and simple to use. The stove's efficient combustion chamber increases the energy efficiency and reduces the time required to boil water and to cook meals. Furthermore, its ventilation system allows flue gas to escape the house and prevents indoors air pollution.

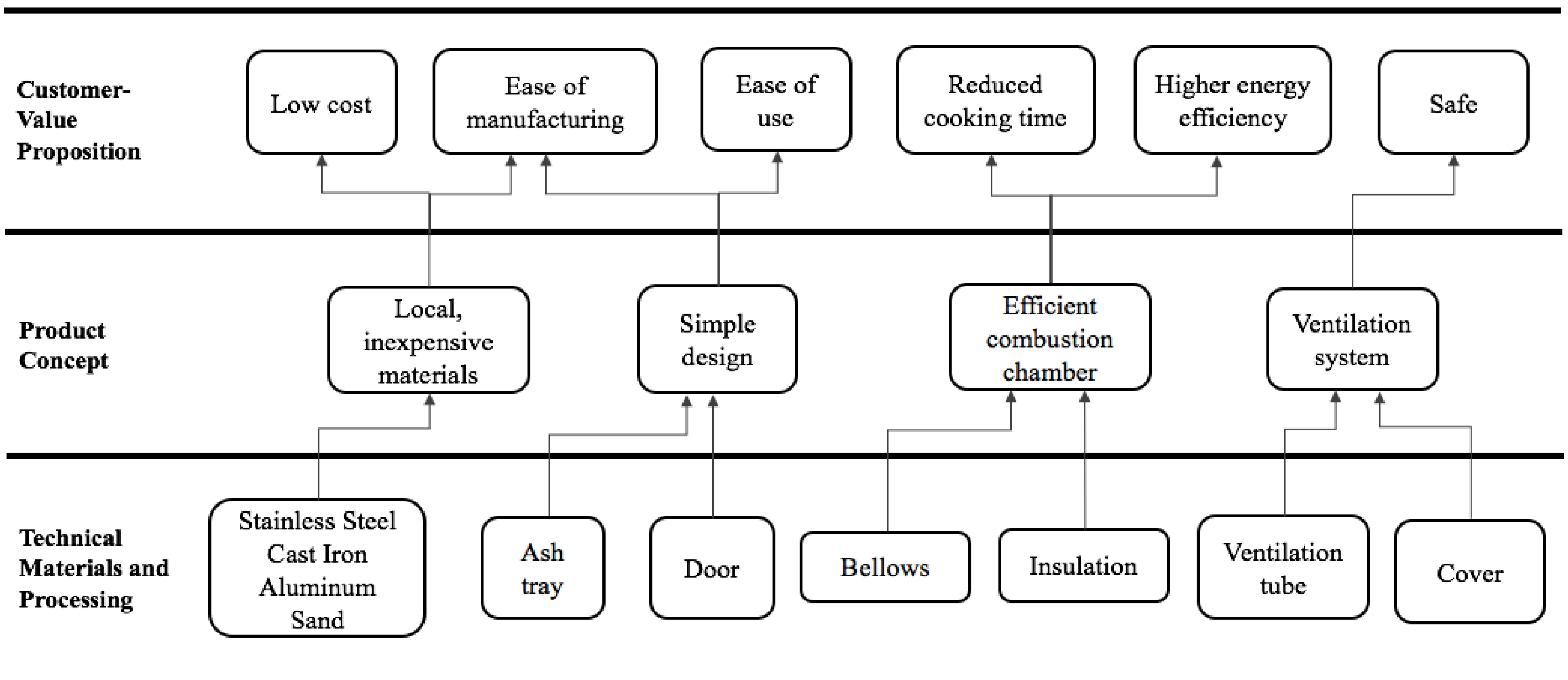


Figure 2.3. Innovation map for efficient cooking stove in developing countries.

3. Concept Stage

The concept stage is the brainstorming period where the initial needs of the product are assessed. Before a product can be designed, the need in the market for a new product, the existence of any other competitors, the desired attributes of the end customer, and the manufacturing constraints must be determined.

3.1. Market and Competitive Analysis

Over one-third of the world's population – 2.8 billion people – rely on open fire or inefficient stoves to cook and heat their homes, which creates dangerous burning conditions and toxic fumes. Each year, more than 4 million people die from diseases related to smoke exposure from open flames (Barna, 2017). Thus, the market for more efficient and safer cooking stoves and fuel sources is worth billions of dollars. Many people are trying to capitalize on the growing concern of smoke inhalation and fuel waste, but each stove concept currently on the market has its flaws. Current competitors include Turbococina, Ecocina, solar cooking arrays, and many others.

While our product has the potential to be sold around the world, the market scope of this project involves the rural village of Las Delicias, El Salvador, where current cooking uses rudimentary open flame racks. The population of Las Delicias is nearly 3,000 (Project Las Delicias, n.d.), or 600 households, assuming that each household is 5 people. Here, families make on average $350/month, and spend on average about $1 every day on firewood (Household Income Up 10% in El Salvador, 2014). This means that families spend about 9% of their total income on fuel alone. The spending on fuel could be drastically reduced if a more efficient stove was used.

It was calculated that our stove design can reduce the amount of fuel needed by nearly 50%. If this product were to cost $65, then it would pay for itself after 9 months of use. It would seem that every household should purchase a new stove, but assuming that some families already have better stoves, some will choose to purchase a different stove, and some would not want to pay the upfront capital cost, the demand for our product would be closer to 200 units. Since our stove has an estimated lifespan of 7 years, this 200-unit demand should be renewed every 7 years. In the future, demand could be expanded to other developing countries. A more detailed economic analysis can found in Section 11.

There are numerous competitors in the market such as Turbococina, Ecocina, and solar cooking arrays. This section serves as a brief overview of available stoves and their economics. A detailed patent and design analysis of the Turbococina and Ecocina can be found in Section 6 (Comparative Patent Analysis). Many of these devices are distributed to El Salvadorian rural citizens at a highly-discounted price or free of charge. In order to compete, our product may also need to be sold with a subsidy or distributed through a non-governmental organization (NGO).

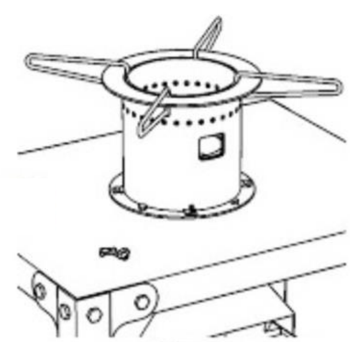


Figure 3.1. Turbococina

The Turbococina shown in Figure 3.1 is a biomass combustion stove made from steel. The innovative combustion chamber reduces fuel consumption by up to 90%, and needs to be continuously fed with small pieces of firewood. The air and flue gas flow is regulated by an electric fan. Unfortunately, many households in Las Delicias and other rural parts of El Salvador do not have electricity. Therefore, the Turbococina has mostly been given for free to public schools to prepare lunch, and over 1,200 have been deployed through a Ministry of Education initiative. Although the retail price of this stove has not been released, it has been estimated that the mass production cost is around $140 per unit (El Salvador, n.d.). While this stove is more efficient than our design, it is not practical for household use in rural areas without electricity.

Figure 3.2. Ecocina

The Ecocina (Figure 3.2) is another stove that has gained popularity in El Salvador. This stove is a cement stove that has an L-shaped combustion chamber. Medium sized firewood is fed through the front opening, and the heat rises up to a cooking apparatus. The design reduces required firewood by 50% and reduces indoor air pollution by 70%. The stove retails for $65, but most of the 20,000 units distributed in El Salvador so far have been sold for far cheaper than the retail price (El Salvador, n.d.). Since the Ecocina does not have a chimney, the flue gases escape into the house, unlike our design which directs smoke though a pipe to outside. In order to maintain competitiveness, our stove will most likely have to be sold at a similar price to the Ecocina.

Other potential, but not as widespread competitors are solar cooking devices, such as the ones displayed in Figure 3.3. These cookers consist of a box or parabolic-shaped container that is surrounded by metallic material. The cooker is left outside in the sun, where the reflective metal directs solar energy to a pot to cook food. Solar cookers are extremely cheap to produce, easy to operate, and do not require an additional fuel source. The obvious disadvantages are that these devices only work when the sun is out, and that the required cooking time is much longer than traditional wood or charcoal burning stoves. These downfalls are the reason why solar stoves are mostly used in extremely poor areas, and would not be popular in a village like Las Delicias.

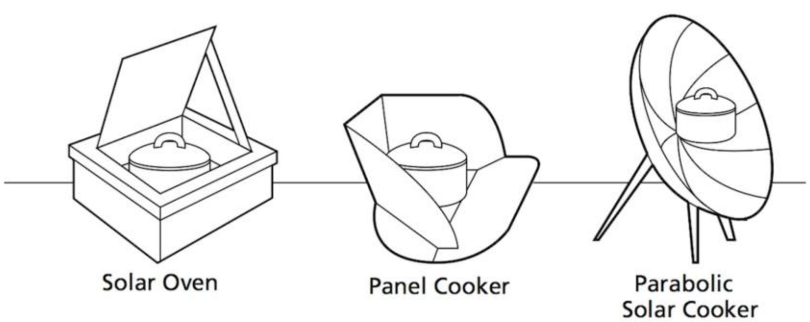


Figure 3.3. Solar Cooking Device Examples

3.2. Customer Requirements

3.2.1. Cost

For the families in Las Delicias to be able to afford the stove, it must be priced at a cost reasonable given their income level. Considering the low income earned per household in Las Delicias, most families consume much of their income by the end of each month and have limited savings.

3.2.2. Safety

One of the main safety concerns with cooking stoves in developing countries is that most of them use solid fuels, mainly wood and charcoal, as a source of energy. Using these stoves indoors can cause the flue gas generated by burning the fuel to accumulate inside the house and be inhaled by the occupants. The gas produced by burning charcoal is composed of mostly carbon dioxide, although some carbon monoxide is produced when the charcoal is burnt in an oxygen deficient atmosphere. While low concentrations of carbon dioxide are not harmful, high concentrations of carbon dioxide can affect respiratory function and depression of the central nervous system. Carbon monoxide is a toxic gas and can be dangerous to human health. While carbon monoxide is not abundant, chronic exposure to low levels of carbon monoxide can lead to depression, confusion, and memory loss. More than 4 million people die each year from illnesses related to indoor air pollution. Children are especially affected by air pollution inside homes, causing them to suffer respiratory problems and chronic pulmonary diseases (Barna, 2017). In Las Delicias, inhabitants tend to cook indoors to protect themselves from harsh weather conditions such as high temperatures or storms. Their houses are small, unventilated spaces where flue gas generated by cooking stoves can easily accumulate inside the room, making ventilation a major safety concern.

Another main safety concern with cooking stoves is the high temperatures of the outside walls. Depending on the temperature, prolonged contact with the outside walls can cause severe burns. In South America, 18% of children with burns end up having permanent disability (Burns, 2016). Therefore, the temperature of the outside walls of the stove should not be decreased as much as possible to prevent its users or the people around it from burning.

3.2.3. Required Cooking Time

Often, developing rural areas do not have adequate stoves to cook meals. For instance, in Las Delicias, inhabitants use an open rack, shown in Figure 2.1, to prepare their meals. This technique is highly inefficient because a large fraction of the heat being generated by combustion is lost to the surrounding.

Villagers in Las Delicias need a cooking stove that directs the heat generated by the fire into the cooking surface as efficiently as possible. By directing the heat more efficiently, the amount of time required to cook food or to boil water decreases. Villagers would likely only be willing to purchase a stove with an efficiency considerably higher than the one they currently have, one that would help them save considerable amounts of time and money.

3.2.4. Ease of Use

Every good product should be user-friendly. The villagers should be able to use sources of fuel available in the area, such as charcoal and wood, to operate the stove. The stove should be easy to start. Once the fuel is burning, users should have access to the combustion chamber to add more fuel if necessary. After using the stove, it should be easy to clean and remove the accumulated ash.

3.2.5. Ease of Manufacturing

This project aims to develop a stove that can be manufactured locally by villagers in Las Delicias to create employment and provide a new economic opportunity in the area. Therefore, it is essential that all the materials, tools, and labor skills be found in the region.

3.2.6. Cultural Acceptance

The cooking stove not only has to meet all the requirements above, but also must be appropriate for the culture where it is used. In Las Delicias, women want to prepare tortillas the way they used to for generations. They will only purchase a stove that allows them to keep cooking their food in the same way. It is common in the village to use either wood or charcoal to cook meals. Gathering fuel, such as wood and charcoal, is a way for people to socialize in the village. Households that use propane stoves tend to use them for heating, rather than cooking. The stove should also be designed to prepare their traditional meals. Villagers not only need to be able to heat up cooking pots to make soups, sauces, etc., but also need a flat surface to cook food such as meat or *pupusas*, which are thick, handmade corn tortillas.

3.3. Product Requirements

Our product was designed by taking into account the wants and needs of our target consumer – a family. These customer requirements were determined by analyzing the complaints and concerns from villagers in Las Delicias regarding their current cooking methods and through considering existing expectations of wood and charcoal stoves.

3.3.1. Cost

To account for the cost, our stove is designed to be constructed from inexpensive material accessible to the people of Las Delicias. Additionally, the constituting metal has been optimized to limit the amount of material used without compromising the structural integrity of the stove.

The stoves are also meant to be made within the village. This will provide a stimulant to the economy and ensure fair pricing for labor and materials.

3.3.2. Safety

As mentioned earlier, safety was one of the most important factor of our design. The purpose of the project was to design a stove as an alternative to the current dangerous practices that are currently available. To accomplish this, we defined the major safety concerns expressed in the customer requirements and sought solutions to each one to implement in our design. We ensured to provide solutions for the exposed flame, flue gas in the environment, and the temperature of the walls of the stove.

The current cooking method provides no enclosure for the flame and its fuel source. To both contain the burning ash and prevent unwanted flammable material from coming into contact with the flame, our stove features a container for the fuel and fire. Fuel will be placed on a grill inside of four metal walls contained within two additional chambers. This eliminates the possibility of fire spreading out of control or material burning on accident. Interacting with the fire can be can be safely done from the door in the front on the stove.

To prevent flue gas from reaching harmful levels in the environment, our stove is designed with a cover over the top of the fire. The top cover provides a surface for cooking, while preventing flue gas from freely escaping into the atmosphere. One side of the stove has a hole used for the ventilation of the flue gas. The ventilation hole allows the flue gas to safely be directed away from the cooking space through a heat resistant silicone rubber hose, while also preventing pressure buildup within the inner chamber of the stove. This ventilation system will keep the environment below the maximum carbon monoxide level of 9 ppm defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (CO Knowledge Center, 2017).

To ensure the walls of the stove are kept at sufficiently low temperatures, our stove features a layer of insulation between the outer chamber and the middle chamber. Using sand as an insulator, we were able to decrease the temperature of the outer walls by 182°C. However, the exterior is still hot enough to burn flesh through contact.

3.3.3. Cooking Time

Indicators of an effective stove are quick heating times and sufficient temperatures to cook meals. To create effective cooking, our stove utilizes air holes on the bottom of the outer and inner chambers. These holes promote air flow to the fire, providing oxygen for the combustion of the fuel. The air flow can also be supplemented through the optional use of a bellows that pumps air through a hole on the side of the stove into the inner chamber. The increased oxygen to the fire allows the flame to reach higher temperatures, expediting cooking times.

3.3.4. Ease of Use

Our stove features unique aspects specifically chosen to promote its ease of use. An important feature that highlights this is the removable stove top. The stove top can be taken off the stove, which comes with a multitude of benefits. The stove can be opened to quickly add more coals or wood in larger amounts while the stove is off. It also allows the user to easily clean the inside of the stove. Additionally, the fuel can be lit from a large open space rather than a small opening like a door. While the stove is lit, the fire can be manipulated through the door on the front of the stove. This door allows the user to safely move fuel or add additional fuel.

3.3.5. Ease of Manufacturing

Manufacturing the stove in Las Delicias has the potential of economic stimulus to the village through the creation of jobs and money staying within the community. To take advantage of this benefit, we designed our stove to be manufactured by local blacksmiths. Our stove can be manufactured through bending and welding sheet metal, and punching and drilling holes rather than being shaped and cut by heavy machinery.

4. Product Concepts

The design of our stove went through various changes during the development of its design. This section of the report chronicles the different concepts that were deemed impractical or infeasible for the scope of the project.

4.1. Material

4.1.1. Cast Iron

Early designs of our stove were entirely fashioned out of cast iron. Cast iron remains structurally sound under high temperature and has a high thermal conductivity. Additionally, fabricating cast iron is a common practice feasible in most developing countries at a low cost of production.

Despite these benefits, our team decided cast iron was not the optimal material for construction of the stove body. Cast iron is very rigid and cannot be bent through traditional means. This means that each part of the stove must be casted from a mold and cutting or puncturing the iron is almost impossible due to its brittleness. Molding also takes more time and more skill than bending and cutting sheet metal. Cast iron is also a very dense metal making which would make the stove very heavy and not easily movable around the house or cooking area.

4.1.2. Aluminum

Aluminum is a very inexpensive metal with low density and high strength. Constructing the stove entirely out of aluminum would decrease the cost while also significantly decreasing the weight of the stove.

Aluminum, however, has a low melting point of about 660.3°C. This is too close to the burning temperature of charcoal which can reach to temperatures above 600°C (Engineering ToolBox, n.d.). As aluminum approaches its melting temperature, it begins to deform. This deformation can cause the stove to no longer fit together as it should or in extreme cases cause the stove to collapse. Aluminum cookware has also been reported to dissolve aluminum into food when heated to high temperatures (The Safe Use of Cookware, 2015). While the dissolving aluminum would likely not find its way into the consumer's diet, the effect of dissolved aluminum from aluminum cookware has not been fully understood. Therefore, we determined it would be safer not to include aluminum in places on the stove that would come into contact with high temperatures.

4.1.3. Fire Brick

Fire brick is a commonly used material for constructing kilns and ovens due to its high compressive strength, its durability, and its cheap, accessible raw material. Additionally, fire brick is highly heat resistant and has a simple manufacturing process.

Fire brick was not chosen in the final design due to its lower conductivity when compared to metals, its weight, its time-consuming construction process, and its difficulty to clean. While it makes an effective kiln or oven, fire brick does not allow efficient conduction from the heating source to desired surface to be heated, thus fire brick would only be suitable as the casing for the fuel source. However, to have acceptable compressive and tensile strength, the fire brick would have to be relatively thick. Increased thickness would cause the stove to be larger and heavier than one constructed of thin metal making in a permanent structure in the kitchen rather than a mobile one. Furthermore, its rough, porous surface can be difficult to clean. Due to the stoves exposure to food and moisture, there is a risk of mold growing within the pores if not properly cleaned.

4.2. Insulation Material

4.2.1. Clay

Clay is a decent insulator due to its low thermal conductivity of $0.15\ \frac{W}{m \cdot K}$ (Engineering ToolBox, n.d.). Additionally, clay is incredibly accessible and virtually free. Despite this, our team decided that clay was not the optimum insulation material. Clay does not easily fit into the tight space of the insulation chamber of our stove. To fit clay into the space, it would have to be very hydrated to the point where is flows freely. The clay would then have to dry to reach a lower conductivity as wet clay is a better conductor than dried clay. While this would be possible given the high temperatures of the stove, with the alternatives available, it is better to avoid the additional steps.

4.2.2. Fiberglass

Fiberglass is one of the most effective insulators on the market due to its low conductivity $\left(0.15\ \frac{W}{m \cdot K}\right)$ and its ability to be packed into tight spaces. Many household stoves and ovens in developed countries use fiberglass as insulation. However, fiberglass is very expensive and would have to be shipped from a more developed area due to its complex production. To keep the cost of production as low as possible and to ensure that the materials of the stove are easily acquirable, fiberglass was not chosen as an insulation material.

4.2.3. Air

Stationary air has a very low thermal conductivity of $0.024\ \frac{W}{m \cdot K}$, making it an ideal insulator. However, due to the heat from the stove, the air will move due to convection. Air in motion has a high thermal conductivity of $10\ \frac{W}{m \cdot K}$, significantly reducing its utility as an insulator (Engineering ToolBox, n.d.). Using an empty chamber as an insulator is only possible if the insulation chamber was evacuated. This was deemed impossible given the manufacturing capabilities of developing countries.

4.3. Fuel Source

4.3.1. Propane Gas

While propane gas burns cleaner and more efficiently than wood and charcoal, it is a much more expensive fuel source. Constructing a gas stove also requires proper storage of the gas fuel. Given the inexperience of our design group, attempting to use gas could potentially risk explosion or a gas leak.

4.3.2. Solar Energy

Solar energy is free and abundant due to Las Delicias tropical climate. Constructing a stove to take advantage of this energy proved to complicate the design increasing the cost to manufacture the stove. Furthermore, using solar energy is limited to time when the sun is out, which excludes rainy days or night-time. The utility of the additional energy provided through solar energy was deemed less than the additional cost due to these limitations.

4.4. Shape

4.4.1. Cylindrical

Initially, our stove was designed to be cylindrical in shape. Cylinders have the advantage of maximizing surface area to volume ratios, allowing less material to be used in construction. Circular objects also hold pressure better than flat surfaces sharp edges that may deflect or act as stress raisers respectively. Many existing stove designs feature a cylindrical shape for this reason.

While a cylindrical shape is more efficient, it is very difficult to produce given the technological constraints of developing countries. Bending sheet steel into a cylinder of precise radius is an extreme challenge without appropriate machinery to assist the blacksmith. If the cylinders are distorted, there is a possibility they will not fit together making it difficult or impossible to assemble the stove depending the significance of the distortion. If a village does have the machinery necessary to construct accurate cylinders for the stove, the cost of the production would increase due to the advanced skill and equipment needed to make the product. Due to these constraints, we determined a cylindrical shape was not an appropriate shape for our stove.

4.5. Manufacturing Method

4.5.1. Casting

Casting provides the benefit of a structured mold for the stove. Given a proper mold, molten metal will flow into the desired cavity, thus the production of each component of the stove is made in a very straight forward and reproducible process. Additionally, casting is often one of the cheapest production methods.

While cheap and straightforward, casting also has key limitations that invalidate it as a production method for the stove. With casting, defects are usually unavoidable which could affect the structural integrity of the stove. These defects are furthered by the dimensional inaccuracies common in the sand casting process. Also, while cheap and straightforward in its directions, sand casting is very labor intensive compared to welding and cutting.

4.6. Accessories/ Features

4.6.1. Ash Funnel

Early concepts of our stoves featured a funnel located under the grill to direct falling ash directly onto a removable tray making it easy to clear ash from the system. The funnel was determined to be unnecessary because the ash had a natural tendency to fall onto the tray without assistance. Moreover, the bottom cover is also removable for cleaning given any ash were to fall outside of the tray space.

4.6.2. Air Guide

After the removal of the ash funnel, our team designed an upward parabolic ring to be welded under the grill and attached to the middle chamber. The ring served to direct air blown by the bellows to the flame in the inner chamber. The guide was deemed to be unnecessary since the air will travel through the path of least resistance. With holes on the inner chamber, air will naturally travel to the flame without the guide's assistance. Constructing the air guide is also a complex process, increasing the time and the cost to produce with miniscule utility.

5. Superior Product Concept

After assessing the available options, a final product design for the stove can be formed. The following section details the final design and justifications for its superiority to the former concepts.

5.1. Materials

5.1.1. 16 Gauge AISI 304 Sheet Steel

AISI 304 is a cheaper lower grade stainless steel, yet still fulfills all of the necessary functions for the stove. It resists corrosion, fire and heat, is hygienic and is easily fabricated. Thus, to keep cost down, this steel was chosen as opposed to more expensive higher quality steel.

Ultimately, AISI 304 sheet steel was determined to be the most effective material to construct the body of the stove. While it is more expensive than aluminum and cast iron, this steel provides numerous advantages. Unlike cast iron, sheet steel can be bent with relative ease. Rather than casting each separate component in a different mold, this steel is flexible enough to be bent into the desired shape and welded into position. Furthermore, steel can be cut through traditional cutting and drilling methods, allowing the manufacturer to drill and cut features into the sheet rather than having to cast them. Additionally, this steel is significantly lighter than cast iron reducing the overall weight of the stove and making the stove more transportable. The tensile strength of steel allows for the walls to be considerably thinner than cast iron or fire brick without sacrificing structural integrity.

Steel also has a high melting point of 1400 °C and is typically used in cooking because of its resistance to degradation or deformation under high temperatures (Melting Temperature Ranges for Stainless Steels, n.d.). Contrary to aluminum, AISI 304 steel will not compromise under the range of temperatures, 400-700 °C, at which charcoal can burn nor is there risk of it dissolving into the food. Its low reactivity hinders rust from forming and increases its longevity. Because of its smooth surface, it is very easy to clean, making it more sanitary than porous materials like fire brick.

5.1.2. Cast Iron

While it made for an ineffective material for the body of the stove, cast iron is the most effective material to be used for the grill and the stove top. Cast iron has a high thermal conductivity $\left(58\ \frac{W}{m \cdot K}\right)$, high melting point (1,200 °C), and low production cost, making it an ideal material to be used as the stove cover and the grill for the surface of the fuel combustion. These two features are not welded nor fitted exactly into position on the stove, so exact dimensions are not imperative. The small inaccuracies and defects associated with cast molding will not factor into these parts' functionality. Additionally, a mold can easily be made and casted because of the simple shape of the grill and stove cover.

5.2. Insulation

5.2.1. Sand

Dry sand shares the same low thermal conductivity as clay $\left(0.15\ \frac{W}{m \cdot K}\right)$ while also being virtually free. Sand, unlike clay, flows very easily and will fit into its container without additional manipulation. Due to its ease of use and its low conductivity, sand was determined the optimal material for insulation.

The insulation serves to reduce the temperature of the outer chamber to prevent accidental burn, thus increasing the overall safety of our stove. Insulation also serves to keep the heat from leaving the system through the walls of the stove, so that instead heat will travel through the top cover of the stove and be used for cooking.

5.3. Fuel Source

5.3.1. Wood and Charcoal

Wood and charcoal are very common fuel sources, especially in developing countries. In order to be fully culturally accepted by Las Delicias, our stove was designed to be able to use both wood and charcoal, but charcoal would be preferred due to higher energy content and cleaner burning.

5.4. Shape

5.4.1. Rectangular Cuboid with Rounded Edges

The advantages of a rectangular stove lie in its ease of production. Recognizing that while cylinders optimize material usage per volume, they are very difficult to fabricate, our stove is designed rectangular in shape. While it sacrifices surface area to volume ratio, it is much easier to bend metal into corners than into a circle. Also, straight flat surfaces are easier to dimension than cylindrical shapes. This allows our product to be designed more easily by developing countries making it more accessible. To minimize stress raisers in the corners of the rectangular stove, the edges of the stove are rounded rather than bent at 90°, distributing the forces over a wider area.

5.4.2. Three Chambers

Our stove features three chambers made from three coaxial boxes (Figure 5.1). The innermost chamber formed on the inside of the inner box functions as the combustion chamber, as shown in Figure 5.2. The base of this chamber is the grill used to hold the fuel sources and the grill support. This chamber has a volume 1764 in^3 providing ample volume for the combustion reaction, while

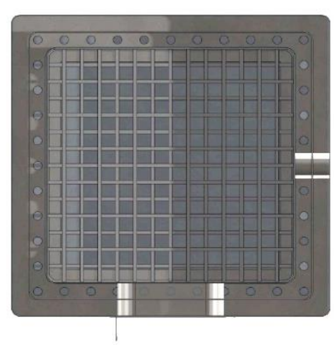


Figure 5.1. Top view of the three chambers

also providing a close distance between the grill and top cover to facilitate efficient heating of the cooking surface. A 6"×4" opening on the face of the chamber wall serves as a door for reloading and stoking fuel. Air travels into the chamber through the air holes lining the bottom and through the open spaces from the grill. A 2”-diameter ventilation hole is located two inches from the top edge of the chamber. This hole functions as an outlet for the flue gas that it produced from the combustion reaction. The chamber is fastened to the rest of the stove through welding to the upper frame, the door seal, and the ventilation seal.

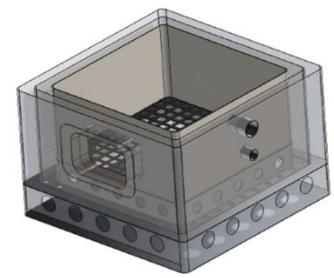


Figure 5.2. First Chamber

The second chamber is the air chamber, located between the middle cylinder and the inner cylinder (Figure 5.3). Air occupies this chamber with a volume of 504 in^3. On the front wall, a 6"×4" door hole identical to the one located on the inner wall providing the user with access to the combustion chamber. Located 2” from the top of the top of the middle wall is a 2”-diameter ventilation hole that allows flue gas to pass from the combustion chamber through this chamber. The ventilation hole is sealed by a steel tube that prevents flue gas from escaping into the chamber. Below the ventilation hole is a 1”-diameter hole that serves as an inlet to air pumped by a bellows. This chamber serves as a space to preheat air pumped by the bellows and to deliver it to the inner combustion chamber through the holes on the inner walls and the holes in the lower frame. Air occupying and passing through this chamber are heated due to high temperatures of the combustion chamber. The addition of preheated air to the combustion reaction increases the efficiency of combustion, allowing the stove to burn at

Figure 5.3. Second Chamber

higher temperatures without burning additional fuel. The chamber is fastened to the stove through welding to the upper frame, the door seal, the bellows seal, the ventilation seal, and the lower frame.

The third chamber serves as a chamber for insulation, formed from the space between the middle and outer walls. A ventilation hole, bellows hole, and door opening are also present on the face of the chamber. A hinge door is attached to the outside of the outer wall closing off the combustion chamber from outside the system. Insulation fills the space created by the inner and outer walls and the seal from the lower frame with a total volume of 612 in^3. The lower and upper frame keep the insulation from coming out of the stove from the top and bottom. The insulation within this chamber serves to significantly decrease the temperature of the outer walls of the stove reducing the possibility of the user being injured while operating the stove, while also containing the heat produced by the stove allowing more heat to pass through the top cover to be used for cooking. This portion is connected through welding to the upper and lower frames, the bellows seal, the door seal, and the ventilation seal.

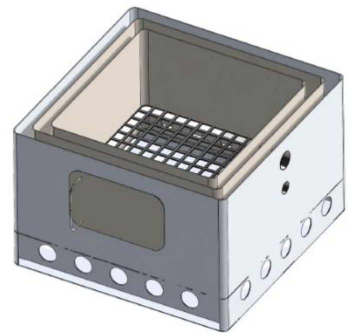


Figure 5.4. Third Chamber

5.5. Manufacturing Method

5.5.1. Steelwork Techniques

To construct the body of the stove common simple steelwork techniques are used. With sheet steel as the material of construction, parts can be shaped through bending and cut through metal cutting and drilling. Parts are fastened together through riveting and welding.

5.5.2. Casting

The grill and top cover are made through casting. Because of their simplistic shape and lenience for minor deformities, sand casting is an effective method for production.

5.6. Accessories/Features

5.6.1. Top Cover

Our product features a cast iron stove cover as a surface for cooking. Cast iron has a high thermal conductivity allowing heat to transfer from the combustion chamber through the cover to with low heat loss. The cover prevents noxious fumes produced through combustion from freely entering the atmosphere; instead forcing the gas through the ventilation hole. The cover is removable, which allows the user to easily clean the interior or add fuel while the stove is off.

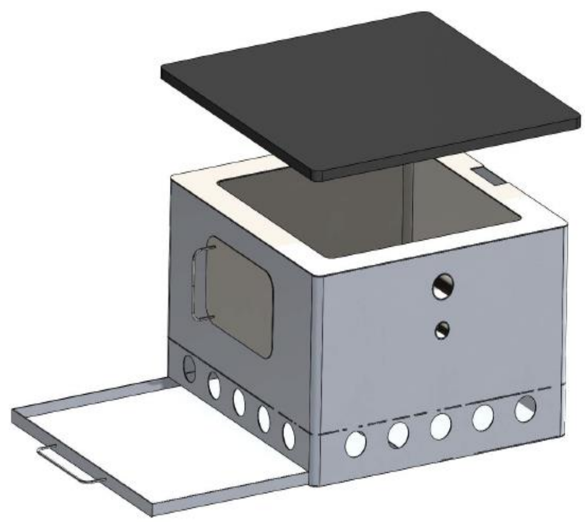


Figure 5.5 Full assembly of the stove

5.6.2. Bellows

Air can be pumped through the smaller 1”-diameter hole on the side of the stove using a bellows. The bellows can be attached using a heat resistant silicone tube. The air pumped by the bellows is preheated by travelling through the air chamber and provides supplementary oxygen to the combustion chamber. The additional oxygen fuels the combustion reaction increasing the temperature depending on the amount of air supplied. When not in use, the tube can be disconnected.

5.6.3. Tray

A removable tray with dimensions 18"×18"×0.75" is located at the bottom of the stove. The tray is purposed to catch the ash that falls from the grill and be easily removeable to facilitate cleaning and prevent ash build up within the stove. This tray fits in a slot on the outer wall of the stove and rests above the bottom cover. The tray features a handle made of a 0.5” diameter rod that allows the user to grab the tray.

5.6.4. Ventilation

A 2”-diameter ventilation hole passes through from the combustion chamber to the outside of the stove. Flue gas produced during the combustion of fuel passes through the hole and leaves the stove. Heat resistant silicone tubing is attached to the hole and direct the harmful gases out of the home or cooking space. This method of ventilation keeps the level of air quality within the home at acceptable and safe levels, providing a huge benefit in our products safety. Additionally, this hole serves to maintain the pressure within the stove at safe levels by providing an outlet for matter to leave the system, which prevents pressure buildup.

6. Comparative Patent Analysis

Being a staple to human ingenuity, stove designs have a vast collection of patents. Patent law typically limits product design; however, our design is assured to be unique to any existing stove. Through a comparative patent analysis, we determined the unique aspects of our superior product concept from similar designs and industry leaders in stoves designed for developing countries.

6.1. Turbococina (US Patent 6651645)

Figure 6.1. Turbococina with a pot resting on the top

The Turbococina, shown in Figure 6.1, is designed as a combustion and heat transfer device capable of both industrial and residential usage, such as cooking and heating. The apparatus is comprised of wood fired cook stove, a heat sink where cooking will take place, and an air inlet chamber. Wood fuel is supplied and combusted in the bottom of the stove where the heat rises in the cylindrical chamber to the heat sink. The containment of the flame reflects radiated heat to combustion gases, reducing heat loss. The air inlet chamber is comprised of an electric fan that forces fresh air into the heating chamber to supply the combustion reaction with additional oxygen. The electric convection circulates hot air rapidly through the interior to ensure uniform temperatures and heat transfer. The stove's use of air injectors greatly increases the efficiency of the stove, and allows for better temperature control than natural convection. At the top of the heating chamber, ventilation holes alleviate pressure buildup (US Patent No. 6651645, 2013).

While our stove also uses forced convection to increase the stoves efficiency, our design used the mechanical energy of a bellows rather than the electrical energy required for the fan. Additionally, our stove features a chamber to preheat the air before entering the combustion chamber. At the top of our stove is also a hole dedicated to ventilation and pressure alleviation, however our design features a single larger hole that is to be connected to a tube to guide flue gas as opposed to freely allowing it to enter the atmosphere.

6.2. Solo Stove™ (US Patent 701721)

The Solo Stove™, as seen in Figure 6.2, is a 304-stainless steel wood stove that is lightweight and durable. It is dominantly used as a bonfire or recreational camping stove. Wood fuel is loaded and combusted on a perforated plate inside a cylindrical chamber. The chamber containing fuel resides inside an additional chamber containing air. The outer chamber of the stove features holes lining the bottom wall, which function as an inlet for the movement of air into the system through natural convection. Air flows through the bottom holes upward through to the combustion chamber fueling the fire. A portion of the air also travels upward in the air chamber through holes located at the top of the walls of the combustion chamber to the fire. As the air travels through the air chamber, it is heated before being supplied to the flame, increasing the efficiency of the combustion. The flame produced by combustion burns freely out of the top of the stove where cookware can be placed on top resting on the burn chamber (US Patent No. 701721, 2014).

Figure 6.2. Solo Stove™ Campfire

Our stove also features multiple chambers, with one dedicated to preheating air, and is also constructed of mostly 304 stainless steel. However, our stove preheats the air through forced convection through holes located on the bottom of the inner chamber. While the Solo Stove™ is purposed for recreational use, our stove is tailored to domestic use in the homes impoverished communities. Because of this, our stove features a third chamber dedicated to insulation to prevent burns common in household kitchens. Also, our stove features a cover over the top to limit the uncontrolled escape of flue gas, while the Solo Stove™ provides no barrier for flue gas due to its intended outdoor usage. Given the target consumer, our stove is manufactured using less robust production methods due to the limitations of the community.

6.3. The Ecocina (Patent Pending)

Figure 6.3 Ecocina Stove

The Ecocina, Figure 6.3, is a wood fire cooking stove produced by StoveTeam International®. Like our stove, it is intended to replace the common practice of dangerous open cooking fires. Ecocina stoves are comprised by an internal chimney constructed out of low fired tile surrounded by pumice as support an insulation. Wood is fed through an opening in the front of the stove and combusted in an inner chamber. The interior of the stove is shaped in the form of an elbow, using the common stove design “Rocket Elbow”. Air flows through natural convection through the bottom opening fueling combustion while directing heat upwards toward the cooking pot. The top of the stove is covered by a removable plate or “*plancha*” used as a cooking surface. The stove can also support pots and pot supports without the use of the *plancha* (The Ecocina, n.d.).

Our design and the Ecocina share a feature of a removable cooking surface. The *plancha* is commonly used in Latin American cooking and is important to include to ensure that the stove is culturally accepted. Aside from this feature, the two stoves do not overlap in any intellectual property.

7. Material Balances and Airflow Requirements

In this section, the fundamental relationship of the combustion of charcoal is used to estimate the rate of air flow and of flue gas. Air enters the stove through the bottom, reacts with charcoal in a combustion process, and leaves through the ventilation tube as flue gas. The combustion of charcoal is an exothermic process defined by the chemical equation below (Eqn. 7.1),

$$C + (1+\psi)(O_2 + 3.76N_2) \rightarrow CO_2 + \psi O_2 + (1+\psi)3.76N_2 \tag{7.1}$$

where ψ is the fraction of excess air. In this analysis, charcoal is treated as a solid made of pure carbon. The composition of air is modeled as 21% oxygen and 79% nitrogen (a ratio of 1 to 3.76), and the presence of argon is ignored. The argon present in the air does not participate in the combustion process or affect the process in any way, and leaves the stove unreacted with the fuel gas. The flow of primary air is assumed to be large enough to achieve complete combustion. At high temperatures, nitrogen and oxygen can combine to form nitrogen oxides. However, at the temperatures at which the stove operates, the formation of nitrogen oxides is low enough to assume it is negligible.

The first term of left hand side of Equation 7.1 represents the elemental composition of charcoal, and the second term represents the air required for combustion. Terms on the product side indicate the flue gas composition. Knowing the burning rate of charcoal, the theoretical amount of primary air requirement can be determined. Inside the combustion chamber, it is assumed that the charcoal should burn at a rate of about $1{\times}10^{-4}$ kg/s. This assumption is from experiments done on charcoal combustion (Kausley & Pandit, 2010). The actual burn rate may vary inside the stove depending on the use of the bellows. According to stoichiometric calculations from Equation 7.1, a burn rate of $1{\times}10^{-4}$ kg/s would require a minimum air flow rate of 0.93 L/s.

However, the actual air flow rate of the stove is higher than the required flow rate. Based on a study of the Harsha stove (Gogoi & Baruah, 2016), which has a similar design for bottom air flow to our product, our stove should have an air flow rate at the bottom holes of about 1.2 L/s, meaning that there is sufficient natural air flow to feed the charcoal.

8. Steady-State Heat Transfer Analysis

8.1. Model Overview

The model described in this section analyzes heat transfer inside the stove to estimate its performance, primarily measured by its energy efficiency and the time it takes to boil water. The bottom holes in the stove allow air to enter the stove by natural draft. Once the charcoal is ignited, the oxygen in the primary air entering through the bottom reacts with the fuel and generates heat. During the combustion process, the ignition of the top layer results in a flame from the volatile fraction of the charcoal, while the fixed carbon portion continues igniting. These two elements are considered as the primary sources of thermal energy in the stove, which will propagate into the different components of the stove. The amount of heat released during the combustion process can be estimated from the product of the rate of fuel burned and the net calorific value of charcoal.

Heat generated by the flame is transferred to the top cover, the combustion chamber walls, primary air, and the bottom layers of the fuel bed to sustain the ignition process. The heat carried away by the flue gas is also transferred to the cover and the combustion chamber walls. Meanwhile, the heat from the combustion of fixed carbon available in the top fuel layer is transferred to the layers beneath it, to the combustion chamber, to the cover, and to the primary air. Part of the heat released downwards through the fuel bed is also used to evaporate fuel moisture in the downward layers.

All of these heat components in the stove are governed by a combination of the three mechanisms of heat transfer (i.e. conduction, convection, and radiation), and all heat received (or lost) by any component under consideration will consist of a sum of these, as shown in Equation 8.1,

$$Q_{total} = Q_{conv} + Q_{rad} + Q_{cond} \tag{8.1}$$

where, Q_{total}, Q_{cond}, Q_{conv} and Q_{rad} are the net total heat, conductive heat, convective heat and radiation heat, respectively, in watts, received (or lost) by a component of the system under consideration. The individual components in Equation 8.1 are described by the fundamental relationships in Table 8.1.

Table 8.1. Fundamental heat transfer equations.

Heat Transfer Model	Formula
Conduction	$Q_{cond} = kA\left(\frac{\Delta T}{\Delta x}\right)$
Convection	$Q_{conv} = hA\Delta T$
Radiation	$Q_{rad} = FA\varepsilon\sigma(T_{max}^4 - T_{min}^4)$

These relationships, along with the relationship used for fuel combustion, for sensible heat change of air/flue gas, and heat required for evaporation of fuel moisture, are considered for the development of the heat transfer model described in Section 8.3. Table 8.3, Figure 8.1, and Figure 8.2 summarize all the heat components that are modeled in this section.

Equation 8.2 is used in this analysis to estimate the heat transfer coefficient for the different convection heat transfer components,

$$\overline{h_L} = \frac{\overline{Nu_L}\,k}{L} \tag{8.2}$$

where $\overline{h_L}$ represents the average heat transfer coefficient (in $\frac{W}{m^2 \cdot K}$) across a plate of length L, k is the thermal conductivity of the fluid, and $\overline{Nu_L}$ is the average Nusselt number for a plate of length L. The Nusselt number depends on the type of convection, and the formula used in each scenario is specified on each section. The dimensionless numbers in Table 8.2 are useful to estimate the Nusselt numbers for the different heat transfer coefficients modeled in this section.

Table 8.2. Dimensionless numbers for heat transfer

Name	Symbol	Formula
Prandtl number	Pr	$\frac{c_{p\,\mu}}{k}$
Reynolds number	Re	$\frac{\rho\, u\, L}{\mu}$
Rayleigh number	Ra	$Gr_L \cdot Pr$
Grashof number	Gr	$\frac{g\beta(T_c - T_{surr})L^3}{\nu^2}$

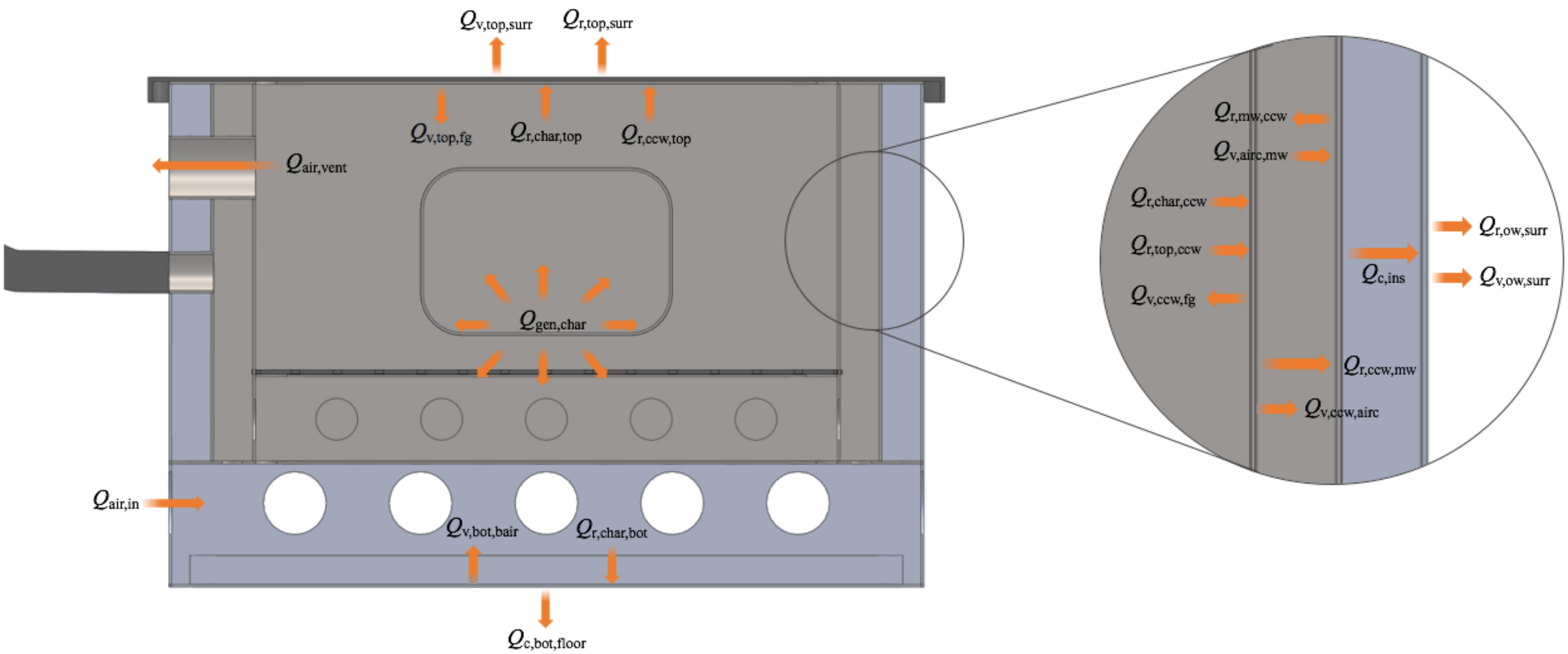


Figure 8.1. Schematic diagram of steady-state heat transfer model of the stove (Part 1)

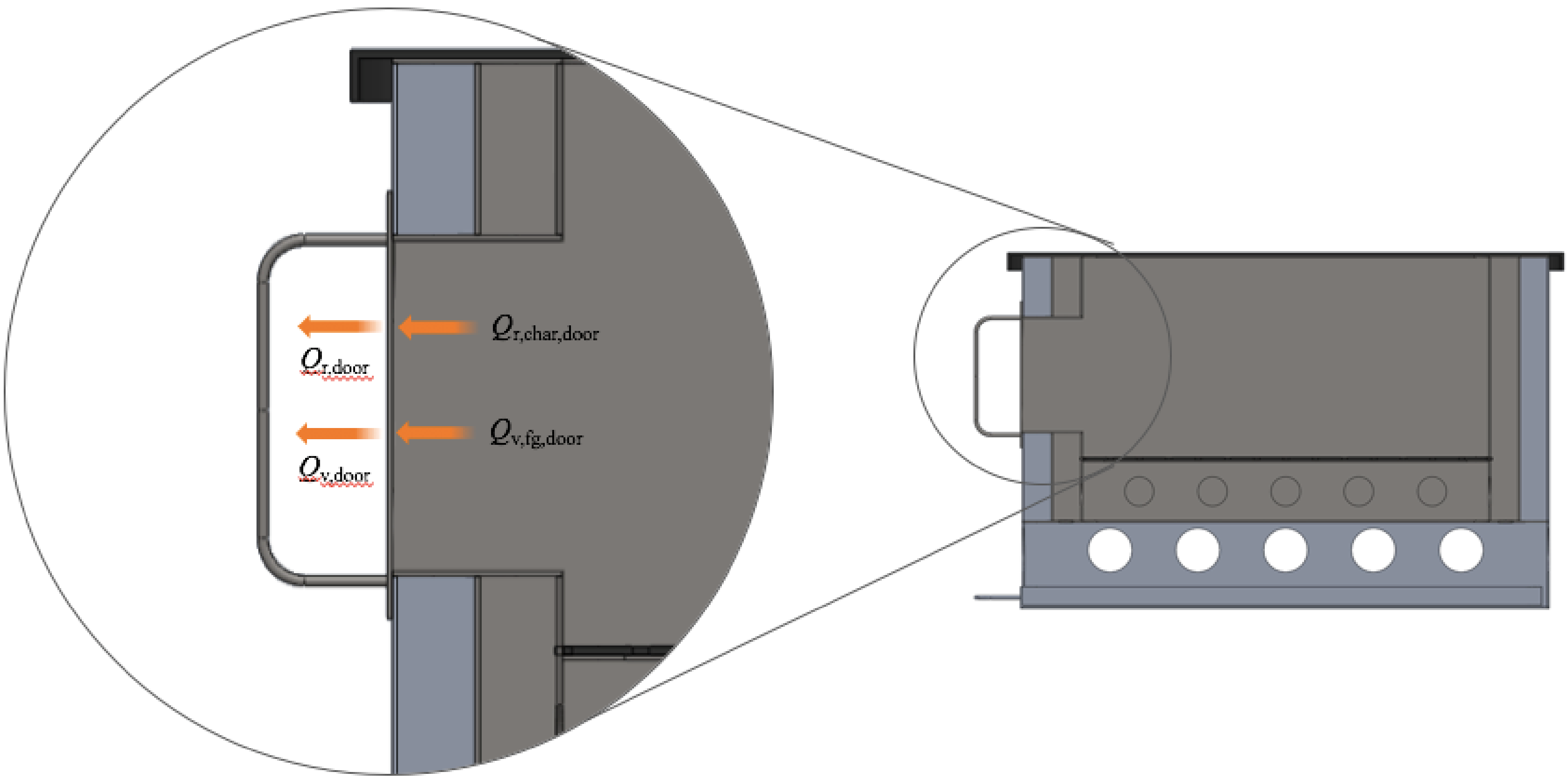


Figure 8.2. Schematic diagram of steady-state heat transfer model of the stove (Part 2)

Table 8.3. Heat transfer components in stove. Meaning of abbreviations can be found in the appendix.

Symbol	Heat Transfer Component	Model of Heat Transfer
$Q_{v,top,fg}$	Cover to flue gas	Convection
$Q_{r,char,top}$	Burning charcoal to cover	Radiation
$Q_{r,ccw,top}$	Combustion chamber walls to cover	Radiation (net)
$Q_{c,top}$	Upper frame to cover	Conduction
$Q_{v,ccw,fg}$	Flue gas to combustion chamber walls	Convection
$Q_{r,char,ccw}$	Burning charcoal to cover	Radiation
$Q_{v,top,surr}$	Cover to surrounding air	Convection
$Q_{r,top,surr}$	Cover to surrounding air	Radiation
$Q_{r,ccw,mw}$	Combustion chamber wall to middle wall	Radiation (net)
$Q_{v,ccw,airc}$	Combustion chamber wall to inner air chamber	Convection
$Q_{v,airc,mw}$	Inner air chamber to middle wall	Convection
$Q_{c,ins}$	Conduction through insulation	Conduction
$Q_{r,ow,surr}$	Outer wall to surrounding air	Radiation
$Q_{v,ow,surr}$	Outer wall to surrounding air	Convection
$Q_{r,char,bot}$	Burning charcoal to stove bottom	Radiation
$Q_{v,bot,bair}$	Stove bottom to bottom air	Convection
$Q_{v,fg,door}$	Flue gas to door	Convection
$Q_{r,char,door}$	Burning charcoal to door	Radiation
$Q_{r,door,surr}$	Door to surrounding air	Radiation
$Q_{v,door,surr}$	Door to surrounding air	Convection
$Q_{air,vent}$	Air exiting stove through ventilation tube	Internal
$Q_{air,in}$	Air entering stove through bottom holes	Internal
$Q_{gen,char}$	Heat of combustion from burning charcoal	Combustion
$Q_{c,bot,floor}$	Stove bottom to floor	Conduction

8.2. Assumptions of the Model

The operation of the stove consists of three distinct phases: initial transient state, operational stage, and post-operational stage. Section 8 focuses on the operational stage, while Section 9 focuses on modeling the initial transient state. The main assumption in this model is that the operational stage is at steady-state. In actual practice, the non-homogeneous fuel with varying air flow is expected to cause unsteady operation in the stove. However, prediction of these parameters is difficult, and therefore ignored in this analysis. Thus, this model assumes fuel homogeneity and uniform flow of primary air. Other major considerations in this model are outlined below.

i. Each component of the stove (i.e. top cover, side walls, flue gas, fuel bed, flame, cooking pot, cooking pot contents) is at a different temperature, but overall the temperature of each component is spatially uniform. As the metals used for the stove walls (i.e. stainless steel, aluminum, and cast iron) have high thermal conductivities, and the walls are relatively thin, it is assumed that there is no temperature gradient across the metal components.

ii. As the model has more unknown variables than constraints, the following temperature assumptions were made to solve it. The temperature of the combustion chamber walls is 50°C degrees higher than the temperature of the cover, and the temperature of the flue gas 200°C lower than the temperature of the charcoal. These approximations were developed based on similar approximations made in a study of the Harsha stove (Gogoi & Baruah, 2016).

iii. As mentioned in Section 7.1, the two primary sources of thermal energy in the stove are the flame in the ignited volatile fraction of charcoal, and the fixed carbon portion. During the combustion of other fuel sources such as wood, the flame and the fixed carbon portion can easily be modeled separately, as the flame is large and at a much higher temperature than the unburnt wood. However, the flame formed when burning charcoal is small and at a similar temperature to the burning charcoal. Thus, in this model the two components are modeled as one, and it is assumed they are at the same temperature.

8.3. Model Components

This section describes all the stove components modeled for heat transfer at steady-state. The steady-state input values to the model are summarized in Table 8.4, and are used to calculate the different heat transfer and temperature values described in this section.

Table 8.4. Steady-state input values to the model. Thermodynamic data retrieved from Engineering ToolBox (Engineering ToolBox, n.d.).

Category	Parameter	Unit	Value
Ambient air	Temperature	K	300
Properties of air at 27°C	Heat capacity	$kJ/kg \cdot K$	1.047
	Dynamic viscosity (μ)	$Pa \cdot s$	1.983×10^{-5}
	Thermal conductivity	$W/(m \cdot K)$	0.0454
	Kinematic viscosity (ν)	m^2/s	47.85×10^{-6}
Cooking pot	Diameter	m	0.38
	Height	m	0.25
	Thickness	m	0.0015
	Material and emissivity		Aluminum $\varepsilon = 0.07$
	Thermal conductivity	$W/(m \cdot K)$	205
Stove	Combustion chamber dimensions	m	0.36×0.36×0.23
	Combustion chamber wall material and emissivity		Stainless steel $\varepsilon = 0.44$
	Mode of primary air supply		Natural draft (without bellow)
	Fuel type		Charcoal
	Fuel emissivity		0.75
	Middle wall material and emissivity		Stainless steel $\varepsilon = 0.44$
	Outer wall material and emissivity		Stainless steel $\varepsilon = 0.44$
	Cover material and emissivity		Cast iron (ε = 0.44)
	Cover thermal conductivity	$W/(m \cdot K)$	60
View factors	Charcoal to cover		0.42
	Charcoal to sides		0.30
	Sides to cover		0.15
Insulation	Thickness	m	0.0254
	Thermal conductivity	$W/(m \cdot K)$	0.15
Flue gas properties	Density	kg/m^3	0.51
	Dynamic viscosity	$Pa \cdot s$	3.21×10^{-5}
	Specific heat	$J/(kg \cdot K)$	1120.35
	Thermal conductivity	$W/(m \cdot K)$	0.049
	Velocity	m/s	0.70
Water	Boiling temperature	K	373.15
	Initial temperature	K	300
Saturated water properties at 373.15K	Density	kg/m^3	957.9
	Specific heat	$J/(kg \cdot K)$	4217
	Viscosity	$Pa \cdot s$	2.79×10^{-4}
Saturated water vapor properties at 373.15K	Density	kg/m^3	0.595

8.3.1. Air entering stove

Air enters the stove through the bottom hole and the oxygen in it reacts with the charcoal to sustain the combustion process. The change in the air's internal energy as it enters the stove is defined by Equation 8.3,

$$Q_{air,in} = \dot{m} c_p \Delta T \tag{8.3}$$

where $\dot{m}$ is the air flow rate (in kg/s), c_p is the air heat capacity (in J/kg K), and ΔT is the temperature difference between the surrounding air and the air inside the stove. The flow rate of air entering the stove was measured experimentally by performing a test on the stove. Therefore, an estimate of 1.2 L/s was used as the air flow rate in this analysis, based on the air flow rate at the bottom air gaps of similar stoves, such as the Harsha stove (Gogoi & Baruah, 2016).

8.3.2. Heat Transfer through Cover

The cover receives heat from the radiation of the burning charcoal ($Q_{r,char,top}$) and the combustion chamber walls ($Q_{r,ccw,top}$), and from the contact with the upper frame ($Q_{c,top}$). More details about the design of the upper frame can be found in Section 10.1. Heat is transferred from the cover to the surroundings through convection ($Q_{v,top,surr}$) and radiation ($Q_{r,top,surr}$). Given the temperature difference between the cover and the flue gas inside the combustion chamber, heat is also transferred between these components by convection ($Q_{v,top,fg}$).

The heat transfer coefficient for convection from the flue gas to the cover was calculated using the correlations for convection to the lower surface of a hot plate, given by the Nusselt number in Equation 8.4. The Grashof, Prandtl, Rayleigh, and Nusselt numbers were calculated to be 6.1×10^7, 0.73, 4.5×10^7, and 17.6 respectively, yielding a heat transfer coefficient of 2.5 $\frac{W}{m^2 \cdot K}$.

$$\overline{Nu}_L = 0.52\, Ra_L^{1/5} \quad (10^4 \lesssim Ra_L \lesssim 10^9, Pr \gtrsim 0.7) \tag{8.4}$$

The heat transfer coefficient for convection from the top surface of the cover to ambient air was calculated using the correlations for free laminar convection on the upper surface of a hot plate. For a Rayleigh number of 2×10^{7} ($< 10^{9}$ is considered laminar) and a Prandtl number of 0.46, the correlation for the average Nusselt number is shown in Equation 8.5.

$$\overline{Nu}_L = 0.15Ra_L^{1/3} \quad (10^7 \lesssim Ra_L \lesssim 10^{11}, All\ Pr) \tag{8.5}$$

The heat transfer coefficient was calculated using Equation 8.2, yielding a result of 6.0 $\frac{W}{m^2\cdot K}$.

8.3.3. Heat Transfer through Side Walls

The net amount of heat that reaches the walls of the combustion chamber ($Q_{r,char,ccw} - Q_{r,ccw,top} - Q_{r,ccw,fg}$) is transferred to the chamber walls through conduction. The heat that reaches the opposite side of the walls is transferred into the secondary air chamber ($Q_{v,ccw,airc}$), and the air transfers the heat across the chamber into the second wall through convection ($Q_{v,airc,mw}$). Some heat is also transferred through radiation from the combustion chamber wall to the middle wall ($Q_{r,ccw,mw}$). Heat is then transferred through conduction across the insulation material to the outside wall ($Q_{c,ins}$), where it is transferred through radiation ($Q_{r,ow,surr}$) and convection ($Q_{v,ow,surr}$) to the surroundings. All these heat components are shown in Figure 8.1.

The heat transfer coefficient of convection from the flue gas to the combustion chamber walls was modeled assuming internal flow in a tube. The flow was found to be in the transition region between laminar and turbulent ($Re = 3950$). The correlation provided by Gnielinski (Bergman, Lavine, Incropera, & Dewitt, 2011) used to calculate the Nusselt number is shown below in Equation 8.6, which is valid for smooth tubes over a large Reynolds number range ($3000 \lesssim Re_D \lesssim 5\times10^{6}$) including the transition region.

$$Nu_D = \frac{(f/8)(Re_D - 1000)Pr}{1 + 12.7(f/8)^{1/2}(Pr^{2/3} - 1)} \tag{8.6}$$

The Prandtl number was found to be 0.73. The friction factor was obtained using Equation 8.7, and was found to be 0.042, yielding a Nusselt number of 13.6. Equation 8.2 was then used to calculate the heat transfer coefficient from these values, obtaining 1.9 $\frac{W}{m^2 \cdot K}$.

$$f = (0.790 \ln Re_D - 1.64)^{-2} \tag{8.7}$$

The heat transfer coefficient of convection for the air inside the secondary air chamber was modeled using the heat transfer correlations for a concentric tube annulus (Figure 8.3). The equations for the heat flux and Nusselt numbers for each surface are shown in Table 8.5. The inner and outer heat transfer coefficients were obtained by setting the two Nusselt numbers for each surface equal and substituting the equations for heat flux into the expression. The heat transfer coefficients obtained for the inner and outer surfaces were 3.57 $\frac{W}{m^2 \cdot K}$ and 3.54 $\frac{W}{m^2 \cdot K}$, respectively. The coefficient used in the final calculations was the average of the inner and outer coefficients, given their proximity.

Table 8.5. Heat flux equations and Nusselt number correlations for flow through a concentric tube annulus. D_h represents the hydraulic diameter, defined as $D_h = 4A_c/P$ (A_c = cross-sectional area, P = perimeter).

Surface	**Heat flux**	**Nusselt Number (1)**	**Nusselt Number (2)**
Inner	$q''_i = h_i(T_{s,i} - T_m)$	$Nu_i = \frac{h_i D_h}{k}$	$Nu_i = \frac{Nu_{ii}}{1 - (q''_o/q''_i)\theta_i^*}$
Outer	$q''_o = h_o(T_{s,o} - T_m)$	$Nu_o = \frac{h_o D_h}{k}$	$Nu_o = \frac{Nu_{oo}}{1 - (q''_i/q''_o)\theta_o^*}$

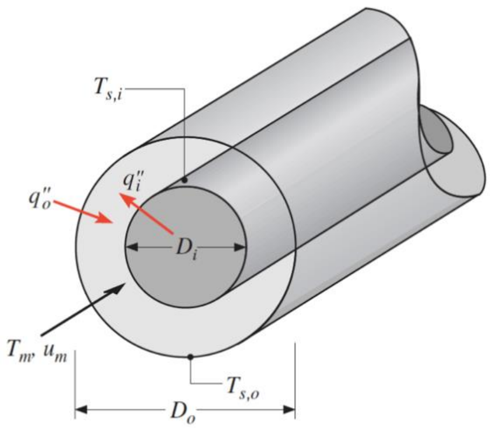


Figure 8.3. Concentric tube annulus

The heat transfer coefficient for convection from the outer wall surface of the stove to the surroundings was obtained using the correlations for laminar free convection on a vertical surface. The average Nusselt number used is shown in Equation 8.8, where L represents the height of the fraction of the stove with insulation (9 inches).

$$Nu_L = \frac{4}{3}\left(\frac{Gr_L}{4}\right)^{1/4} g\{Pr\} \tag{8.8}$$

The Prandtl number obtained for air heat capacity, viscosity, and thermal conductivity at 27 °C was 0.46, and the Grashof number, using kinematic viscosity of air at 27 °C, was 4.54×10^{-7}. These values give a Rayleigh number of 2×10^{-7}, confirming that laminar flow can be assumed ($Ra < 10^9$). The Prandtl number dependent term, $g\{Pr\}$ is defined below in Equation 8.9, and was found to be 0.43.

$$g(\mathrm{Pr}) = \frac{0.75\, Pr^{1/2}}{(0.609 + 1.221Pr^{1/2} + 1.238Pr)^{1/4}} \tag{8.9}$$

For an average Nusselt number of 33.0, the heat transfer coefficient obtained, using Equation 8.2, was 5.4 $\frac{W}{m^2 \cdot K}$.

8.3.4. Heat Transfer Through Door

The door is the only section of the combustion chamber wall that is not surrounded by insulation. Therefore, the heat loss through that area is larger than through any other area of the combustion chamber. The inner surface of the wall receives radiation from the burning charcoal ($Q_{r,char,door}$) and convection from the flue gas ($Q_{v,fg,door}$), while the outer surface releases heat to the surrounding air through convection ($Q_{v,door,surr}$) and radiation ($Q_{r,door,surr}$). The convective heat transfer coefficients for convection of flue gas to and from the door to the surrounding air were approximated using the results obtained for the heat transfer coefficients for convection from the flue gas to the combustion chamber walls and from the outer wall to the surrounding air.

8.3.5. Heat Transfer through Ventilation Tube

The amount of heat loss through the ventilation tube is a function of the temperature difference between the flue gas and the outside temperature, the velocity of the flue gas and the area of the exit hole, as shown in Equations 8.10 and 8.11. These equations were solved using the properties of flue gas found in Table 8.4.

$$Q_{air,vent} = \dot{m}c_{p,fg}\left(T_{fg} - T_{surr}\right) \quad (8.10)$$

$$\dot{m} = \rho_{fg}u_{fg}A_{hole} \quad (8.11)$$

8.3.6. Heat Transfer through Bottom

The stove bottom receives radiation heat from the burning charcoal ($Q_{r,char,bot}$), and releases heat to the air in the bottom chamber through convection ($Q_{v,bot,bair}$) and to the floor by conduction ($Q_{c,bot,floor}$). This analysis assumed the stove was standing on a pile of compact dirt of one foot in height. The properties of soil can be found in Table 8.4.

8.4. Steady-State Analysis Results

The heat analysis transfer model was solved using the Solver Add-in on Excel. The objective of the model was to close the energy balance, that is, make all the heat components exiting the system equal the heat being generated by and entering the system. The varied parameters in the model were the unknown temperatures of multiple components of the stove. The constraints in the model were equations that set the energy balances on each of the surfaces of the stove (top cover, combustion chamber wall, middle wall, outer wall, door, and bottom) to zero. Specifically, the heat entering a wall or surface, minus the heat exiting it had to equal zero.

Figure 8.4 summarizes the values obtained for the main heat transfer components of the model. It was calculated that 33% of the heat exited the system through the cover. The heat loss through the bottom was larger than through the sides, given that the sides were insulated. If an insulating material were placed below the stove, these bottom losses could be reduced and the energy efficiency would increase.

As shown in Figure 8.5, the cover reaches a steady-state value of 414°C under a fire temperature of 576 °C. The side air chamber only decreases the temperature by of the middle walls by 30 °C (compared to the combustion chamber walls). However, the goal of this chamber is not to provide insulation, but to allow air pre-heated air to be pumped into the combustion chamber with the use of bellows. The temperature of the outer wall goes down from 432 °C to 182 °C because of the insulation. Having an insulation layer of 1-inch thickness has a considerable effect on the temperature of the outer wall. Section 8.6 discusses the effect that increasing the insulation thickness would have on the temperature of the outer wall.

Figure 8.6 reveals that most of the heat reaching the top cover comes from the radiation of the burning charcoal, followed by the heat transfer from the contact between the upper frame and the cover. The heat transfer from the cover to the surroundings is evenly distributed between convection and radiation. Out of the 620 watts of heat lost through the side walls, 40% corresponds to radiation and 60% to convection.

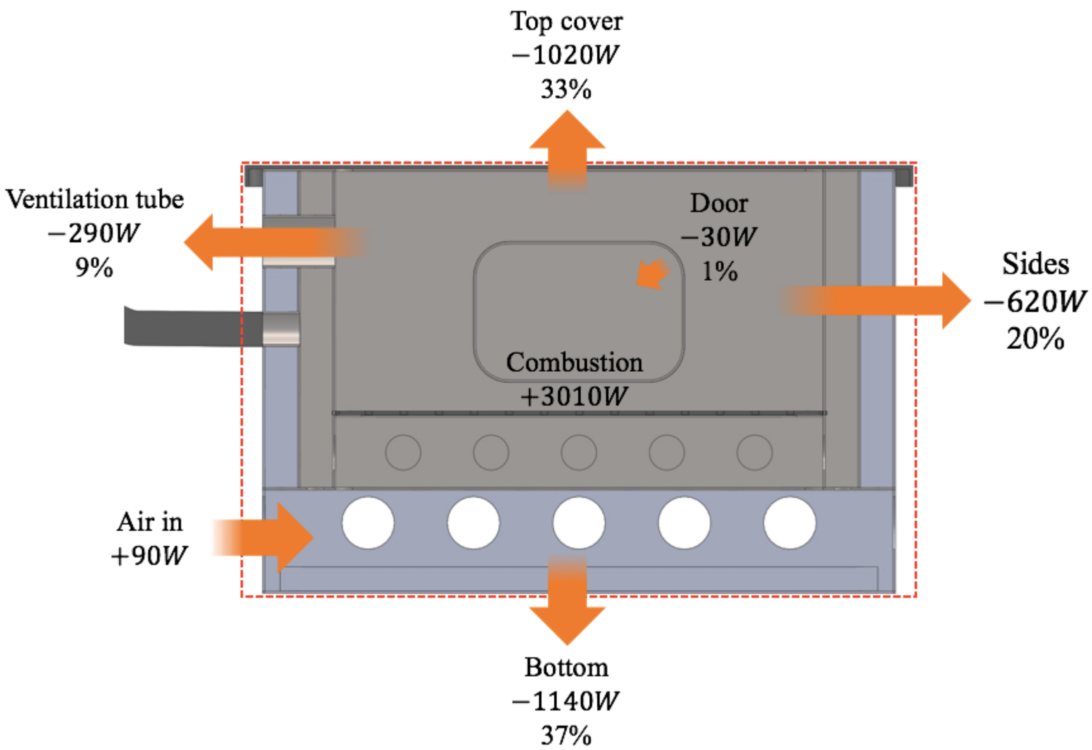
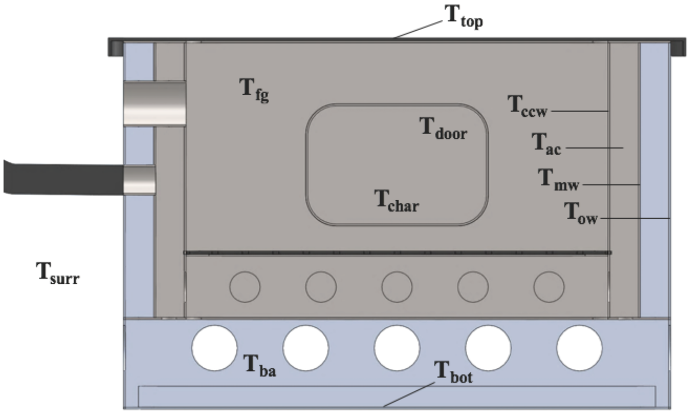


Figure 8.4. Overall heat components of the system.



Component	Symbol	Temperature (°C)
Burning charcoal	char	576
Flue gas	fg	376
Cover	top	414
Combustion chamber wall	ccw	464
Middle wall	mw	432
Air chamber	ac	435
Outer wall	ow	182
Door	door	188
Stove bottom	bot	326
Bottom air	ba	216
Surrounding air	surr	27

Figure 8.5. Temperature of stove components

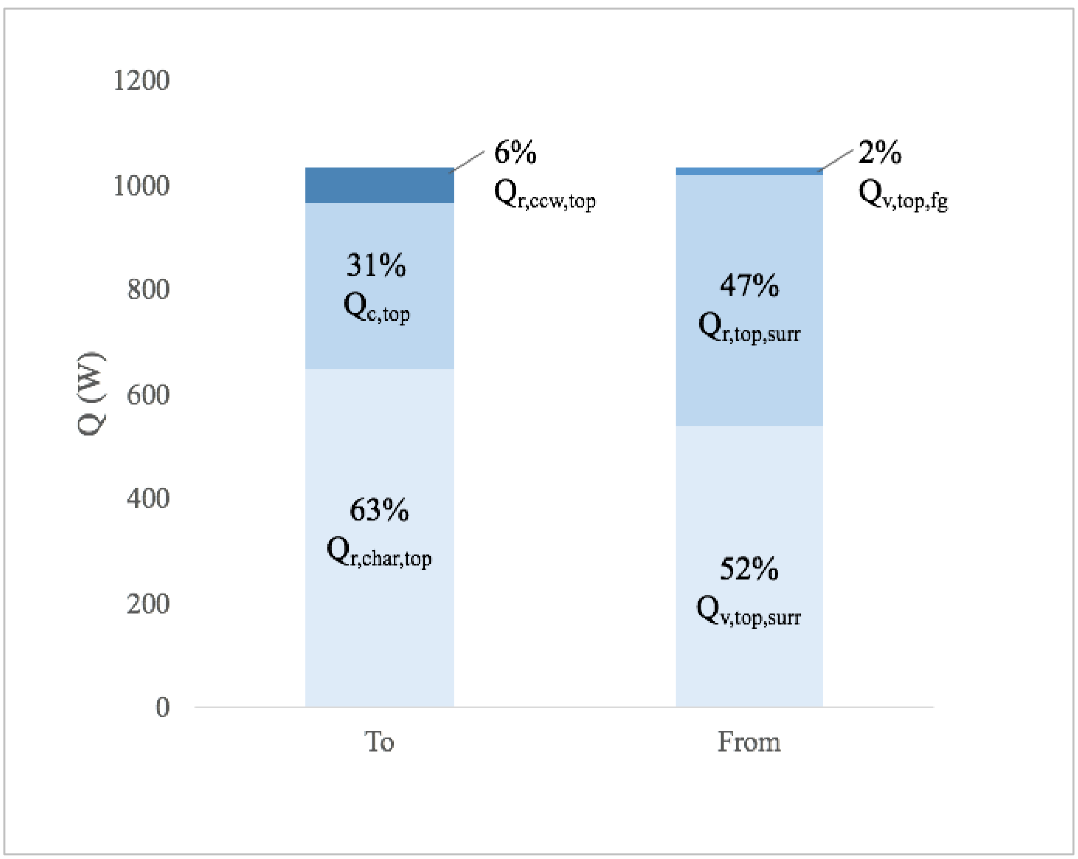


Figure 8.5. Energy balance of cover plate

8.5. Stove Performance

The energy efficiency of the stove is defined ratio of the heat transferring through the cover to the heat being lost through the other parts of the stove, and is defined in Equation 8.12. The energy efficiency of the stove was estimated to be 33%.

$$\eta_{stove} = \frac{Q_{cover}}{Q_{tot}} = \frac{Q_{cover}}{Q_{cover} + Q_{sides} + Q_{bottom} + Q_{vent} + Q_{door}} \tag{8.12}$$

The amount of time required to boil a given amount of water at steady-state is defined in Equation 8.13.

$$Time\ to\ boil = \frac{m_w c_p \Delta T}{Q} \tag{8.13}$$

The size of the cooking pot used for the analysis was of 15 inches in diameter and 10 inches in height, as meals are often cooked in large sizes in rural areas of El Salvador. The total heat (in joules) transferred into the water during a given time period was calculated using Equation 8.14.

$$q = UA\Delta T \tag{8.14}$$

The overall heat transfer coefficient (U) was obtained by calculating the inverse of the sum of the resistances between the combustion chamber and the water, as shown in Equation 8.15,

$$U = \frac{1}{R_{tot}A} = \frac{1}{A\left[\frac{1}{h_{rad} + h_{fg}} + \frac{L_{top}}{k_{top}} + R_{CI-Al} + \frac{L_{pot}}{k_{pot}} + \frac{1}{h_{water}}\right]} \tag{8.15}$$

where h_{rad} represents the radiative heat transfer coefficient of radiation from the burning charcoal to the cover, h_{fg} the convective heat transfer of convection from the flue gas to the cover, L_{top} and L_{pot} the thicknesses of the cover and the pot, respectively, k the thermal conductivity of the material of the part under consideration, R_{CI-Al} the thermal contact resistance between the cast iron cover and the aluminum cooking pot, and h_{water} the heat transfer coefficient from the cooking pot to the water. The properties of the cover, cooking pot, and water used in these calculations can be found in Table 8.4. The radiative heat transfer coefficient was calculated using Equation 8.16, and the coefficient was found to be $78\ \frac{W}{m^2 \cdot K}$.

$$h_{rad} = \varepsilon\sigma\left(T_{char}^2 - T_{top}^2\right)\left(T_{char} + T_{top}\right) \tag{8.16}$$

The heat transfer coefficient h_{fg} was calculated to be $2.5\ \frac{W}{m^2 \cdot K}$ in Section 8.3. The thermal contact resistance for cast iron and aluminum (R_{CI-Al}) was approximated as $10^{-4}\ \frac{m^2 \cdot K}{W}$. The heat transfer coefficient from the cooking pot to the water (h_{water}) and the Nusselt number associated with it were estimated using Equations 8.2 and 8.17. The heat transfer coefficient was calculated to be $1296\ \frac{W}{m^2 \cdot K}$.

$$\overline{Nu}_L = 0.15\ Ra_L^{1/3} \quad \left(10^7 \lesssim Ra_L \lesssim 10^{11}, Pr \gtrsim 0.7\right) \tag{8.17}$$

The calculated value for the overall heat transfer coefficient was $34\ \frac{W}{m^2 \cdot K}$. The heat transferred into the pot decreases over time as the temperature of the water increases. To estimate the time required to boil 5 liters of water in a 14” diameter pot, the change in heat transfer and water temperature was calculated over time, and it was found that it took about 19-20 minutes to boil 5 liters of water. However, this result is highly dependent on the bottom area of the cooking pot, so this should be taken into consideration when estimating the boiling time for other pot sizes. Additionally, this is the minimum amount of time required to boil water assuming that all of the energy that enters the pot is used to heat the water. In reality, some energy will be lost from the pot to the surroundings and from the evaporation of some of the water. The actual boiling time will most likely be around 25 minutes.

8.6. Sensitivity Analysis

The results presented in Section 8.4. are subject to a set of constraints such as the thickness and the material of the insulation. This section analyzes how varying those parameters affects the top cover temperature, outer wall temperature, and energy efficiency of the stove.

Figures 8.10, 8.11, and 8.12, show that adding the first inch of insulation has the largest effect on the efficiency and outer temperatures of the stove. The effect of insulation on these parameters decreases as the thickness increases. The temperature of the outer side walls with one inch of insulation is 182°C, which is dangerous to touch. By adding an additional 6 inches of insulation, the temperature decreases to 70°C, which is still unsafe. Therefore, as the outside walls are too hot with either design, it is more beneficial to have 1 inch of insulation, as it occupies less space.

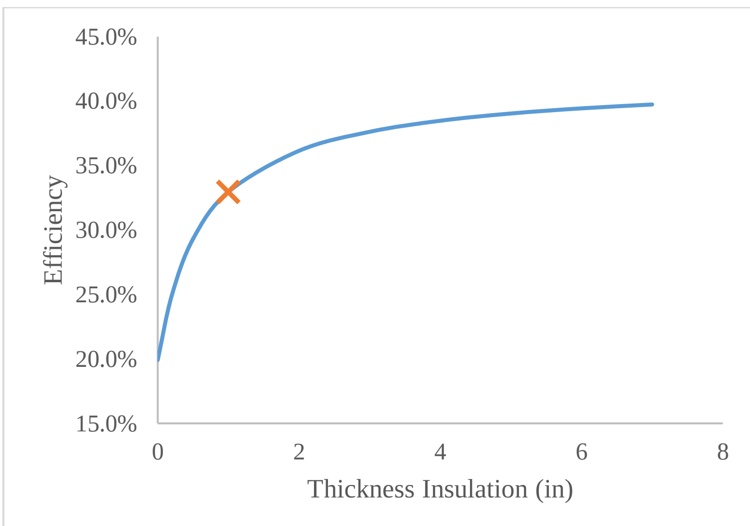


Figure 8.9. Stove efficiency as a function of insulation thickness.

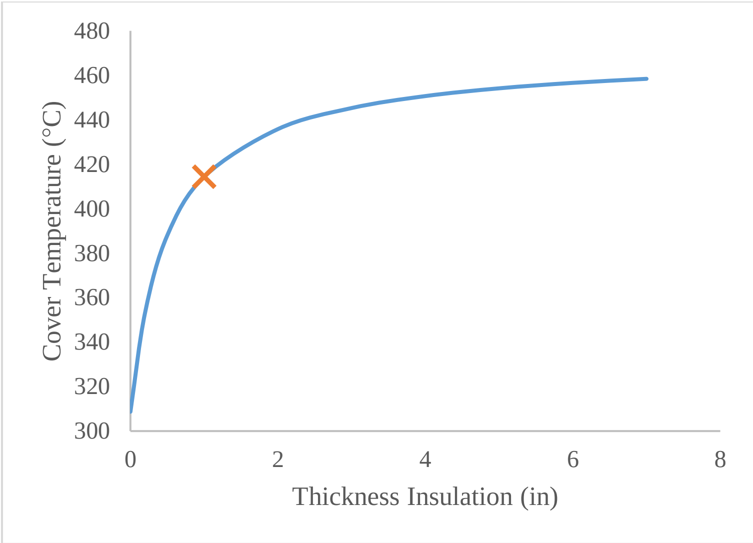


Figure 8.10. Cover temperature as a function of insulation thickness.

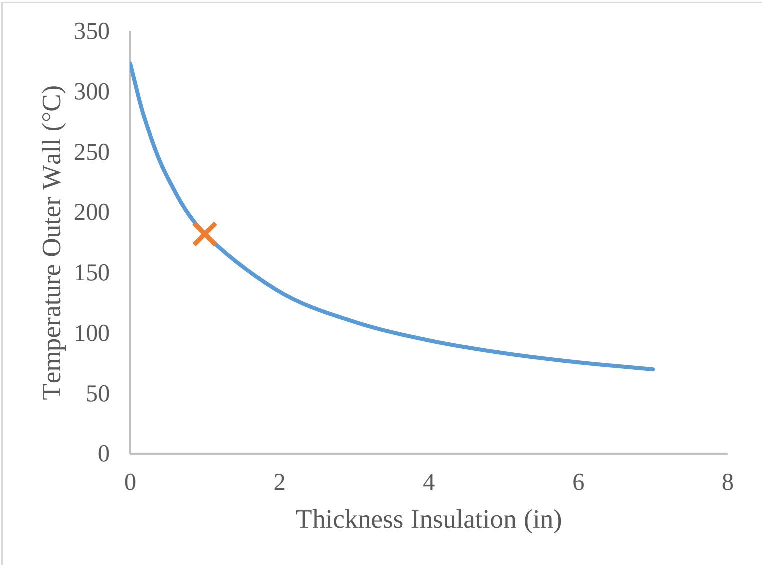


Figure 8.11. Outer wall temperature as a function of insulation thickness.

Figure 8.12 examines the differences in the main heat components exiting the stove for a design with an inch of insulation versus a design without insulation. By adding an inch of insulation, the heat transfer through the sides reduces by practically half. That heat is transferred into the other components including the cover, which boosts the efficiency of the stove.

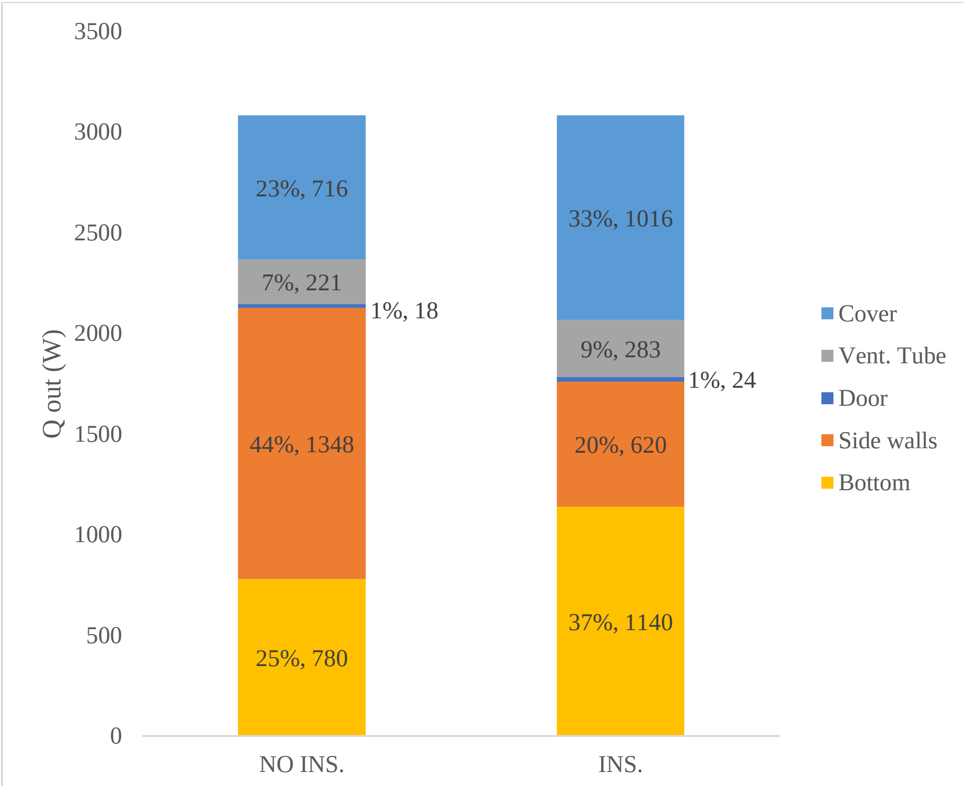


Figure 8.12. Stove with an inch of insulation versus with no insulation.

The material of the insulation has a significant effect on the efficiency and outer temperatures of the stove. A perfect insulator could boost the energy efficiency of the stove to almost 42%, and decrease the outer wall temperature to ambient air temperature. Fiberglass, with a conductivity of 0.05 $W/m^2 \cdot K$, increases the efficiency to 38%, and reduces the temperature of the outside walls to 109°C.

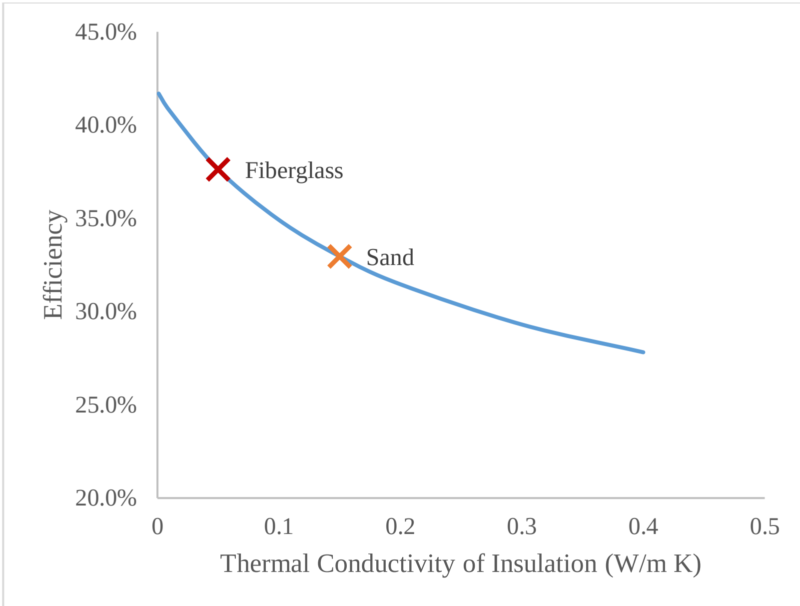


Figure 8.13. Stove energy efficiency as a function of the thermal conductivity of the insulation.

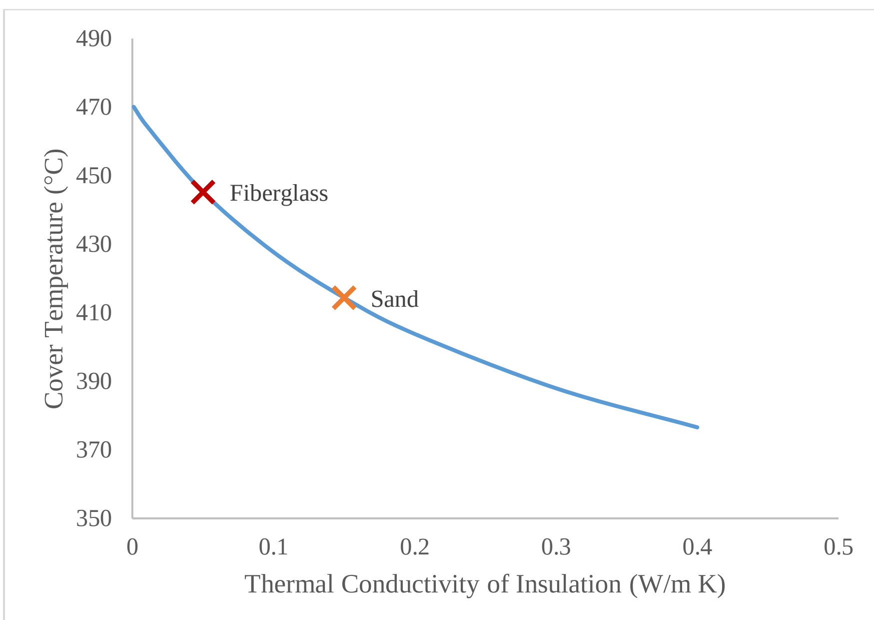


Figure 8.14. Cover temperature as a function of the thermal conductivity of the insulation.

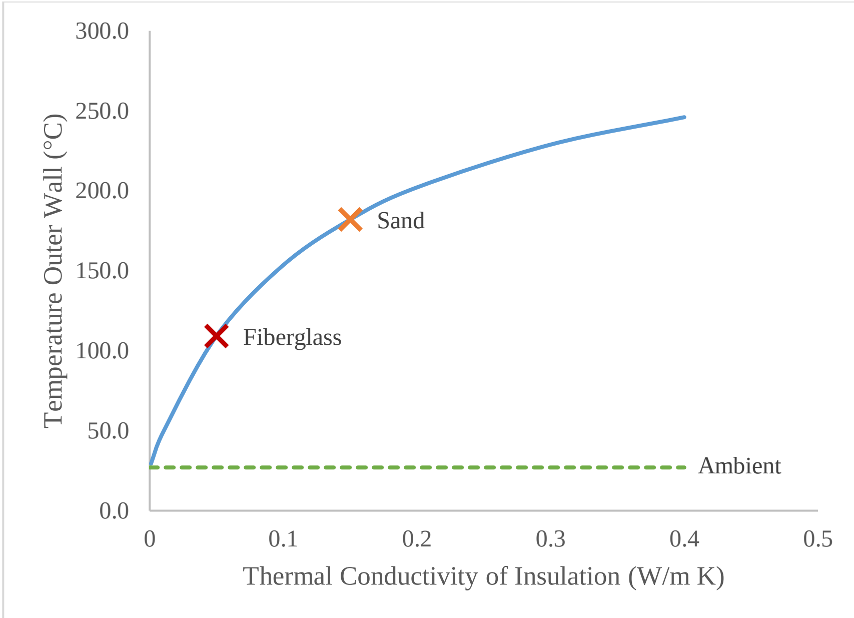


Figure 8.15. Outer wall temperature as a function of the thermal conductivity of the insulation.

8.7. Heat Transfer Analysis of Product Concept Variations

The design of this product includes a square combustion chamber and a top cover. This section analyzes the effect that those decisions had on the heat transfer components and overall energy efficiency of the stove. Changing the geometry of the stove from cylindrical (18-inch diameter) to square (18-inch width) increased the overall outside surface area of the stove. For a given combustion power output, a larger area increases heat losses. While the heat loss through the sides would be larger, the heat transfer through the cover would increase too, and therefore the energy efficiency is not significantly affected.

Adding a top cover to the design to prevent inside air pollution consequently increases the required boiling time for water. Without a cover, the burning charcoal would radiate directly into the cooking pot, and eliminate the intermediate step of transferring heat through the cover. Additionally, the hot flue gas would transfer heat by convection to the pot. In the current design, the flue gas is at a similar temperature than the cover, and therefore at steady state there is only minor heat transfer between the flue gas and the cover, and most of the heat transfer is due to radiation. However, by removing the cover, the flue gas would be in direct contact with the cooking pot, and given the large temperature difference between them, the heat exchange would be significant. Therefore, removing the cover and placing the pot directly on a rack above the flame will reduce the cooking time required, but will not provide a vent for the flue gas.

9. Transient-State Heat Transfer Analysis

This section models the initial transient state of the operation of the stove to estimate the time that it will take the stove to reach steady-state and the temperature of the cover as a function of time. As the cover has a thickness (L_c) of 3.175 mm, a thermal conductivity (k) of 0.21 $\frac{W}{m \cdot K}$, and a convective heat transfer coefficient of 6.0 $\frac{W}{m \cdot K}$ for the upper surface, the Biot number associated with this system, calculated using Equation 9.1, is 0.09.

$$Bi = \frac{hL_c}{k} \tag{9.1}$$

As the Biot number is less than 0.1, the lumped capacitance method is valid for this analysis. This means that the assumption that the temperature of the cover is spatially uniform at any instant during the transient process is valid. The energy balance equation in the cover can be simplified to Equation 9.2,

$$Q_{cc,top}(t) - hA(T - T_{surr}) - A\varepsilon\sigma(T^4 - T_{surr}^4) = \rho V c_p \frac{dT}{dt} \tag{9.2}$$

where $Q_{cc,top}$ represents the total amount of heat (in watts) transferred to the top cover from the combustion chamber, which during the initial operation phase is a function of time. The second and third terms on the left-hand side of the equation correspond to the heat transferred from the cover to the surroundings by convection and radiation, respectively. The right-hand side represents the change in the temperature of the cover over time. A diagram of the system under consideration is shown in Figure 9.1.

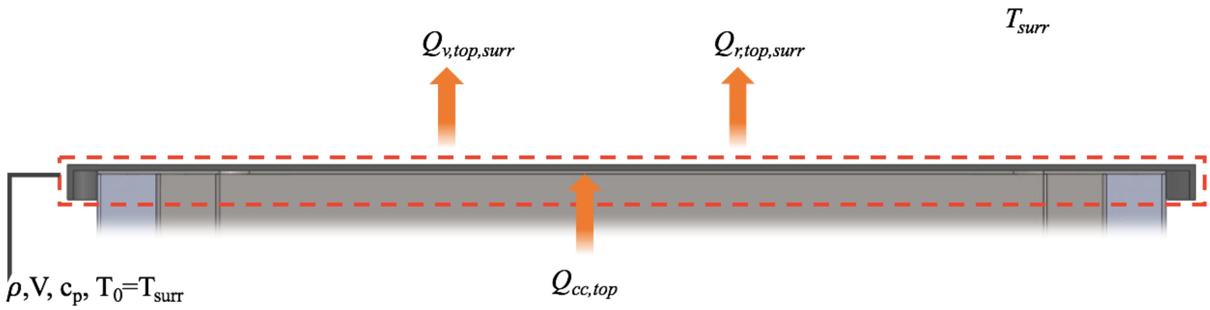


Figure 9.1. Diagram for transient energy balance on stove cover.

The amount of heat transferred to the top cover from the combustion chamber over time ($Q_{cc,top}\{t\}$) was modeled using the logistic growth curve (Equation 9.3),

$$\frac{d^2Q}{dt^2} - r\frac{dQ}{dt} + \frac{2r}{Q_{ss}}Q = 0 \tag{9.3}$$

where *r* is the rate of growth, and Q_{ss} is the carrying capacity (i.e. the maximum value of for heat transfer, reached at steady-state). On average, charcoal takes from 15 to 20 minutes to pre-heat, and as discussed in Section 8.4, the fraction of heat transferring directly from the combustion chamber into the cover at steady-state should be 1020W (Q_{ss}). A rate of growth value of 0.4 was used to model Equation 9.3, as this value allowed $Q_{cc,top}\{t\}$ to approach its maximum after 15 to 20 minutes. The estimated model for $Q_{cc,top}\{t\}$ is shown in Figure 9.2.

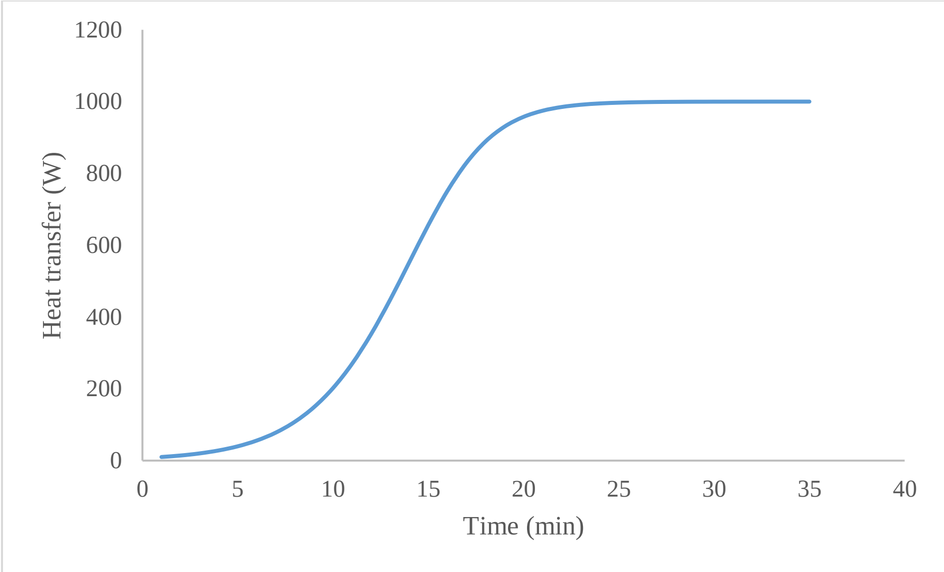


Figure 9.2. Model of heat transfer from combustion chamber to cover over time.

The transient energy balance in Equation 9.2 was solved numerically on Microsoft Excel, and the results obtained for the change in the temperature of the cover over time are shown in Figure 9.3. After 20 to 30 minutes, the cover reaches a temperature high enough to cook a meal. It can be observed that the temperature reaches a steady-state value of 414 °C, which matches with the results obtained in the steady-state analysis in Section 8.4.

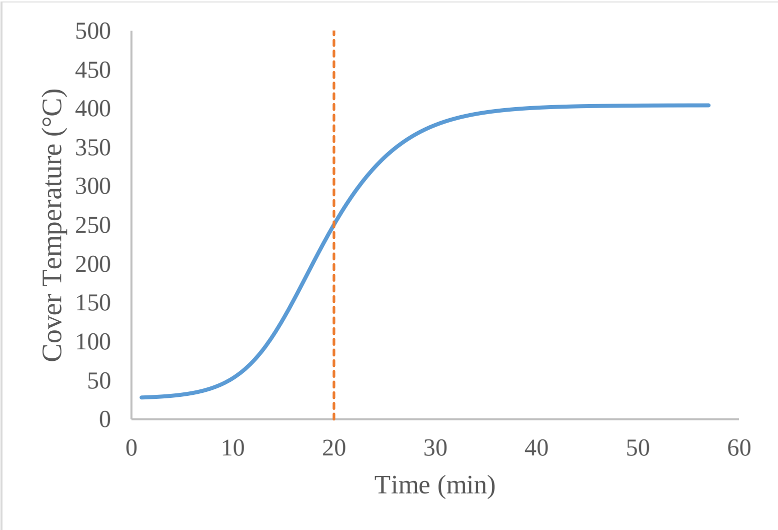


Figure 9.3. Model of change in temperature of cover over time during initial transient stage of stove operation.

10. Product Manufacturing

Our stove is designed to be cheap and easy to manufacture. The body is fabricated by bending and welding 16 gauge AISI 304 sheet steel while the body and grill is produced through casting iron. The following equipment and materials will be required:

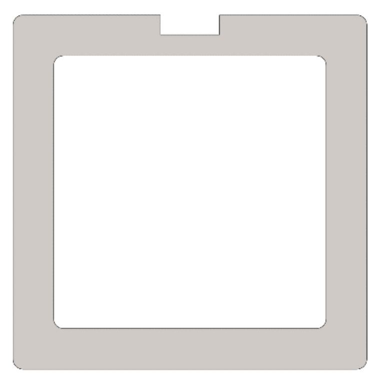
- 18 ft^2 of 16 gauge AISI 304 sheet steel
- 15 lbs. of casting iron
- Sheet metal bender
- Casting sand
- Metal furnace
- Welding Equipment

Most of the supplies listed are found at a standard blacksmith.

10.1. Component Production

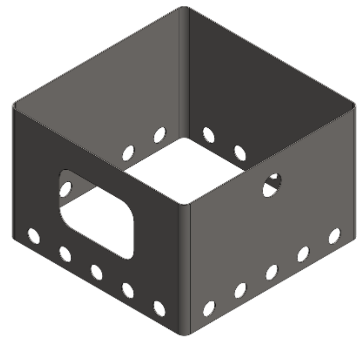
Each of the stove's components is manufactured prior to assembly. The following is a list of all of the components along with the production details:

a. Upper frame – This is the top part of the stove that seals the top gaps of the triple wall arrangement. The rectangular cutout at the top of this part is to allow sand to be loaded in the insulation chamber. The upper frame is manufactured by cutting a 9"×9" piece of sheet metal, and cutting a 7"×7" hole in the center. The insulation hole is 3"×1".



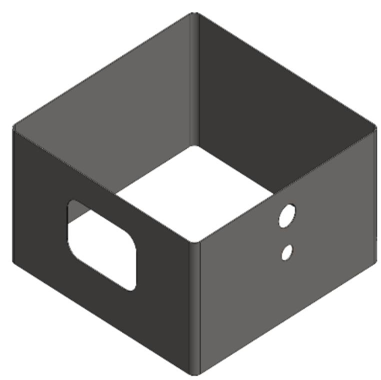
10.a. Upper Frame

b. Inner Combustion Chamber – The most inner wall of the stove is constructed from a 56"×9" piece of sheet metal. The long side is bent into a 14"×14" square, and the seal is welded shut. 20 1"-diameter air holes are drilled evenly around the bottom, with the center of each hole at 1" from the bottom of the part. A door opening that is 6" in length and 4" in height is cut in the front of the part. The opening is located in the horizontal center of the side, and top edge of the door opening is located 2" vertically from the top edge of the part. A ventilation hole is cut on the right adjacent side of the door. The hole is 1.5" in diameter, and is located horizontally in the center of the side. The vertical position of the center of the hole is 2" from the top edge of the part.



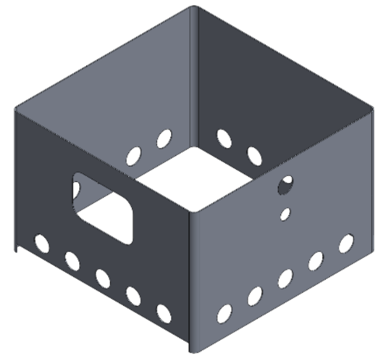
10.b. Combustion Chamber

c. Middle Stove Wall – The middle wall is fabricated from a 64"×9" piece of sheet metal. The long side is bent into a 16"×16" square, and the seal is welded shut. A door opening that is 6" in length and 4" in height is cut in the front of the part. The opening is located in the horizontal center of the side, and top edge of the door opening is located 2" vertically from the top edge of the part. A ventilation hole is cut on the right adjacent side of the door. The hole is 1.5" in diameter, and is located horizontally in the center of the side. The vertical position of the center of the hole is 2" from the top edge of the part. A bellows hole is cut below the ventilation hole. The hole is 1" in diameter, and is located horizontally in the center of the side. The vertical position of the center of the hole is 4.5" from the top edge of the part.



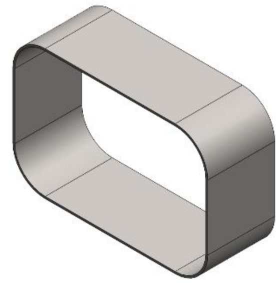
10.c. Middle Wall

d. Outer Stove Wall – The outer wall is made from a 72"×12" piece of sheet metal. The long side is bent into a 18"×18" square, and the seal is welded shut. 20 1.5"-diameter air holes are drilled evenly around the bottom, with the center of each hole at 2" from the bottom of the part. A door opening that is 6" in length and 4" in height is cut in the front of the part. The opening is located in the horizontal center of the side, and top edge of the door opening is located 2" vertically from the top edge of the part. A ventilation hole is cut on the right adjacent side of the door. The hole is 1.5" in diameter, and is located horizontally in the center of the side. The vertical position of the center of the hole is 2" from the top edge of the part. A bellows hole is cut below the ventilation hole. The hole is 1" in diameter, and is located horizontally in the center of the side. The vertical position of the center of the hole is 4.5" from the top edge of the part. An opening for the ash tray is cut on the front side at the bottom at the horizontal center. This opening is a rectangle that is 17" in length and 0.75" in height.



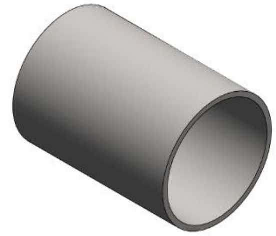
10.d. Outer Wall

e. Inner Door Seal – This component is meant to seal the gap between the walls at the door opening when the stove is assembled. Therefore, this part has the same outer dimensions as the door opening. It is made from sheet steel, and has a 6" length, 4" height, and 2" depth.



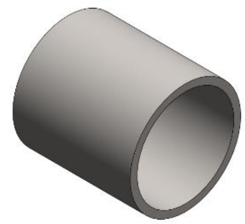
10.e. Door Seal

f. Ventilation Hole Seal – This component is meant to seal the gap between the walls at the ventilation hole when the stove is assembled. Therefore, this part has the same outer dimensions as the hole. It is made from sheet steel, and should have an outer diameter of 1.5", and a depth of 2".



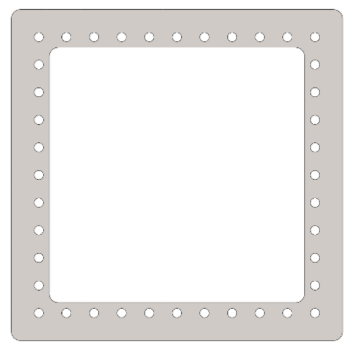
10.f. Ventilation Seal

g. Bellows Hole Seal – This component is meant to seal the gap between the walls at the bellows hole when the stove is assembled. Therefore, this part has the same outer dimensions as the hole. It is made from sheet steel, and should have an outer diameter of 1", and a depth of 1".



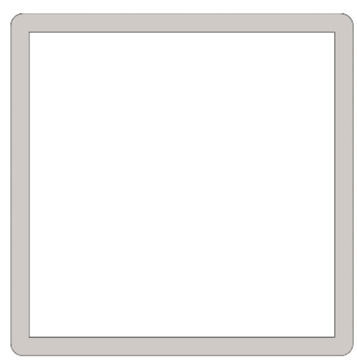
10.g. Bellows Seal

h. Lower Frame – This component is meant to provide weight support for the two inner walls, and to seal the insulation chamber at the bottom. The holes cut out of the piece are to allow for air flow into the air chamber between the walls. The upper frame is manufactured by cutting a 9”×9” piece of sheet metal, and cutting a 7”×7” hole in the center. The 40 air holes are each 0.5" in diameter, and are punched in an even frame with the center of each hole located 0.5" away from the inner edge.



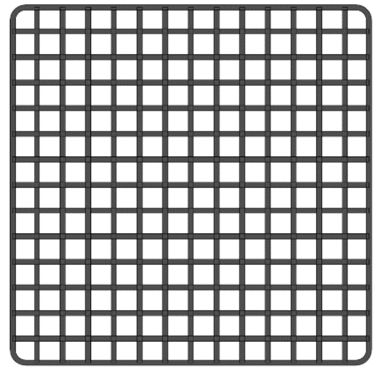
10.h. Lower Frame

i. Grill Support – This part is welded to the inner combustion chamber and supports the removable grill. It is fabricated with a 14"×14" piece of sheet metal. A 12.5"×12.5" hole is cut out of the center of the sheet.



10.i. Grill Support

j. Grill – The removable part is made of cast iron from a casting sand mold. The original is a square shaped rack that has 13 bands vertically and horizontally each spaced 1" apart. The actual grill does not have to be this exact design, but just any grate that fit the specifications of the inner combustion chamber.

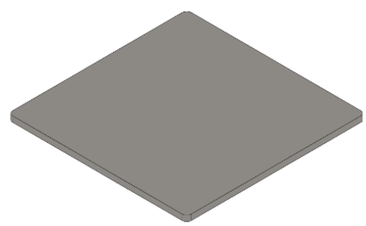


10.j. Grill

k. Bottom Cover – The bottom cover is a solid square of sheet metal that measures 18"×18". These are the same dimensions as the bottom of the outer stove wall.

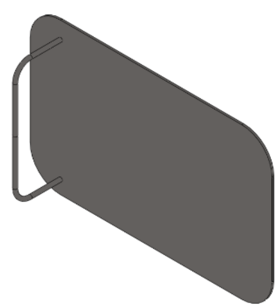
10.k. Bottom Cover

l. Stove Cover – This is a cast iron cover that will be creating using an original and casting sand. The piece is a square that measures 19"×19" and has a thickness of 0.125". The edges have a lip that extends 0.5" down to prevent the cover from sliding off the stove while in use.



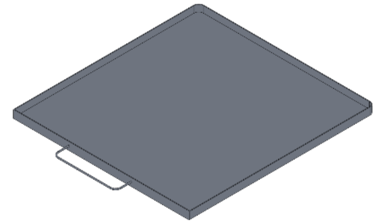
10.l. Stove Cover

m. Stove Door – This part is a rectangular cut piece of sheet metal that measures 8"×6". These dimensions are larger than the door opening, so that the door creates a 1" overlap on the face of the stove. A handle of any form is added to the door. The handle shown in this example is a bent 0.5" diameter metal rod that is welded vertically onto the door.



10.m. Stove Door

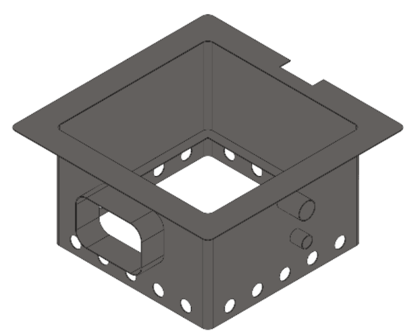
n. Ash Tray – This component is a removable tray that is constructed from a 18"×18" piece of sheet metal. The sides may have to be trimmed down so that the tray can fit into the opening on the front of the stove. There is a raised lip along the outer edge of the part to prevent ash from sliding off. This lip is 0.75" in height, and is made by welding 0.75" sheet metal strips along the tray bottom edge. A handle of any form is added to the door. The handle shown in this example is a bent 0.5" diameter metal rod that is welded horizontally onto the front of the tray.


10.n. Ash Tray

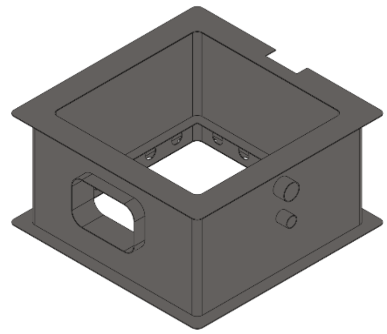
10.2. Stove Assembly

After all of the components are fabricated, assembly of the stove can begin. The components are joined together through welding, and this procedure is designed so that no additional metal bending is required. The following are step by step instructions with illustrations on the final assembly of this stove:

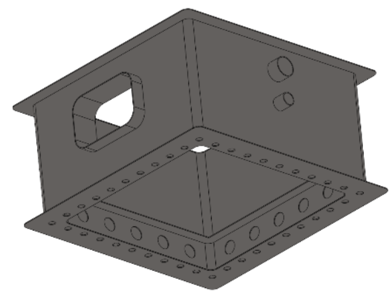
1. The stove is built starting with the inner combustion chamber, and welding on all of the smaller metal components. The top of the combustion chamber is welded to the inner edge of the upper cover. The door, ventilation, and bellows seals are all welded on their edges to their respective cuts in the combustion chamber. The grill support is welded to the inside of the chamber wall at 2" above the bottom edge of the wall. All of the joints are welded on both sides.


10.1. Step 1

2. The middle stove wall is attached next. This is done by sliding the assembly from step 1 into the shell of the middle wall. The openings for the door, ventilation, and bellows are lined up with their respective seals, and welded together. The top edge of the middle wall is also welded to the upper frame. The lower frame is then attached to the bottom by welding the inner edge of the frame to the combustion chamber edge and by welding the bottom edges of the middle wall. Schematics from the top and bottom of this step are shown here.

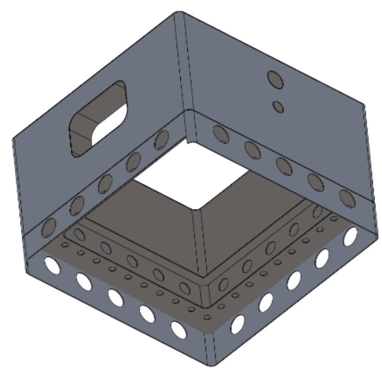


10.2.a. Step 2 Top View



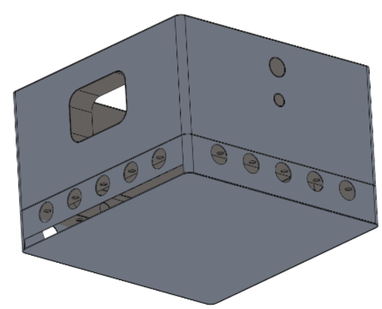
10.2.b. Step 2 Bottom View

3. Next, the outer stove wall is attached. This is done by flipping the outer wall and the assembly from Step 2 upside-down. The Step 2 assembly slides into the outer wall, and the edge of the lower frame is welded to the inside of the outer wall.



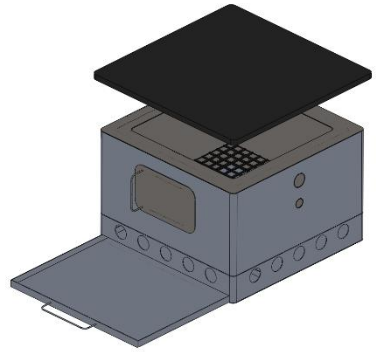
10.3. Step 3

4. The bottom cover is now attached by aligning it to the bottom edge of the outer wall, and welding around the edges. The stove is then flipped right-side up, and the outer wall is welded to the upper frame. Finally, a hinge is welded to the front face to allow the door to be attached.



10.4. Step 4

5. Now all of the welding for the stove assembly has been completed. The final steps are to attach the door to the hinge, to place the grill on top of the grill support, to slide the ash tray into the stove bottom, and to place on the top cover.



10.5. Step 5

11. Economic Analysis

With a population of only 3,000, and an average income of about $350 per month, it is expected that the demand for this new stove product will not be extremely high or continuous. If this product were to be introduced into other markets, such as the rest of El Salvador and other developing countries, then demand would definitely increase. As discussed in the market analysis, it is projected that 200 families will initially want the stove. However, since alternatives such as the Ecocina are being sold at a price point of around $30, our stove will likely need a subsidy to compete in the market. This means that the stove should be distributed through the government or an NGO, but the producers in El Salvador should receive payment of the wholesale price of the stove.

11.1. Production Costs and Profitability

One of the goals of this project is to source production locally in Las Delicias. An economic analysis was performed in order to estimate the production cost of each stove unit. Since a learning curve and economies of scale would apply, the marginal cost of producing each additional stove should decrease as quantity increases. This economic analysis is performed assuming bulk purchase of materials and with estimated average production times.

When raw goods are bought in bulk, the price is significantly cheaper than buying in small quantities. For this cost of goods sold analysis, it is assumed that production will occur in a centralized location in Las Delicias, so that one blacksmith would produce 200 stoves in total. For variable costs, these stoves would each require about 45 lbs. of sheet metal, 15 lbs. of cast iron, and all associated labor and utilities. According to Alibaba.com, wholesale 16-gauge steel costs $1500 per metric ton, and pig iron costs $350 per metric ton (Alibaba, 2017). This means that to make 200 stoves, a blacksmith would have to purchase approximately $6,750 of sheet steel and

\$525 of pig iron. Each stove will have a raw material cost of \$36.38. Utilities add another \$1.97 to the variable costs. Assuming the use of a standard 100 Amp arc welder at a voltage of 120 V for a total of 1 hour, the welding would require a total of 12 kWh of electricity. The calculation is $100\ \frac{C}{s} \times 120\ \frac{J}{C} \times \frac{1\ kW}{1000\ W} \times 1\ hr = 12\ kWh$. The standard electricity rate in El Salvador is $\$0.139/kWh$ in USD, so the electricity cost is \$1.67. On average, it takes 0.5 lbs. of coal to melt 1 lb. of iron. At a purchase rate of \$0.03 per lb., the cost of the 7.5 lbs. of coal needed to melt the 15 lbs. of iron is \$0.23. The raw materials and utilities costs are summarized in Table 11.1.

Cost of Materials/Utilities (Variable)				
Item	Amount	Units	Cost/Unit	Cost
Stainless Steel Sheet Metal	45	lbs.	0.75	\$ 33.75
Cast Iron Lid	9	lbs.	0.175	\$ 1.58
Cast Iron Grill	6	lbs.	0.175	\$ 1.05
Electricity for Welding	12	kWh	0.139	\$ 1.67
Coal for Metal Kiln	7.5	lbs.	0.03	\$ 0.23
				\$ 38.27

Table 11.1. Summary of Raw Materials and Utilities Costs

The last component of the variable costs is the labor. It is assumed that a local blacksmith employee earns about $\$2/hr$. This wage is more than twice the minimum wage in El Salvador. Table 11.2 shows a summary of he expected labor hours and cost of producing each component of the stove and of welding all of the pieces together. Each of these calculations is simply an estimate, and should not be considered definitive values. Due to a learning curve, it would most likely take a worker longer than the estimated time of 6.75 hours to produce the first stove. As more stoves are produced, the worker would become more experienced, and the production time could very well take under 6.75 hours. After raw materials, utilities, and labor, the total variable cost of production is \$51.77 per stove.

Cost of Labor (Variable)			
Production Step	Hours	Wage ($/hr.)	Cost
Upper/Lower Frames	0.5	2	$ 1.00
Inner Wall	0.5	2	$ 1.00
Middle Wall	0.5	2	$ 1.00
Outer Wall	0.5	2	$ 1.00
Hole Seals	0.5	2	$ 1.00
Grill Support	0.25	2	$ 0.50
Grill	1	2	$ 2.00
Bottom Cover	0.25	2	$ 0.50
Stove Lid	1	2	$ 2.00
Door	0.25	2	$ 0.50
Tray	0.5	2	$ 1.00
Assembling/Welding	1	2	$ 2.00
			$ 13.50

Table 11.2. Summary of Production Labor Costs

Initial capital costs of welding and metal forming equipment do not need to be taken into account for this project since it is known that the local blacksmith in Las Delicias already owns all of the necessary equipment. This equipment would be a kiln to melt the iron, casting sand, a sheet metal bending brake, a drill for hole boring, and an electric arc welder. Thus, the average total cost to produce 200 stoves in Las Delicias is $51.77 per stove.

Since this stove cost only $52 per unit to mass produce, there is an opportunity for profit by the producer. If the stove were to be set at the same price point as the Ecocina of $65, then the blacksmith would still have a margin of 25%. Additionally, our stove design seems to have better safety features than the Ecocina, which could be a selling point that attracts more families to our stove. While $65 is a retail price that allows for a healthy profit, as discussed earlier, it may not be feasible to sell to consumers at that price. Therefore, the government or a group such as Engineers without Borders may assist in subsidized distribution to maintain competitiveness.

11.2. Operating Costs

It has been estimated that many households that do not have efficient cooking and heating stoves spend $1-$2 every day on fuel, mostly firewood. For the purpose of this analysis, it can be assumed that an average family eats 2.5 meals a day. If an open fire is used to cook, it is estimated that 1.2 kg of firewood is used per meal. The average firewood releases about 280 kcal of useful energy per kg that can be absorbed by a cooking surface (Keita, n.d.). 1.2 kg of fire wood translates to 336 kcal of energy, which is enough energy to bring 4.5 L of water to a boil from room temperature. This energy usage seems reasonable to cook a traditional El Salvadoran meal of *pupusas*, vegetables, and meat. Given a price of wood of $0.25 per kg, a family will spend $0.75 a day on fuel, or about $23 per month. This equates to spending 7% of an average family's $350 per month income on firewood.

Although it is priced at a higher price that firewood, charcoal has a higher usable energy output and releases fewer toxic fumes into the atmosphere. The average cost of charcoal is about $0.50 per kg while the useful energy is 420 kcal/kg (Keita, n.d.). If a family were to burn charcoal instead of wood in an open flame, but use the same amount of energy, then they would have to purchase 2 kg of charcoal per day, spending about $30 per month.

Calculations from the heat transfer model show that our stove design is about 33% efficient, meaning that 33% of the energy released from the charcoal is usable and passes through the top cover. For an open flame, only 15%-18% of the energy actually reaches the cooking vessel (How efficient are open fires and fuel-effect fires?, n.d.). This means that our product is twice as efficient as an open flame, and would require half the amount of fuel to heat up the same food. Instead of spending $30 a month on charcoal, a household would only need to buy $15 per month

Therefore, if a family currently uses firewood, buys our stove, and switches to charcoal fuel, they would be saving $7 per month. At a price of $65, the stove would pay for itself in a little more than 9 months of use, and continue saving fuel for the rest of its lifetime. If a family currently uses charcoal, then the savings would be even greater at $15 per month, meaning the stove would pay for itself in just over 4 months. The economics show that a family would be much better off with our stove compared to an open fire cooking method.

12. Important Considerations

Even though the stove is designed so that it is safe to operate, certain considerations should be taken into account when using the stove. The outer insulation increases the energy efficiency of the stove, and decreases the temperature of the outer wall by more than 200°C, but it is still too hot to touch. Therefore, when operating the stove, users should be careful not to touch the outer walls, and it is recommended that they add a protection fence around the stove to prevent children from getting close. The goal of the ventilation tube and the cover is to remove the flue gas safely from the room. In order to achieve this goal, the cover should be properly placed on top of the stove and the ventilation tube should be directed towards the outside. Additionally, since it will weigh approximately 75 lbs., the stove should not be moved by one person. At least two people should be used to position the stove, and it should not be moved during operation.

13. Conclusions and Recommendations

Our stove is designed to be an efficient and safe alternative to the current method of cooking the exists in Las Delicias village. By implementing our stove in the village cooking areas or households, consumers will witness a multitude of benefits including decreased cook time, reduced fuel consumption, safer cooking practices, and the stimulation of the local economy. The prototype of the design is still being improved due the changing needs and wants of the Las Delicias community.

The design has an advantage in fuel efficiency due to the three-chamber design that allows for heat to be maintained in the system through insulation. Additionally, the chambers allow for preheated air to create better combustion when forced in through the supplementary bellows.

Our stove also provides increased safety measures that remedy the issues in open flame cooking. The insulation of the stove provides a buffer to children or those interacting with the stove from accidental burns. Additionally, the stove cover and ventilation hole featured in the stove provide a safe outlet to noxious flue gas reducing the contaminant levels in the air of the cooking space.

It is recommended that our design be used by the local blacksmith in Las Delicias, El Salvador to manufacture stoves for the citizens of the village. Before any stoves are produced, a survey should be conducted to gauge the demand for the new product, and the price point at which people will purchase it. Most likely, in order to distribute the stove to a high number of households, it will have to be sold with a subsidy at a price lower than the manufacturing cost, similar to how the Ecocina is currently sold. An NGO such as Engineers without Borders may be able to partner with the stove producer to assist in surveying and distribution.

14. Acknowledgements

We would like to thank Professor Warren D. Seider and Professor Bruce M. Vrana for their support and engagement in this project. We would also like to thank Mr. Adam A. Brostow for conceptualizing this project and providing us guidance in completing this project. We extend gratitude to Professor Sue-Ann Bidstrup-Allen for assistance with the heat transfer calculations. We would like to thank the industrial consultants, who offered their expertise in weekly design meetings and email correspondences. Additionally, thanks go to NextFab Labs for fabricating the stove prototype, and allowing us to observe the manufacturing process. Finally, special appreciation goes to the Judy Soley Support for Student Groups Fund in SEAS for providing the funds needed to build the first prototype.

15. Bibliography

Alibaba. (2017). Retrieved from Alibaba: https://www.alibaba.com/

Bansal, M., Saini, R. P., & Khatod, D. K. (2013). Development of cooking sector in rural areas in India—A review. *Renewable and Sustainable Energy Reviews*, 44-53.

Barna, M. (2017, May). *Cooking Clean, Saving Lives*. Retrieved from Discover Magazine: http://discovermagazine.com/2017/may-2017/cooking-clean-saving-lives

Bergman, T. L., Lavine, A. S., Incropera, F. P., & Dewitt, D. P. (2011). *Fundamentals of Heat and Mass Transfer.* Hoboken, NJ: John Wiley & Sons, Inc.

Burns. (2016, September). Retrieved from World Health Organization: http://www.who.int/mediacentre/factsheets/fs365/en/

CO Knowledge Center. (2017). Retrieved from Detect Carbon Monoxide: http://www.detectcarbonmonoxide.com/co-health-risks/

El Salvador. (n.d.). Retrieved from Pan American Health Organization: http://www2.paho.org/hq/index.php?option=com_docman&task=doc_view&Itemid=270&gid=33577&lang=en

Engineering ToolBox. (n.d.). Retrieved from Engineering ToolBox: http://www.engineeringtoolbox.com/

Evans, D. D., & Emmons, H. W. (1977). Combustion of Wood Charcoal. *Fire Safety Journal*, 57-66.

Gogoi, B., & Baruah, D. C. (2016, February). Steady state heat transfer modeling of solid fuel biomass stove: Part 1. *Energy*, 283-295.

Household Income Up 10% in El Salvador. (2014, September 1). Retrieved from Central America Data: http://www.centralamericadata.com/en/article/home/Household_Income_Up_10_in_El_Salvador

How efficient are open fires and fuel-effect fires? (n.d.). Retrieved from Sustainable Energy Authority of Ireland: http://www.seai.ie/Power_of_One/FAQ/Home%20Heating/How_efficient_are_open_fires_and_fuel-effect_fires.html

Jan, J. (2014). *US Patent No. 701721.*

Kausley, S. B., & Pandit, A. B. (2010, March). Modelling of solid fuel stoves. *Fuel*, 782-791.

Keita, J. D. (n.d.). *Wood or charcoal - which is better?* Retrieved from Food and Agriculture Organization of the United Nations: http://www.fao.org/docrep/s4550e/s4550e09.htm

Mauricio, R., & Nunez, S. (2013). *US Patent No. 6651645.*

Melting Temperature Ranges for Stainless Steels. (n.d.). Retrieved from British Stainless Steel Association: http://www.bssa.org.uk/topics.php?article=103

Poverty in El Salvador. (2016). Retrieved from The World Bank: http://povertydata.worldbank.org/poverty/country/SLV

Project Las Delicias. (n.d.). Retrieved from FIMRC: https://www.fimrc.org/el-salvador/

Seider, W. D., Lewin, D. R., Seader, J. D., Widagdo, S., Gani, R., & Ng, K. M. (2017). *Product and Process Design Principles: Synthesis, Analysis and Evaluation.* Hoboken, NJ: John Wiley & Sons, Inc.

Stove Designs | Improved Biomass Cooking Stoves. (2006). Retrieved from BioEnergy Lists: http://stoves.bioenergylists.org/stove_design

The Ecocina. (n.d.). Retrieved from StoveTeam International: http://www.stoveteam.org/services/the-ecocina

The Safe Use of Cookware. (2015, March 18). Retrieved from Government of Canada - Health Services: https://www.canada.ca/en/health-canada/services/household-products/safe-use-cookware.html

Appendix

Nomenclatures

A	area (m^2)
c_p	specific heat (kJ/kg K)
D_h	hydraulic diameter (m)
F	view factor
g	acceleration due to gravity (m/s^2)
Gr	Grashof number
f	friction factor
h	convective heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
L	length (m)
m	mass (kg)
Nu	Nusselt number
Pr	Prandtl number
Q	heat (W)
r	radius (m)
Ra	Rayleigh number
Re	Reynolds number
T	temperature (K or °C)
u	velocity (m/s)

Greek letters

ε	emissivity
ρ	density (kg/m^3)
σ	Stefan Boltzmann constant ($W/m^2 \cdot K^4$)
μ	dynamic viscosity (Pa·s)
ν	kinematic viscosity

Q subscripts

cc	combustion chamber
ccw	combustion chamber wall
mw	middle wall
ow	outer wall
airc	inner air chamber
fg	flue gas
char	burning charcoal
surr	surrounding air
v	convection
r	radiation
bot	stove bottom
bair	bottom air
vent	ventilation tube
door	door
c	conduction

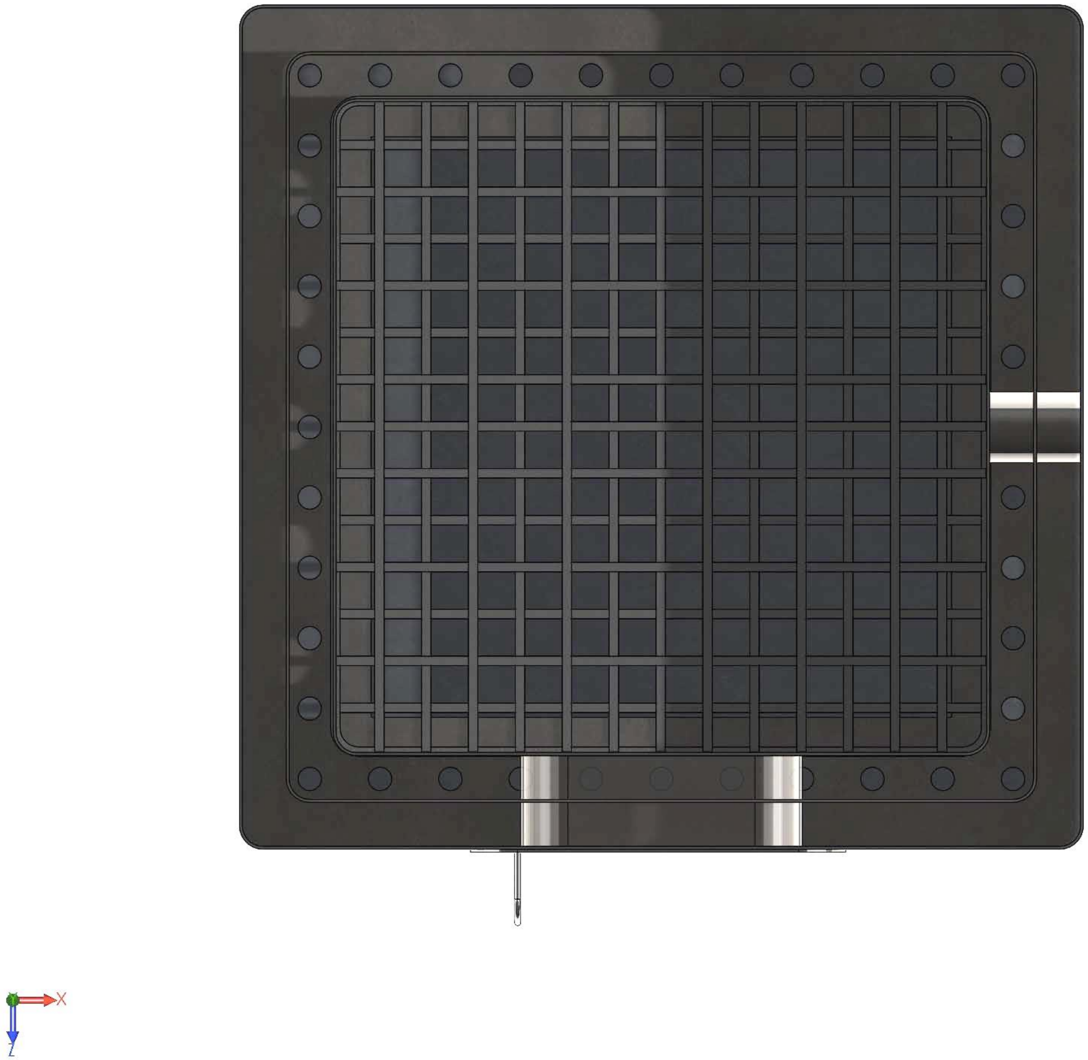


Figure A.1. Top view of stove without cover

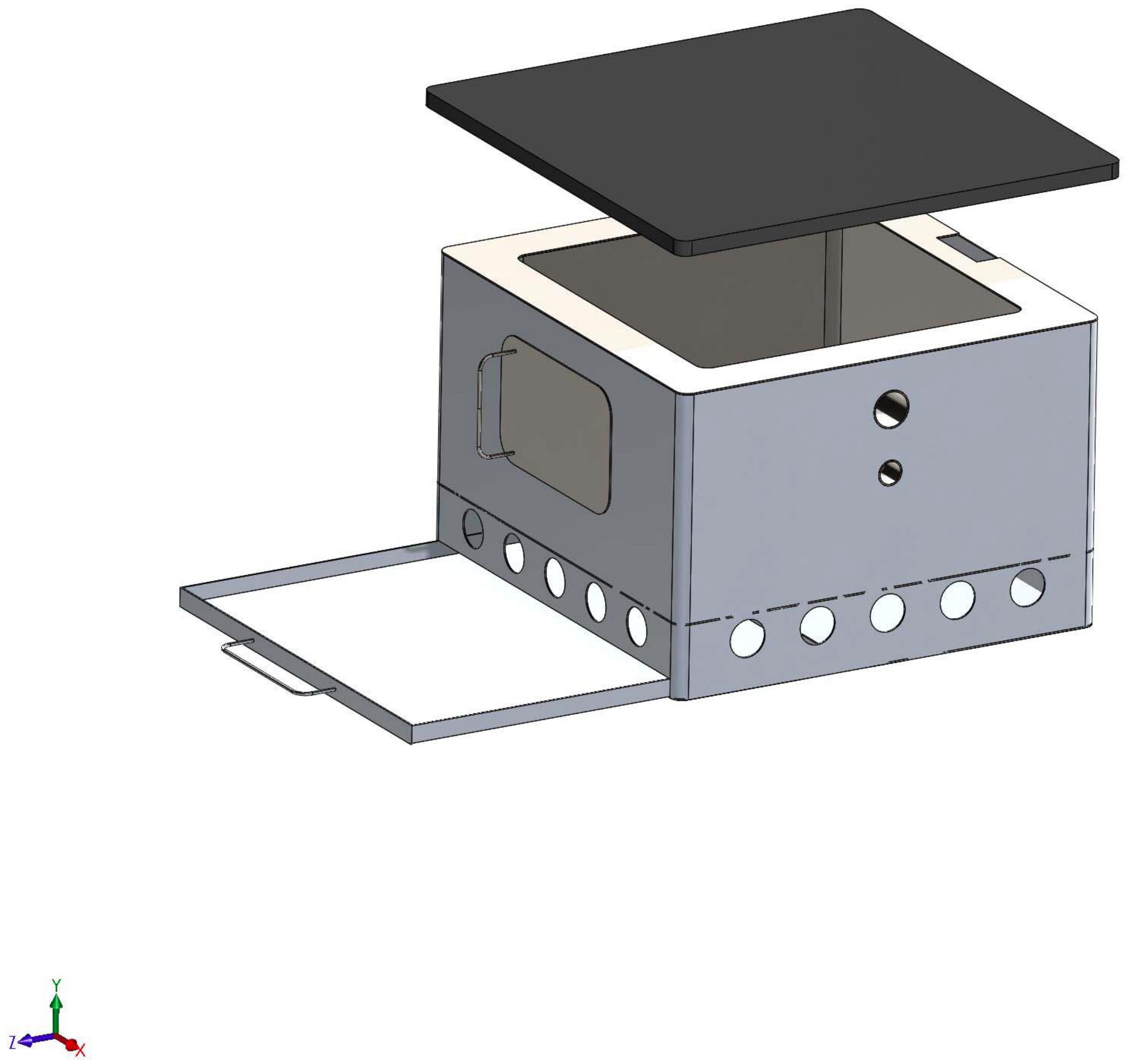


Figure A.2. Stove assembly

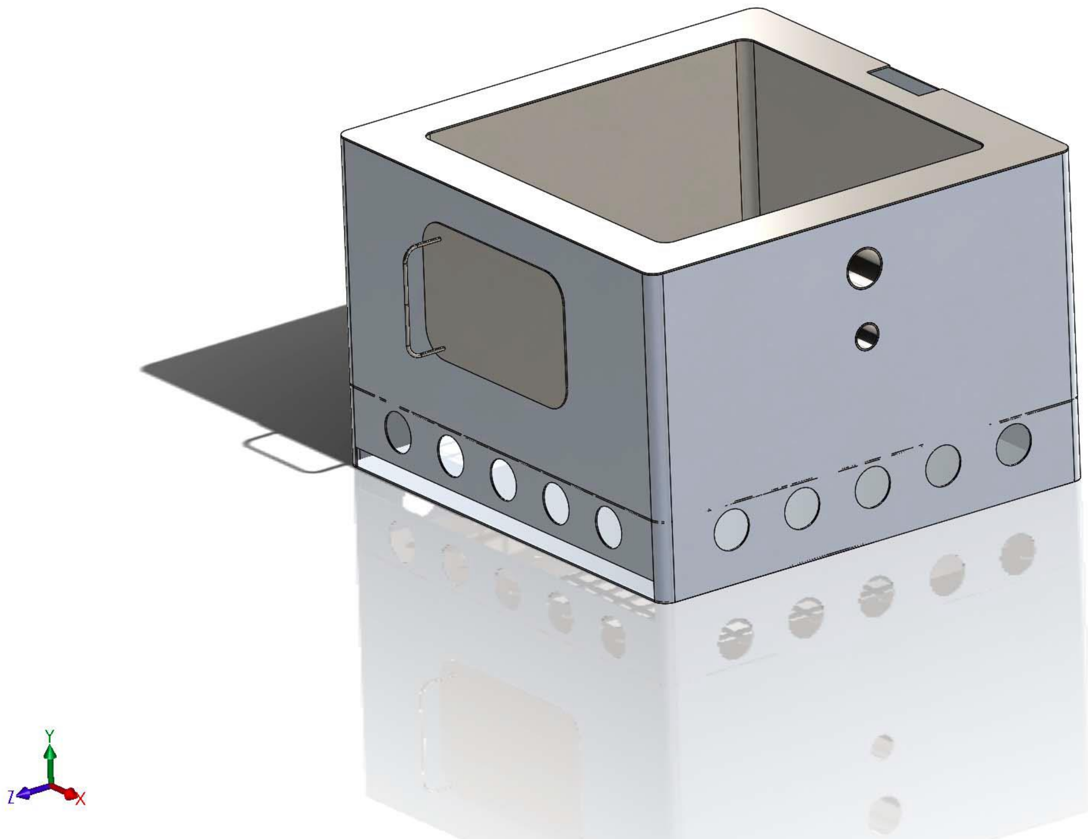


Figure A.3. Outer stove view (without cover and tray)

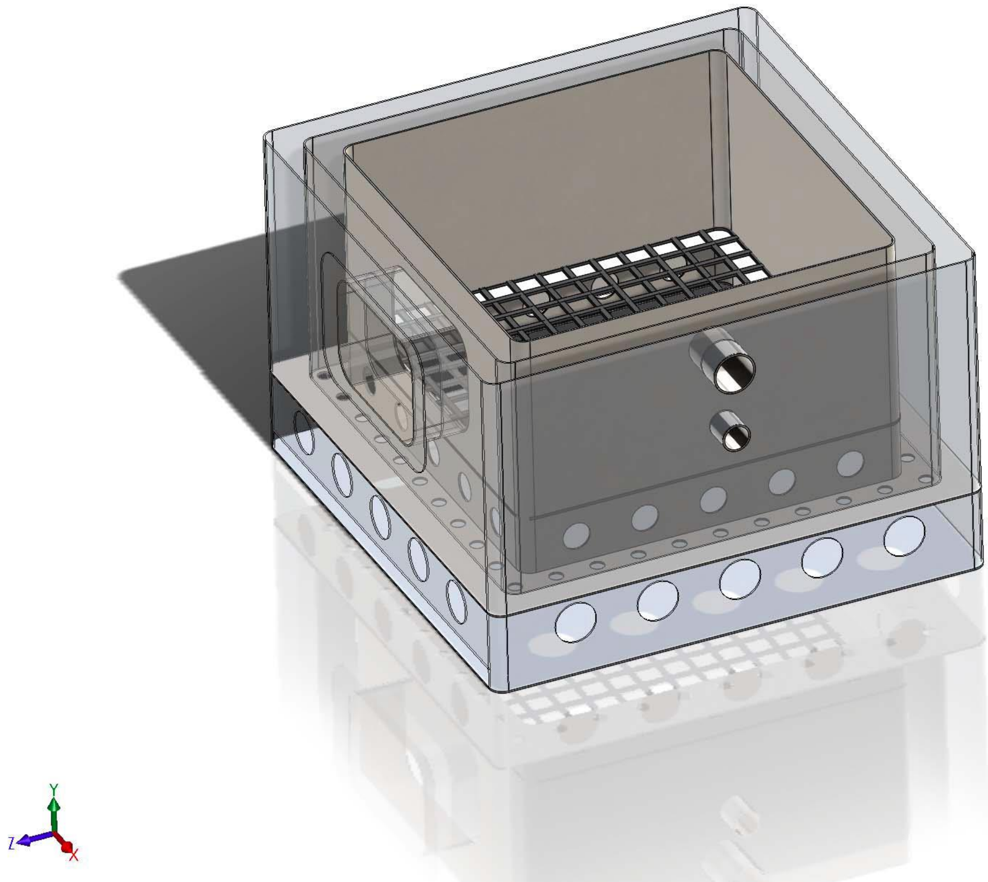


Figure A.4. Inner chamber of stove

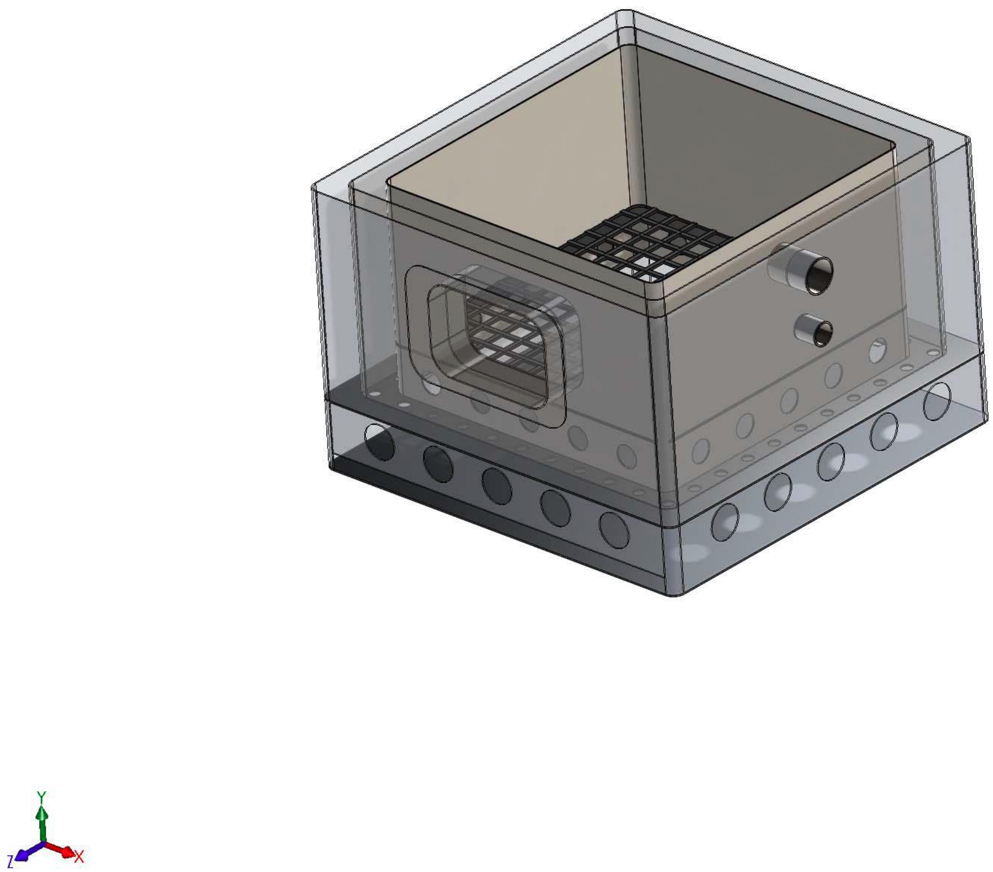


Figure A.5. Stove inner box and combustion chamber

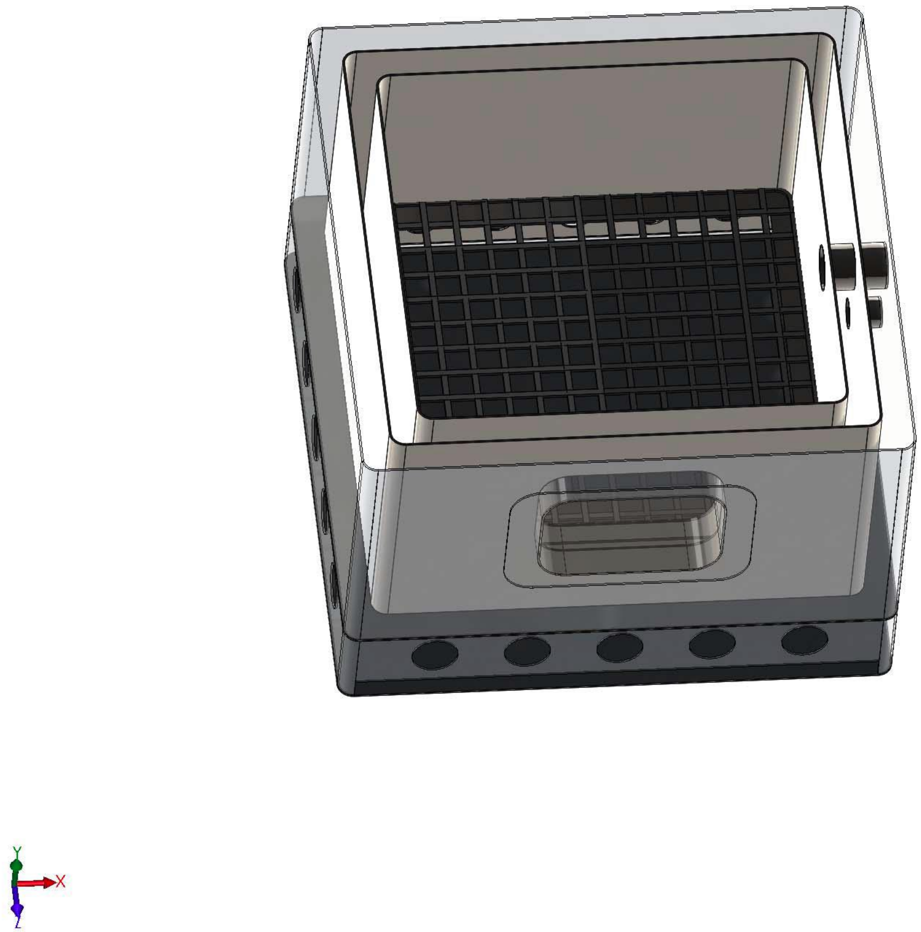


Figure A.6. Stove middle air chamber

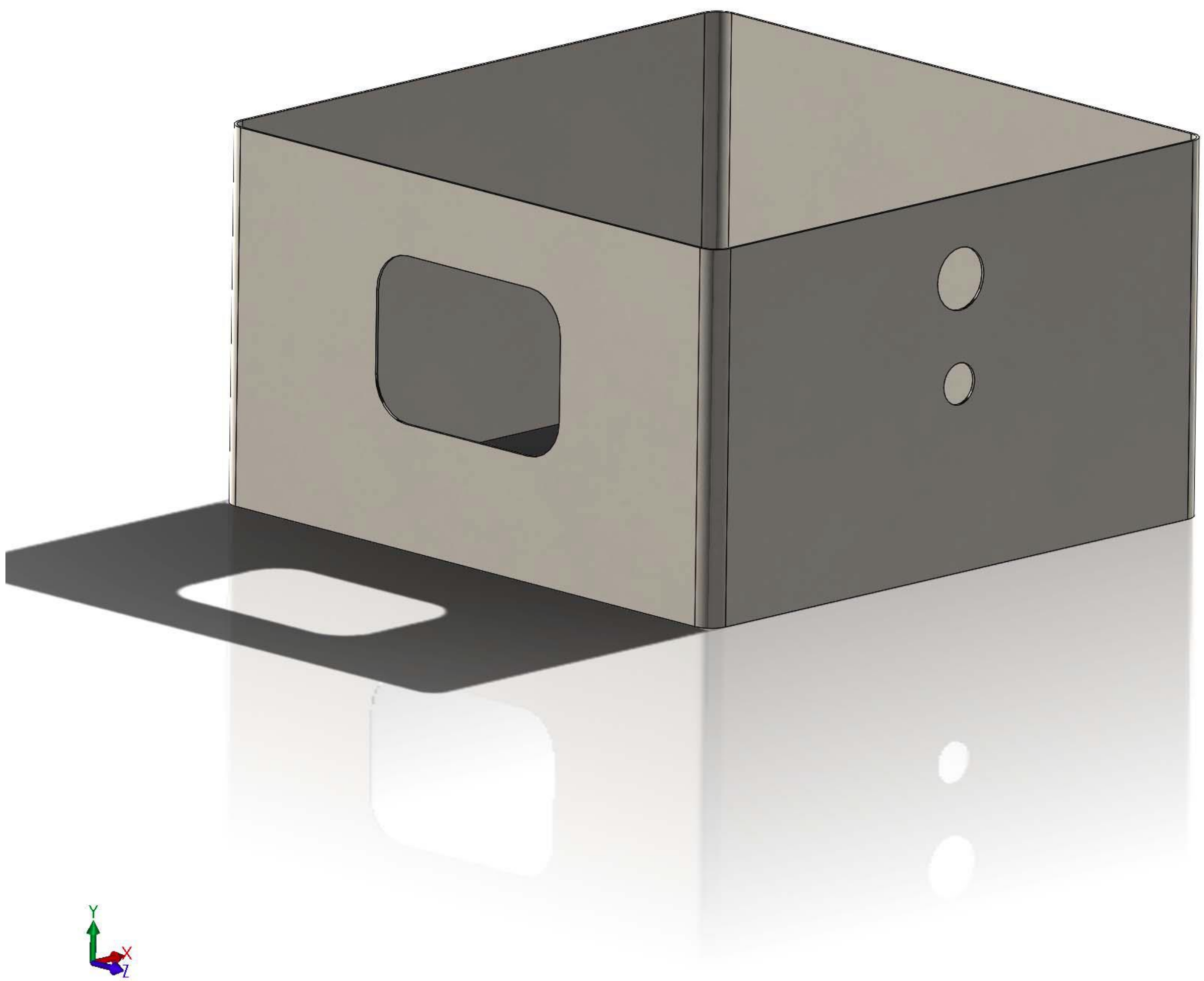


Figure A.7. Stove middle box

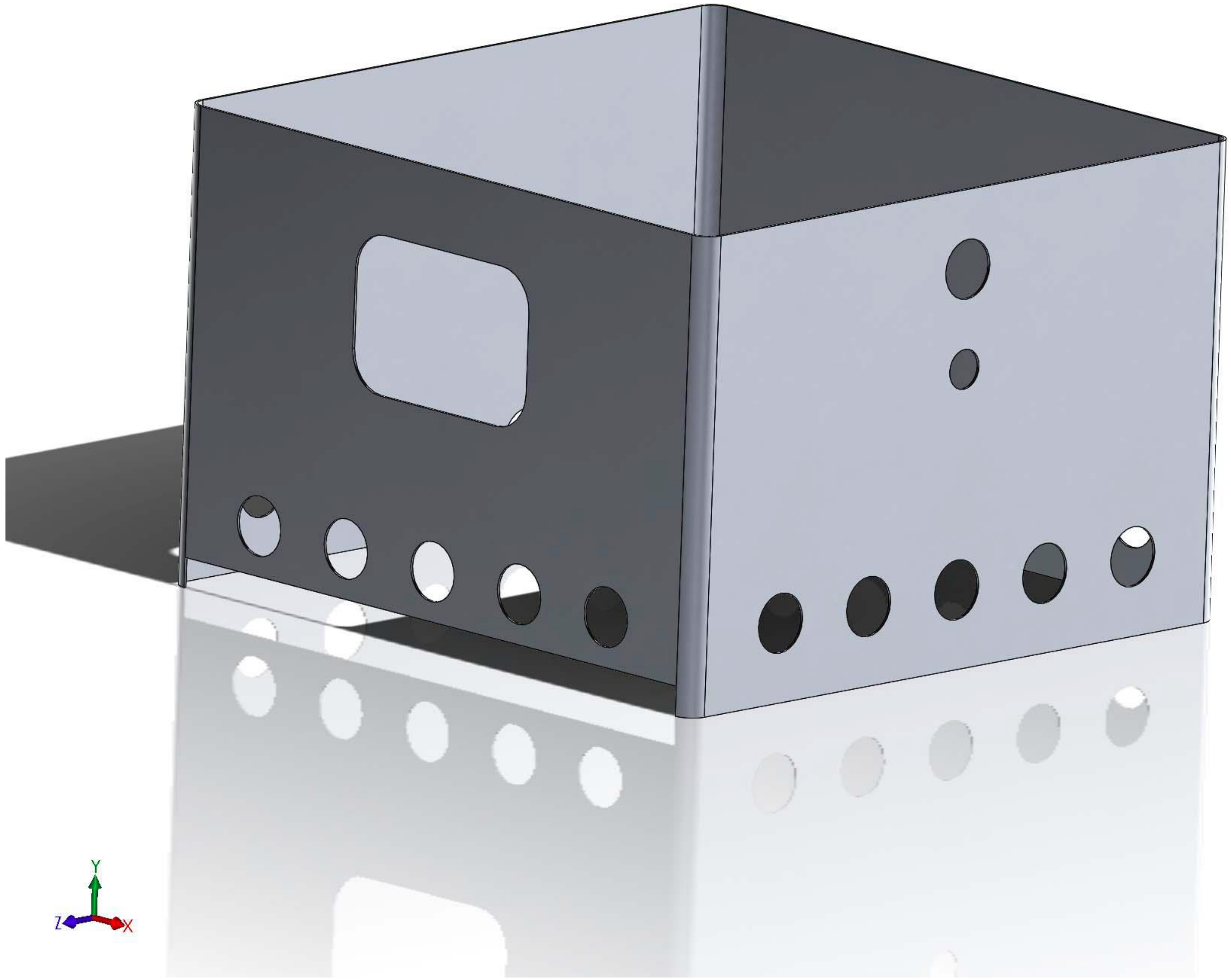


Figure A.8. Outer stove box

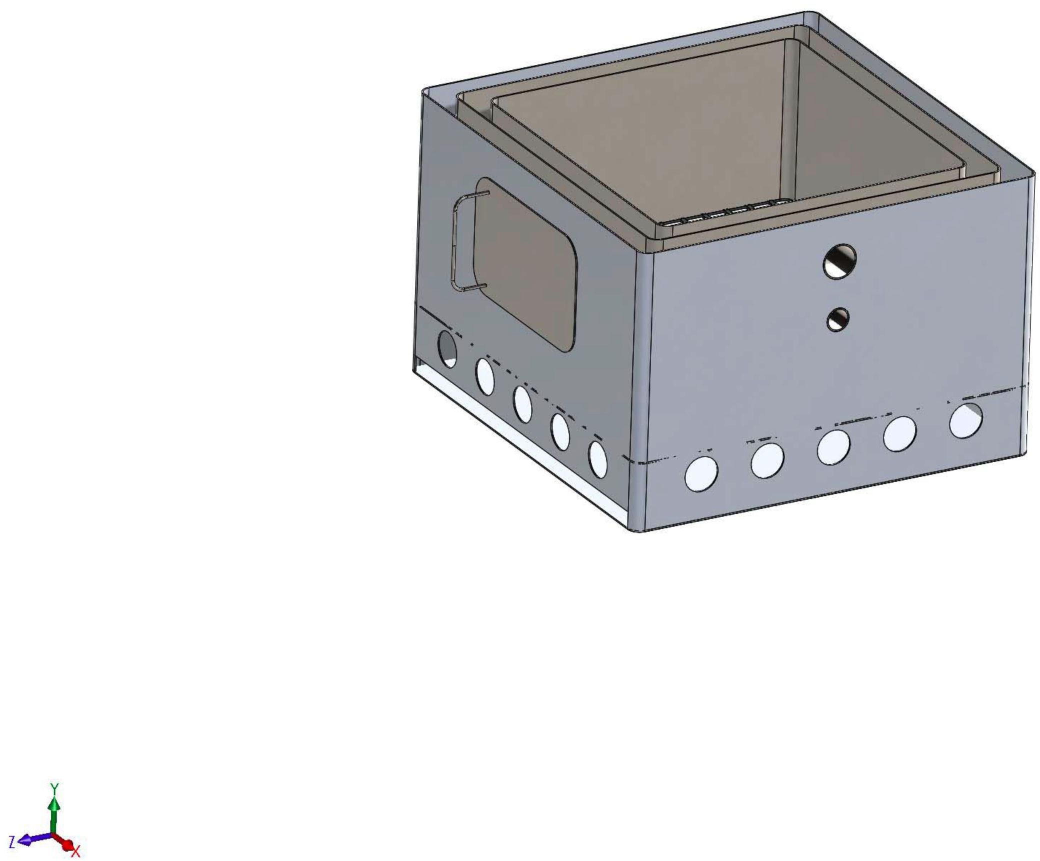


Figure A.9. Outer view of stove’s 3 chambers