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Biomass Cookstoves: an Empirical Study into the Relationship between Thermal Efficiency and Tending Practices for the Developing World

Honors Thesis

Erin Peiffer

Department: Mechanical and Aerospace Engineering

Advisor: Joshua Heyne, Ph.D.

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Abstract

More than 2 billion people in the world use biomass stoves for cooking and heating their homes. Due to incomplete combustion, toxic byproducts such as soot, nitrous oxides and carbon monoxide gasses form. These toxic substances contribute to pollution and can lead to serious health issues over time if inhaled leading to approximately 4 million premature deaths each year. The formation of these toxic substances can be mitigated, in part, through the introduction of increased turbulence intensity allowing for the so-called "well-stirred combustion regime". Here we will be exploring the health, environmental, and social effects of biomass combustion in the developing world, the benefits of "rocket" technology for cooking and agricultural purposes, the potential implementation of well-stirred combustion regimes to further improve upon this technology, and how improved tending practices can increase thermal efficiency for both 3 stone cookstove and clean cookstove use.

Acknowledgements

There are several people I would like to thank for their guidance, support, and expertise over the last year that have helped me in the development of my thesis. Special thanks to Dr. Joshua Heyne for serving as an amazing thesis adviser, continually pushing me to improve upon my technical skills while encouraging personal growth. I appreciate the opportunity provided to me by Dr. Heyne to work on a project that so heavily impacts the developing world, a special passion of mine. I also show special gratitude to Sari Mira for being a wonderful lab partner and mentor these last few months. Present for every single test and step along the way, testing would not have taken place without you. I would also like to thank my family for their support, specifically, my sister Amanda who was a vital source of continued motivation and guidance. Additionally, I would like to thank all of my friends for their patience over the last year, understanding the time commitment of working on a thesis. I would like to express thanks to Rocket Works for serving as a host during my time in South Africa and for the exciting hands-on development of the "rocket" barn. I would, finally, like to recognize the ETHOS Center, the GAR Foundation, and the Palermo Fund for financial support of this thesis.

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Chapter I. Introduction

Biomass Gasification, Human Health, and the Environment

Human health, population growth, and climate change are intimately connected by the food we eat and how we prepare it. While significant attention is paid to agricultural practices domestically, internationally the methods that people use to prepare their meals can be extremely damaging to their family's and the planet's health. Currently, there are over 4 million premature deaths each year due to indoor air pollution resulting from the use of traditional cookstoves [1]. Deforestation and production of greenhouse gases continue to be serious issues in the developing world where these stoves are used along with inefficient agricultural drying methods [2, 3]. New technologies to replace traditional biomass stove and agricultural drying practices have the potential to mitigate the negative effects felt by continued use of these old practices despite the limitations set by population growth and economic development. This chapter will focus 1) on the health, social, and environmental issues that are impacted by the continued use of traditional biomass cookstoves and drying equipment, 2) new technologies that mitigate some negative effects felt by the continued use of traditional cookstoves and drying equipment, and the implications of these improvements.

Biomass cookstoves remain a dominant source for cooking and heating in many parts of the world where over 2 billion people currently use open, biomass cookstoves [1]. Further, recent developments by the Global Alliance for Clean Cookstoves (GACC) to transition 100 million homes to clean cookstoves by 2020 will only account for 3% of the population that uses open cookstoves today, resulting in continued use for the vast majority of that population for decades to come [4]. Cookstoves are any technology used to cook or heat the home, and open cookstoves include technologies such as three stone cookstoves and open fire pits that do not have a defined combustion chamber that directs the fire and exhaust towards the cooking vessel. Due to incomplete combustion in both traditional cook stoves and biomass gasifiers used in agricultural applications in the developing world, human health and the environment suffer. In addition to these problems, serious social issues such as rape and assault occur during the laborious task of collecting firewood, a job most commonly done by women.

Although used by billions of people globally, traditional cook stoves are largely an inefficient cooking method resulting from inefficient heat transfer from the fire to cooking

vessel and incomplete combustion [5]. Three stone cookstoves, a type of traditional cookstove, utilize three uniform height stones in which a pot can be balanced over a fire. Density gradients, resulting from temperature differences between ambient air and air heated by the fire, allow for heat transfer through natural convection from the fire to the cooking vessel. Heat generated through combustion can be lost to the environment through diffusive, conductive and radiative heat losses due to poor insulation, and thermal efficiencies for three stone cookstoves can range anywhere from 5% to 30%, the low end occurring when cooking occurs outside in a windy area and the high end representing very well-tended fires [6]. Because the design requires the fire to be on the ground, the amount of primary air that can mix with the fuel before combusting is limited, thus resulting in decreased combustion efficiencies and increased emissions. In addition to increased emissions, the open nature of the fire increases the risk for burns. A three stone cookstove is shown in Figure 1.

Figure 1. Three stone cookstoves, similar to the one pictured above, are used by over 2 billion people in the world today [1]. Due to poor insulation around the fire, heat generated through combustion is lost to the environment through conduction, diffusion, and radiation. Thermal efficiencies of traditional cook stoves range anywhere from 5-30% resulting in the increased use of fuel [6]. These stoves also facilitate incomplete combustion which results in the release of toxic chemicals [7].

When combustion is not complete due to poor mixing of fuel, oxidizer, and heat, toxic chemicals such as soot, nitrous oxides (NO_x), carbon monoxide (CO), and unburned hydrocarbons (UHC) are produced [7]. Inhaling these toxic chemicals can result in serious

respiratory illnesses [8]. Included in these illnesses is cardiovascular disease, lower respiratory infections, and lung cancer as particulate matter (PM) found indoors from using traditional cookstoves can reach 30 times above what the World Health Organization (WHO) lists as a healthy range [8]. Households that use three stone cookstoves can reach PM levels as high as 10,000 $\mu g/m^3$ when cooking far surpassing the WHO suggested 24-hour mean level of 50 $\mu g/m^3$, and the number of deaths resulting from the inhalation of PM and other toxic chemicals is nearly ten times the amount of deaths seen annually from malaria related illnesses [1, 9, 10].

Children can be especially impacted when breathing in household pollution. Babies living in homes that use three stone cookstoves are exposed to smoke equivalent to smoking three to five cigarettes a day [11]. One report noted even more startling figures, stating women and children could be exposed to smoke equivalent to smoking two *packs* of cigarettes a day [9]. Resulting respiratory diseases, in one form or another, is the number one cause of death for children five years old and younger in developing parts of the world [11]. Pregnant women and their children are at elevated risks as a link was discovered between third trimester exposure to carbon monoxide from wood smoke and decreased cognitive abilities for the resulting child seen around age six [11]. Exposure to wood smoke can also lead to the development of cataracts, which is the leading cause of blindness in developing countries [12]. Burns pose as another risk as most three stone cookstove fires exhaust into the domicile instead of outside the home increasing the likelihood that people receive serious or life threatening burns. The Global Alliance for Clean Cookstoves states that a substantial percentage of the 195,000 annual deaths from burns are a result of three stone cookstoves [12].

With the inefficient heat transfer and incomplete combustion that is associated with three stone biomass cookstoves, excessive amounts of wood are needed to cook meals and heat homes. As a result, women and children spend hours a day salvaging for wood to burn, up to 28 hours a week [13]. During these long treks to collect wood, women and girls and at risk for physical or sexual harm [13]. A 2009 report from Physicians for Human Rights (PHR) stated that 90% of the rapes in Farchana, Chad occurred when women were out collecting firewood to use for cooking [14]. Women and children can also be at risk for head or spinal injuries from the laborious task of carrying firewood on their heads for long distances [12]. In addition to physical or sexual harm, the time needed to collect firewood

takes away from other beneficial activities. Girls could spend this time instead obtaining an education while woman would have more time to provide financially for their families.

The effects of inefficient and incomplete combustion in biomass stoves go far beyond just human health and social well-being. Three stone cookstoves are linked to increased deforestation and air pollution contributing to climate change. Wood burning associated with three stone cookstoves has resulted in 52% of the deforestation in Africa alone, with 34% of fuel unsustainably collected [2]. Additionally, emissions produced from three stone cookstoves account for nearly 12% of global ambient air pollution [3]. Incomplete combustion resulting in the production of black carbon from traditional cookstove use is responsible for 25% of global black carbon emissions, 84% of which are from the developing world [3]. Countries in the developing world will continue to feel the repercussions of climate change as food shortages and decreased availability of water supplies become more prominent [3].

Similar to three stone cookstoves, agricultural industries in the developing world use significant biomass resources to dry crops due to inefficient biomass drying methods. Currently, Malawi, Tanzania, and Zimbabwe produce 75% of Africa's tobacco, an industry that can be tightly linked to the deforestation and land degradation taking place in the developing world [15]. Although many Zimbabwe farmers have greatly benefitted economically from growing tobacco, deforestation has become a major issue for the country as farmers have started to burn forests to increase the land in which they grow tobacco on while cutting down additional trees to supply the fuel needed to cure the tobacco [15]. Curing tobacco requires significant amounts of biomass resources as tobacco leaves need to be kept in a hot barn for up to seven days in order to cure correctly. With deforestation rates at an all-time high, it is predicted that Zimbabwe could become a desert by 2050 as annual deforestation rates have increased from 1.5% in 1997 to over 20% in 2014 [15].

Inefficient drying practices increase the need for biomass fuel, as many of the structures used are poorly insulated with preheated air being exhausted out of a chimney, and these drying methods are responsible for nearly 12% of the deforestation in southern Africa alone [16]. In addition to the inefficiencies seen with traditional drying equipment, poor practices with tending the gasifier can lead to added hardships. In Malawi, those who work with traditional agricultural drying equipment tend to overfeed their gasifiers with wet wood in order to minimize tending and keep temperatures within the correct range for curing [16].

When wet wood is burnt, creosote, a tar like substance, is produced [17]. When there is a buildup of creosote, it can ignite [17]. This is a serious issue as 18% of all the tobacco drying barns used in Malawi will burn down each year reducing the profit of the famers by 30% [16]. Figure 2 shows a traditional tobacco barn that is used in Malawi.

Figure 2. Shown here is a traditional tobacco barn used for curing tobacco leaves in Malawi [18]. Traditional agricultural drying barns oftentimes utilize poorly insulated structures without proper recirculation of preheated air. These drawbacks result in increased deforestation as farmers cut down forests to provide biomass fuel to dry their crops. Nearly 12% of deforestation in Africa has resulted from continued use of these drying methods [16].

Clean Cookstoves and "Rocket" Technology

The development of portable and efficient cooking stoves, also known as clean cookstoves, has aimed to improve upon the problems oftentimes seen with three stone cookstoves. The GACC, founded in 2010, aims to improve and save lives, empower women, and protect the environment through the implementation of clean cookstoves [19]. There are several different types of clean cookstoves including rocket stoves, J-stove, and top lift updraft (TLUD), to name a few. The rocket stove and J-stove are characterized by the shape of their combustion chambers with the former utilizing an L-shaped chamber while the ladder has a J-shape [20]. The J-shape allows for fuel to be gravity fed, reducing the amount of tending that is needed. In contrast to the rocket and J-stove, the TLUD stove is considered a gasifier as it pyrolyzes the fuel before igniting these gases [21]. All three stoves are

designed to increase combustion efficiency while increasing the amount of heat directed to the cooking vessel through insulated chimneys [20]. State-of-the-art rocket stoves can provide about 45-55% heat transfer efficiency rates [6]. Feed designs that allow for the introduction of more primary and secondary air improve combustion efficiencies and reduce the emissions produced. Forced air can also be used to improve combustion efficiency, a concept discussed in depth in Chapter 2.

The GACC ranks clean cookstoves based on efficiency/fuel use, total emissions, indoor emissions, and safety, placing them in one of four tiers for each category, with four being the best [22]. The first three categories can be assessed using the Water Boiling Test (WBT), a standardized test used to assess stove efficiency and the emissions produced [22]. Chapter 3 experimentally examines the rocket stove, J-stove and three stone cookstove technologies through the use of WBT. Figure 3 shows a Rocket Works rocket stove during a burn and Figure 4 shows the drawing of the J-stove, designed and built by Sari Mira, which is used for later testing.

Figure 3. Rocket stoves are portable, efficient stoves designed to improve upon the traditional cookstove. The rocket stove design helps to direct the heat directly to the cooking vessel while also increasing the amount of primary and secondary air the fire receives. This helps to improve both thermal and combustion efficiency. Rocket stoves can have improved thermal efficiencies of 45-55% [6].

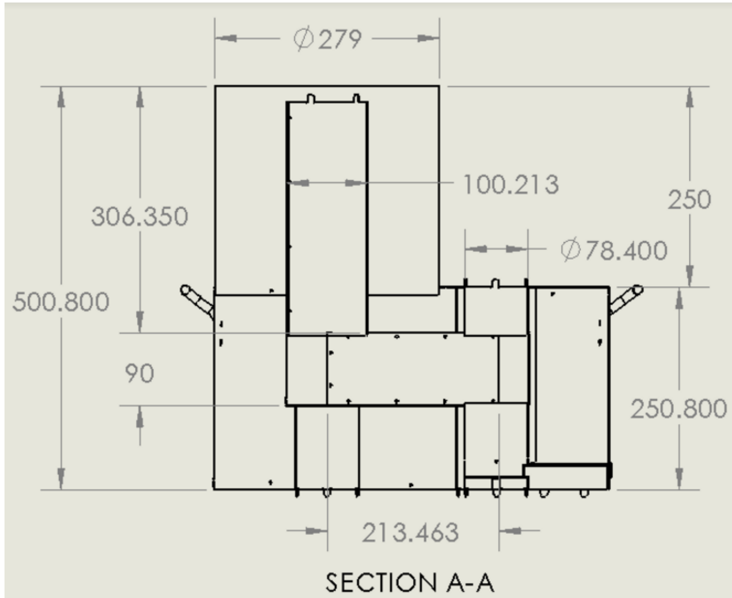

Figure 4. J-stove designed and built by Sari Mira. One benefit of this design over the L-shaped rocket stove is that the feed chamber also for gravity fed fuel which minimizes the amount of tending needed. This stove was used for WBT to track efficiencies and emissions and is discussed more fully in Chapter 3.

Just as clean cookstoves were developed in response to the various issues experienced by three stone cookstoves in the developing world, improved drying methods have become one focus of the agricultural industry to mitigate the environmental and economic damage that traditional drying methods can cause. These more sustainable methods of drying crops are known as rocket barns. Rocket barns utilize the same technologies implemented in rocket stoves in a scaled up gasifier, improving efficiencies in comparison to the current drying methods used. Zimbabwe's Tobacco Research Board (TRB) has adopted the use of rocket barns in an attempt to reduce the amount of deforestation currently taking place in the country and has sold over 10,000 rocket barns to small farmers [15].

Rocket Works, a small company located in Durban, South Africa that primarily manufactures and sells rocket stoves, was brought on to develop and test a new state-of-the-art rocket barn to cure tobacco. This barn, upon completion, would then be implemented in Malawi. By designing a barn that includes an efficient biomass gasifier, insulated structure, and ducting that helps to recirculate pre-heated air inside the barn, the Rocket Works' rocket barn was projected to significantly improve the efficiency of the barn by minimizing the amount of fuel needed to dry a batch of tobacco. Part of the rocket barn designed and built by Rocket Works is shown in Figure 5.

Figure 5. Rocket barns utilize similar technologies as that used in rocket stoves to achieve higher combustion and heating efficiencies in order to reduce the amount of biomass fuel needed to dry crops. Seen here is Rocket Works' partially completed rocket barn. This design utilizes an efficient biomass gasifier, insulated structure, and ducting to recirculate pre-heated air. The foil layer shown here will help to reduce the amount of heat lost to the environment through radiation.

Human Health, Social, and Environmental Impacts of "Rocket" Technology

Improvements to human health and the environment are largely constrained by two factors; population growth and economic development. Currently, environmental issues, specifically land degradation, are largely impacted by human population size and density along with consumption trends. By 2050 it is predicted that the world population will have grown to 9.2 billion from the current 7.4 billion [23, 24]. All of the population growth is predicted to take place in the developing world with Africa's population doubling by that time [23]. Because 50% of the world's population lives on only 3% of the world's surface, this supports the idea that deforestation is largely driven by rural development and consumption needs of the urban middle class [23]. Despite these limitation, implementation of improved biomass technologies, such as clean cookstoves and rocket barns, can significantly improve upon human health and environmental problems.

If clean cookstoves stoves were more popularly used in developing countries, those who normally use traditional cook stoves could expect fewer cases of lower respiratory infections, chronic obstructive pulmonary disease, lung cancers, heart disease, and cataracts [20]. In one study, the implementation of smoke-reducing chimneys in homes was able to

reduce the number of severe pneumonia cases in children by one-third [11]. Children's exposure to CO in their homes also was reduced by 50% when chimneys were used, although this smoke instead gets redirected outside where children can still be exposed to it [9]. Reducing the amount of smoke that women who are pregnant are exposed to can reduce negative health effects for the mother but also improve their children's future potential by reducing the risk of impairment [11]. Although chimneys can be helpful to reduce the amount of smoke being inhaled in the home, clean cookstoves may be the better alternative as they reduce the amount of emissions produced overall instead of redirecting the emissions to the atmosphere. Additionally, cookstove burns could be reduced by as much as 40% through the implementation of clean cookstoves [25].

In addition to these improved health benefits, employing cleaner technologies for cooking and heating the home can increase the number of opportunities available to women and children while reducing the risk of physical harm from collection of firewood. Included in these opportunities is continuing education for children and allowing women the time to obtain a job to help financially support the family. The far reaching implications of this alone have the potential to improve the futures of children throughout the developing world along with their communities. In 2013 an estimated 31 million primary school aged girls were not attending school, which is not only a basic human right, but also the only means necessary to achieving other development goals [26]. Girls who attain secondary education are more likely to delay marriage and have fewer, healthier children, they are more likely to support their children's education, are less likely to get HIV/AIDS, and are more likely to contribute to their local economy [26, 27]. According to UNICEF, "evidence shows that the return to a year of secondary education for girls correlates to a 25 percent increase in wages later in life" [26]. Decreasing household commitments such as collecting firewood play an important part in keeping girls in school which in turn has a ripple effect on reducing poverty and inequalities in developing countries.

Implementation of clean cookstoves in the developing world can reduce the amount of deforestation as some clean cookstoves can decrease the amount of fuel required to cook and heat the home by up to 60% [3]. In 2007 nearly 730 million tons of biomass were burned in the developing world resulting in 1 billion tons of CO_2 emitted [5]. A 60% reduction would mean saving 438 million tons of biomass and 600 million tons of CO_2 annually. Additionally, the implementation of one rocket barn has the potential to offset nearly

9,000lbs of wood in one drying season [28]. If rocket barns replaced the 10,000 current traditional drying barns being used in Malawi today, this could save an additional 45 thousand tons of biomass fuel in Malawi alone [16].

Although clean cookstove implementation has the potential to significantly reduce the amount of negative health effects and deforestation while also increasing the number of positive opportunities for women and children, there are several variables that make the switch from three stone cookstoves to clean cookstoves difficult. Some factors include lack of education, cost, inability for clean cookstoves to meet all consumer needs, the availability of fuel, and certain religious beliefs [29]. Oftentimes those who cook with three stone cookstoves may be unaware of the health risks and environmental effects associated with their stove use. Without an understanding of what is at risk, conformance to switching to a new cookstove may be difficult, especially when improved cookstoves can have high upfront costs. As observed by Martin Fisher, the founder of KickStart International – a non-profit organization that works to abate poverty through entrepreneurial ventures – poor people in developing countries barely have any money to save let alone money to purchase money-saving devices such as clean cookstoves [30]. For people living day-to-day sometimes the idea of purchasing a clean cookstove to save money in the long run is not feasible. Another barrier to clean cookstove implementation revolves around places where fuel sources, such as forests, are abundant and free resulting in reduced incentive to buy a stove that reduces the amount of fuel needed. Finally, religious beliefs associated with traditional stoves in some cultures makes it increasingly difficult to try to implement new cookstove technologies.

Three stone cookstoves continue to be used by over a quarter of the world's population despite the numerous negative health, social, and environmental problems associated with their use [11]. Rocket technology has emerged over past years with the goal of improving upon traditional cookstoves and drying equipment in order to reduce emissions and fuel needed. Even though there are several benefits to switching to rocket technology for cooking and agricultural purposes, there are still several barriers to full implementation of improved cookstoves in the developing world. Factors including lack of education on the risks of using traditional cookstoves and high upfront cost of purchasing clean cookstoves serve as deterrents to embracing this new technology [29]. Chapter 3 outlines a potential second solution to reduce the amount of fuel needed to cook that does not require distribution of clean cookstoves while Chapter 2 continues the discussion of biomass gasification,

focusing on the complexity of achieving complete combustion while highlighting the advantages of implementing well-stirred regimes and trapped vortexes with clean cookstove design to further reduce the formation of emissions.

Chapter II. Theoretical Examination of Well-Stirred Combustion and Trapped Vortexes

Currently, the best biomass stoves are only around 97% combustion efficient because they operate in a combustion regime that facilitates incomplete combustion [31]. Although 97% sounds impressive, considering that only 2,667 ppm (0.27%) of CO has been shown to kill lab rats in 15 minutes, 97% efficient is far from ideal [32]. According to a study conducted by Tsinghua University in China, they found that soot less than 2.5 microns in diameter at greater than 35 micrograms/cubic meter concentration is in part responsible for 670,000 premature deaths in China per year alone [33]. Elimination of toxic chemicals from biomass stoves and gasifiers as well as increasing the efficiency can be achieved via low temperature combustion in a well-stirred regime (WSR), mitigating indoor air pollution.

There are several challenges in trying to achieve complete combustion. In order to examine these challenges, we must first look at the three components involved in combustion: heat, fuel, and oxidizer. Only with the right combination of all three can there be complete combustion in the absence of pollutant emissions; incorrect combinations cause the formation of CO, UHC's, and/or NO_x. Figure 6 illustrates air-fuel ratios and the corresponding emissions.

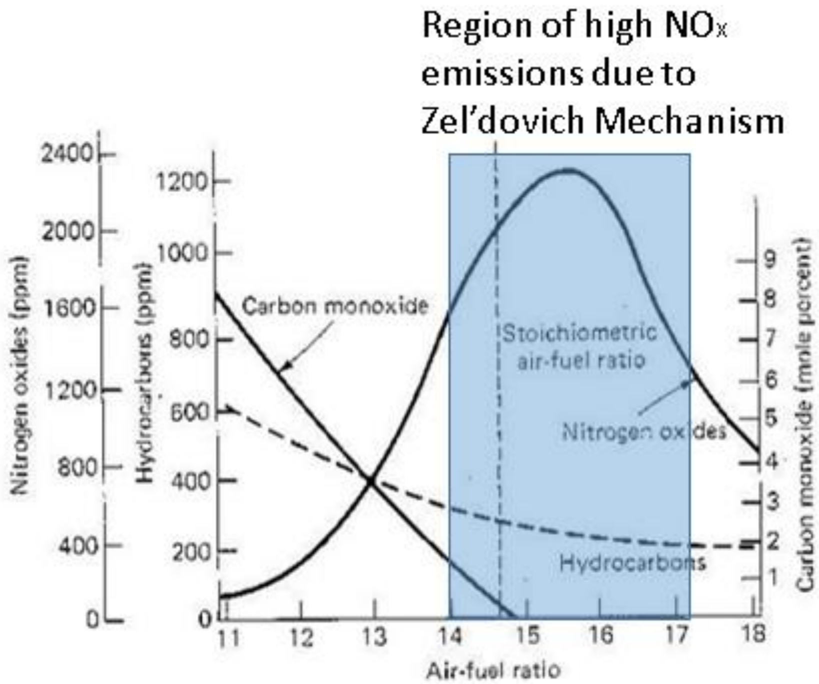

Figure 6. Air-Fuel Ratio for CO, HC, and NO_x. As air-fuel ratios determine the temperature at which combustion takes place, obtaining the correct air-fuel ratio is one factor in reducing combustion products such as NO_x which forms at high temperatures [34].

Figure 7 further relates the effect of primary-zone temperature to NO_x and CO emissions.

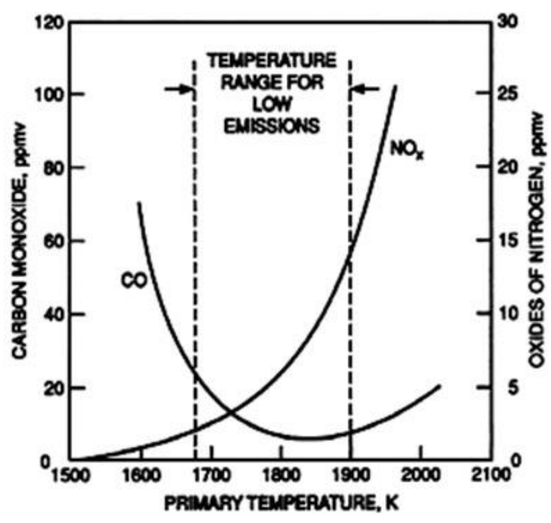

Figure 7. Effect of primary-zone temperature on NO_x and CO emissions. Temperature is a main factor that determines the amount of NO_x and CO products produced. Choosing a combustion temperature can prove challenging as CO forms with low temperature combustion while NO_x forms at high temperatures [35].

Figures 6 and 7 illustrate the difficulties in choosing the best air to fuel ratio, or equivalence ratio, along with combustion temperature to minimize the emissions of the combustion products. During combustion if the equivalence ratio is greater than 1, the combustion is considered rich and there is an excess of fuel. This results in the production of CO, UHC's, and particulate matter (PM) [36]. When temperatures are too low, the equivalence ratio is high, or if there is not enough time for complete combustion, CO and UHC are emitted [37]. One way in which to control the equivalence ratio is through upstream premixing of the fuel and oxidizer which, in turn, allows for control over combustion temperatures. In this manner, premixed combustion can be an effective way to control the production of emissions. With non-premixed combustion, the equivalence ratio cannot be controlled, reducing the ability to limit emissions [38].

Arrhenius kinetics can be used to explain the time and temperature dependency of the reactions that create CO and UHCs. As seen in Equation 1, the Arrhenius equation relates temperature and reaction rate, where k is the rate constant, A is the pre-exponential fact, E_a is the activation energy, R_u is the universal gas constant, and T is the temperature in Kelvin [39].

$$k = A * \exp(-\frac{Ea}{R_u T}) \qquad \text{Eq. (1)}$$

Taking the natural log of both sides results in the linear Equation 2, shown below.

$$\ln(k) = \ln(A) - \frac{Ea}{R_u}(\frac{1}{T}) \qquad \text{Eq. (2)}$$

Figure 8 illustrates this linear relationship between the natural log of the rate constant (k) and the inverse of the temperature.

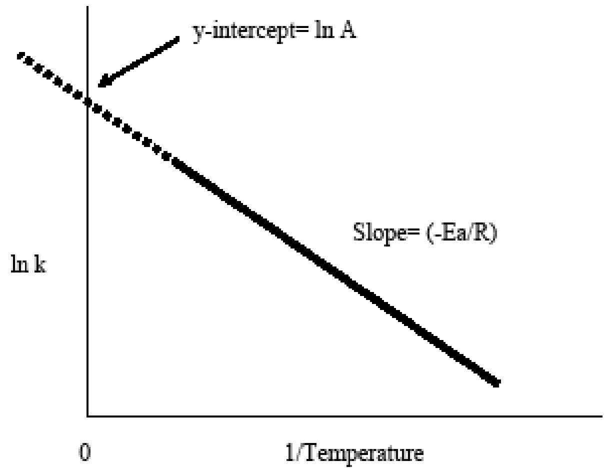

Figure 8. A linear relationship for the natural log of the rate constant (*k*) and the inverse of the temperature forms when the natural log of both sides of the Arrhenius equation is taken, thus requiring high temperatures for combustion to take place [40].

The main heat release in combustion (and the dominant route in CO oxidation) is represented by the chemical equation

$$\mathrm{CO} + \mathrm{OH} \rightarrow \mathrm{CO_2} + \mathrm{H}$$

Because this reaction forms an intermediate complex, the resulting plot is non-Arrhenius. Since the time constant for CO is temperature dependent, too low of combustion temperatures can lead to incomplete combustion.

In contrast to the formation of CO, UHC, and PM, thermal NO_x forms when combustion temperatures are too high, and the formation rate of it is heavily temperature dependent as well. The formation of thermal NO_x can be described by three equations known as the Zel'dovich mechanism [39]

$$\mathrm{O} + \mathrm{N_2} \rightarrow \mathrm{NO} + \mathrm{N}$$

$$\mathrm{N} + \mathrm{O_2} \rightarrow \mathrm{NO} + \mathrm{O}$$

$$\mathrm{N} + \mathrm{OH} \rightarrow \mathrm{NO} + \mathrm{H}$$

Figure 9 below shows the exponential relationship between temperature and NO_x formation for all fuel types.

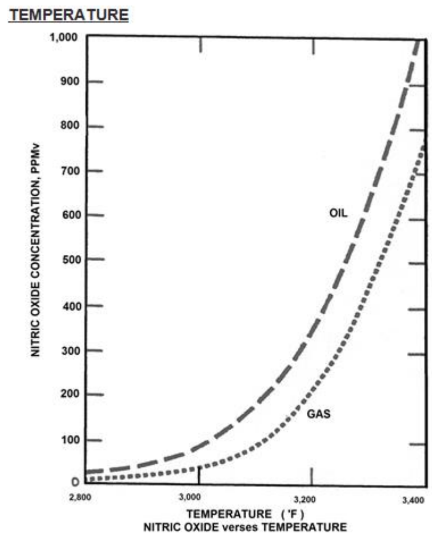

Table I Factors for NO_x Reading Corrections for a Typical (1000 Btu/cf) Natural Gas.

% Oxygen dry	% Oxygen wet	% excess air	factor
0	0	0	0.87
1	0.82	4.53	0.91
1.10	0.90	5	0.91
1.22	1	5.57	0.92
2	1.66	9.54.	0.95
2.09	1.73	10	0.96
2.41	2	11.7	0.97
2.98	2.49	15	1.00
3	2.51	15.1	1.00
3.57	3	18.6	1.03
3.80	3.20	20	1.04
4	3.38	21.4	1.06
4.54	3.85	25	1.09
4.71	4	26.2	1.10
5	4.26	28.4	1.12
5.22	5.02	30	1.13
5.83	5	34.8	1.17
5.85	5.02	35	1.17
6	5.16	36.3	1.18
6.43	5.55	40	1.22
6.92	6	44.6	1.26
7.46	6.50	50	1.30
8	7.01	55.9	1.36
8.38	7.35	60	1.39
9.04	8	68.7	1.47
9.83	8.77	80	1.57
10	8.93	82.6	1.59
11.0	9.92	100	1.74
11.1	10	102	1.75

Figure 9. The formation of NO_x for all fuel types increases exponentially with the temperature as the mechanism of formation is thermal rather than kinetic [41].

In order to minimize the formation of combustion products such as CO, UHC, and PM a stoichiometric ratio should be achieved (refer back to Figure 6) [34]. The problem with this is that at this high temperature NO_x forms at elevated rates. In order to reduce the amount of NO_x formed, the different flame regimes can be taken into account (see Figure 10) or premixing of the fuel and oxidizer can be used to reduce combustion temperatures. Similarly, well-stirred regimes help to mitigate combustion products by creating a combustion regime that facilitates complete combustion. This is achieved when flames fall into the correct regime (broken reaction zone), thus NO_x formation is reduced along with bad mixing that usually results in UHCs and PM [38].

The different flame regimes can be explained using the governing equation for species conservation for diffusion and convention where C_i is the concentration of species, D is diffusivity, $\boldsymbol{v}$ is velocity, $\nabla \cdot$ is the divergence, and ∇ is the gradient (see Eq. 3) [38].

$$\frac{\partial C_i}{\partial t} + \nabla \cdot (\boldsymbol{v} C_i) = \nabla \cdot (D \nabla C_i) + R \qquad \text{Eq. (3)}$$

The first term ($\frac{\partial C_i}{\partial t}$) is the transient term, the second ($\nabla \cdot (D \nabla C)$) is the diffusive term, the third ($\nabla \cdot (\boldsymbol{v} C)$) is the convective term, and the final term (R) is the reactive term [38]. When flames are laminar, the convective term is negligible compared to the characteristic length (l_C) (expressed in Eq. 4) which is much larger than the characteristic

diffusive (l_D), or reactive (l_R) length scales meaning convective fluid motion negligibly interacts with diffusive transport or reaction zone [38].

$$l_c = \frac{v}{s_L} \qquad \text{Eq. (4)}$$

This is represented by the laminar flame region (zone 1) in Figure 10 [38]. As the convective term becomes more dominant over the diffusive term, l_C becomes smaller and moves into the wrinkled and corrugated flamelets regions (zone 2). When l_C becomes smaller than that of the diffusive characteristic length (l_D), the flame then falls into the reaction sheet region (zone 3). Finally, when the l_C is smaller than both the diffusive characteristic length and the characteristic length of the reactive term, the flame reaches the well-stirred reactor (zone 4) which aids in creating a WSR [38].

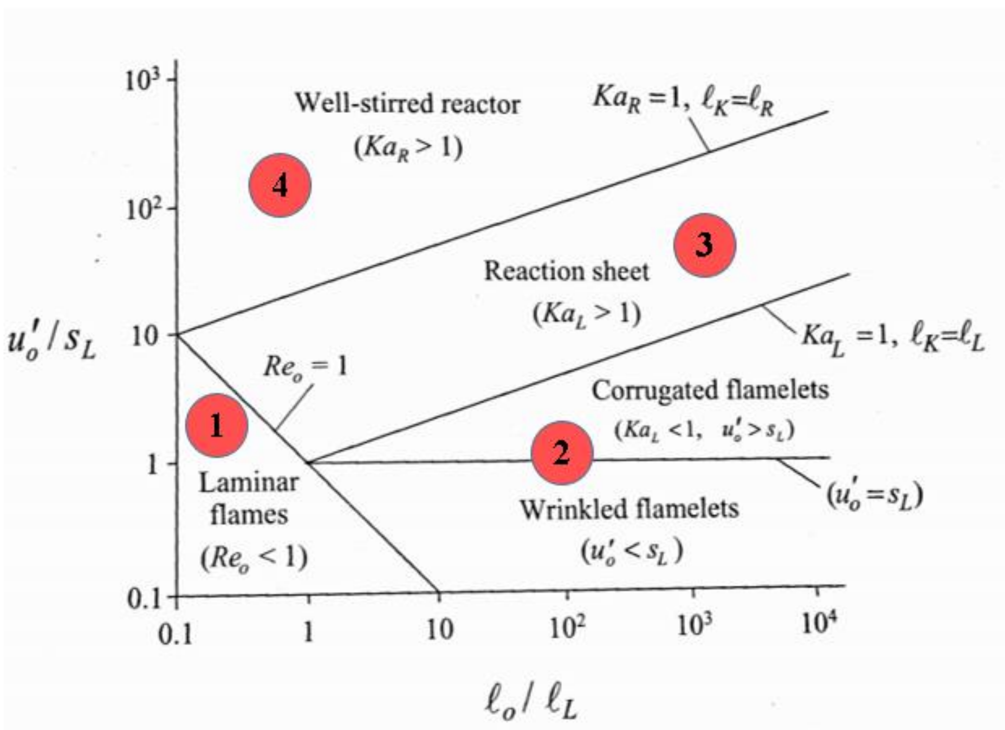

Figure 10. Flame regimes for premixed turbulent combustion. When the Kolmogorov length is smaller than that of the reactive characteristic length a well-stirred regime (WSR) is created. At this time, there is no flame structure and low temperature combustion can be induced via bulk air-fuel flows. The flame turbulence needed to create a WSR is represented by the broken reaction zone [38].

The smallest characteristic lengths are calculated using the Kolmogorov length scale which is a metric for the level of turbulence in a system, mathematically expressed in Equation 5 where ν is kinematic viscosity of the fluid and ε is the average rate of dissipation of turbulence kinetic energy per unit mass [38]. A WSR is achieved when the Kolmogorov length is smaller than that of l_R [38]. The formation of a WSR helps to mitigate the formation of combustion products.

$$l_K \approx \left(\frac{v^3}{\varepsilon}\right)^{1/4} \quad \text{Eq. (5)}$$

The wrinkled flamelet region, corrugated flamelet region, and the reaction-sheet regime flamelet region are shown in Figure 11.

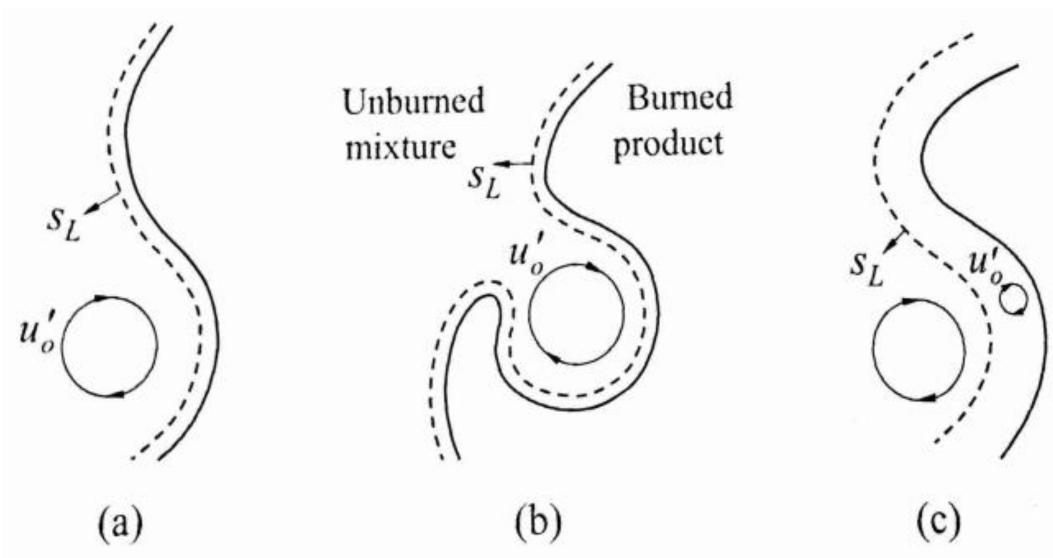

Figure 11. Three different flamelet regions represented: (a) wrinkled flamelet region due to weak flame-vortex interaction (zone 2), (b) corrugated flamelet region from strong flame-vortex interaction (zone 2), (c) reaction-sheet regime flamelet region from strong flame-vortex interaction where smaller eddies have penetrated the flame (zone 3) [38].

NO_x emissions can further be reduced by helping to facilitate a WSR through the use of trapped vortex combustors (TVC) which have been used in the gas turbine industry to facilitate WSR combustion [42]. TVC’s utilize cavities in which a vortex of reactants becomes trapped, promoting more thorough mixing of fuel and oxidizer. A trapped vortex is shown in Figure 12.

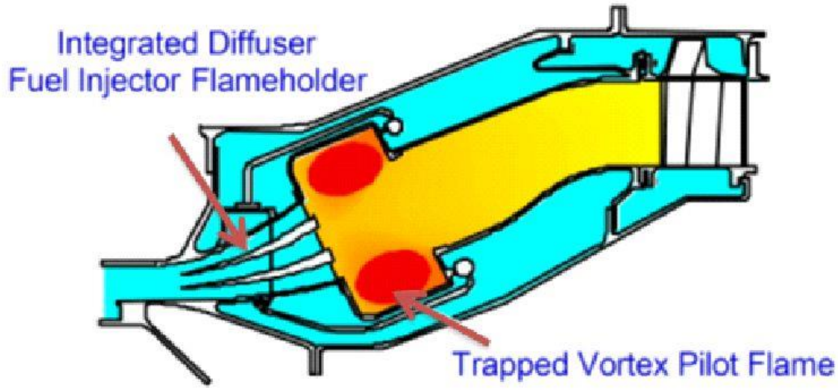

Figure 12. A trapped vortex uses cavities in order to create a vortex in which fuel and oxidizer can mix more thoroughly. This technology promotes more complete combustion and can reduce the amount of NO_x that is emitted [42].

Trapped vortex combustion in conjunction with well-stirred regimes have the potential to mitigate combustion emissions. At low temperatures, WSC can significantly reduce the amount of NO_x, CO, CO_2, and UHC formed via inducing mixing and controlling of global equivalence ratios. Currently, WSC and TVC are being examined with gas turbine engines to improve efficiencies. If this technology could also be applied to biomass cookstoves, which facilitate non-premixed combustion, combustion efficiencies could be further improved upon by eliminating the flame structure and need for premixed combustion altogether. By improving the combustion efficiency of these state-of-the-art stoves, both the amount of emissions produced and the amount of fuel needed to use the stove can be reduced, factors that can benefit both human health and the environment as discussed in Chapter 1.

Chapter III: Experimental Procedure, Results, and Discussion

In order to experimentally test a three stone cookstove, rocket stove, and J-stove for emissions and thermal efficiency, the Water Boiling Test (WBT) was completed for each of these stoves multiple times [43]. Although the test is very useful to compare results from a number of cookstoves, the GACC discusses several limitations of the WBT. Because the test is performed in a lab setting, the results offer limited insight into what actual field testing may show [43]. Additionally, the WBT helps to establish what emissions are produced by the stove, not necessarily what people are exposed to who use

the stove [43]. The Water Boiling Test version 4.2.3 from the Global Alliance of Clean Cookstoves was used as a guide to simulate the act of cooking. All testing fell into the cold-start high power phase which involves using a room temperature pot and pre-weighed fuel to bring room temperature water to boiling.

All testing was completed using a Laboratory Emission Monitoring System (LEMS) from the Aprovecho Research Center, Oregon. The LEMS includes a fume hood and specialized ducting that connects to a control box that records emissions. The LEMS system is specifically made for WBT, Controlled Cooking Tests (CCT), teaching, design, and quality control [44]. Flow is measured using a pressure transducer which outputs a signal based on the measured pressure drop across two pitot tubes inside the ducting [44]. From this measurement, flue gas velocity, volume, and mass flow rate inside the duct are calculated and recorded using the Magnescense pressure transducer [44]. Flow rate and exhaust temperatures are recorded using the Aprovecho system and software. A second pressure measurement is provided by a Magnahelic® sensor through an analogue reading.

A portion of the emissions and air are suctioned from the sample line attached to the ducting to the sensors in order to measure CO, CO_2, and PM. The CO sensor uses an electrochemical cell in which the conductivity between the two electrodes in the cell is proportional to the CO in the sample [44]. The CO_2 sensor uses non-dispersive infrared (NDIR) which outputs a voltage that corresponds to the CO_2 concentration, and the sensor uses nitrogen for a zero reference to self-calibrate [44]. PM was measured with a gravimetric system and filter for an integrated total mass reading for the WBT, and a scattering photometer with a laser light receiver to track the mass concentration of PM instantaneously throughout the WBT. The gravimetric system works by pulling a sample of the flue gas collected from the ducting through the sample line at a consistent rate of 16.7 L/min. A cyclone particle separator collects all of the PM2.5 onto the filter which can then be massed following the test to get the total mass of the PM. Figure 13 shows the gravimetric system.

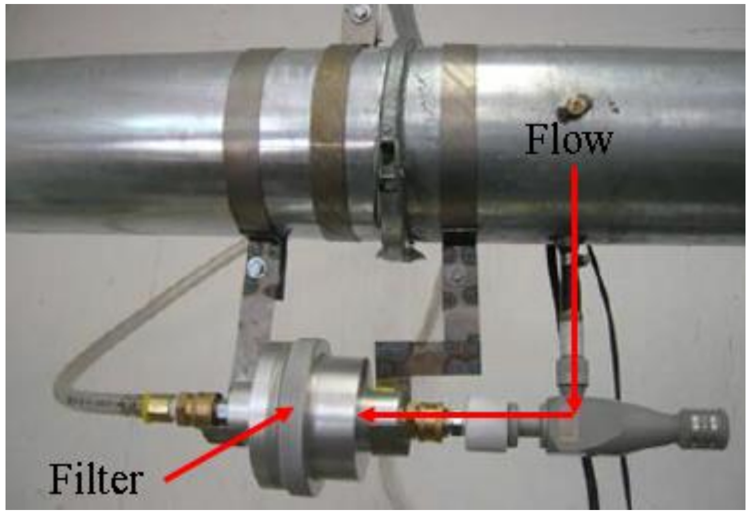

Figure 13. The gravimetric system uses a cyclone particle separator to collect PM2.5 [44]. At a rate of 16.7 L/m, all particles smaller than 1 µm may pass, 10% of 50% of 2.5 µm may pass, and only 10% of particles larger than 5 µm may pass [44].

The scattering photometer, shown in Figure 14, uses a laser and light receiver to measure the mass concentration of PM [44]. When flue gases enter the chamber, particles scatter the light into the receiver. Increased light directed to the receiver corresponds to increased PM [44]. A nephelometer is used to calibrate the scattered light and a constant is applied to estimate the mass concentration of PM [44].

Figure 14. The scattering photometer utilizes a laser and light receiver to measure the mass concentration of PM by scattering light off of the particles and into the receiver. Increased light that is directed to the receiver corresponds to increased PM [44].

The velocity of the flue gases were measured using a Fluke 922 Pitot Tube Airflow Meter with an accuracy of ±2.5% of reading at 10 m/s. With the pitot tubes connected to measure dynamic pressure, the device approximates the velocity of the flue gases using standard ambient conditions.

Experimental Procedure

Testing was broken down into three phases: Phase I – Data collection prior to testing, Phase II – Testing, Phase III – Data collection following testing. All manual data collection was recorded in the WBT Processing Worksheet found in Appendix B. Kindling and paper were used, as necessary, to assist with starting the fire. Additionally, in order to vary the firepower, a measure of how fast the fuel is burning, from test to test, the amount of fuel that was added per batch and the tending practices were altered between tests. All testing was completed with Sari Mira.

Phase I – Data collection prior to testing

Prior to testing, the following mass measurements were collected using the Uline H-1650 scale, accurate up to 0.45 g: first batch of fuel, kindling and paper to start fire, empty stainless steel pot, and pot with five liters of room temperature water. Using the Citizen Instruments CX 265 scale with a resolution of 0.01 mg and linearity of 0.04 mg, 10 measurements of the clean filter were recorded at intervals of ten seconds. These were then averaged together to get the average mass of the filter before testing. The filter was then placed in the cyclone particle separator. The temperature of the ambient air and water inside the pot were recorded using a type K thermocouple. The thermocouple was then placed into the pot of water with the lid placed on top, ensuring that the thermocouple was submerged in the water without touching the sides or bottom of the pot. Finally, before starting testing, the local boiling point was established using Equation 4, where “h” is the altitude in meters [43].

$$T_b = (100 - \frac{h}{300})°C \qquad \text{Eq. (4)}$$

Phase II – Testing

The standard procedure included turning the LEMS on five minutes prior to testing in order for the system to circulate ambient air for calibration. After five minutes, data collection began using the LEMS software, and the cyclone particle separator was then turned on. The pre-massed kindling and paper were added to the stove, the paper

was lit on fire, and the time was recorded. The pre-massed fuel was then hovered over the flame until the fuel caught on fire and the time was recorded. Additional batches of pre-massed fuel were added to the fire as the temperature of the water stabilized, making sure to catch each piece of fuel on fire as to not quench the flame. The time and temperature of the water were recorded at this time. The three sections below describe the varying setups and procedures for the three stone cookstove, rocket stove, and J-stove.

Three Stone Cookstove

To set up the three stone cookstove, six bricks were used. Three formed a triangle on the bottom with holes facing outward to allow for airflow. Another three bricks were laid perpendicular to the ones on the bottom, evenly spaced so that the pot was stable while minimizing contact with the bottom of the pot. The pre-massed kindling and paper were added inside the bottom triangle of bricks while the pre-massed fuel was balanced on top of the bottom bricks over the fire with the fuel being added on all three open sides of the top bricks. The standard procedure was followed. A three stone cookstove WBT is shown in Figure 15.

Figure 15. WBT using a three stone cookstove and LEMS.

Rocket Stove Setup

Using a Rocket Works rocket stove, a pot was placed on top of the chimney [45]. Pre-massed kindling and paper were added to the feed chamber, and the standard procedure was followed. A WBT using a rocket stove is shown in Figure 16.

Figure 16. WBT using a Rocket Works rocket stove and LEMS [45].

J-stove Setup

Before the pot was placed on top of the stove, pre-massed kindling and paper were added to the combustion chamber, lit on fire, and the time was recorded. The fuel was hovered over the flame inside the combustion chamber until it ignited and was then moved into the chimney. By heating up the air inside the chimney, a pressure drop is induced creating a draft that pulls the flame towards the chimney. Once a draft was established, the remaining fuel was added to the combustion chamber ensuring that each piece caught on fire to make sure that the flame was not quenched. Once all the fuel was added, the time was recorded and the pot of water was placed on top of the chimney. The standard procedure was then followed. A WBT using a J-stove is shown in Figure 17.

Figure 17. WBT using a J-Stove and LEMS.

Flue Gas Velocity Measurements

An additional step was added for the various stove setups in order to measure the velocity of the flue gases for later use in creating a convective heat transfer model. With the device set up to measure velocity, readings were recorded at three minute intervals, noting the time and temperature of the water at each interval in the worksheet in Appendix B. The velocity measurements were helpful in understanding the turbulence intensity for each cookstove. Because the stoves were only utilizing natural convection, all three stoves have low turbulent intensities. An example setup using the Fluke 922 Airflow Meter is shown in Figure 18.

Figure 18. To measure the velocity of the flue gases inside the chimney of the J-stove, the Fluke 922 should be inserted into the middle of the chimney before adding the pot of water. Readings should be taken at three minute intervals, recording the velocity, water temperature, and time in the WBT Worksheet in Appendix B.

Phase III – Data collection following testing

Once the water reached boiling and the time was recorded to signify the end of the test, the remaining fuel was immediately quenched in either a bucket of ash or sand. The mass of the pot and water was quickly massed without the lid, and the stove and remaining charcoal were massed as well. The remaining fuel was massed and recorded. Carefully removing the PM filter from the cyclone with forceps, 10 readings were recorded every 10 seconds and average. Future testing should include using a desiccator to remove moisture from the filter for at least 24 hours before massing the filter. This signified the end of all data collection and the WBT Processing Worksheet provided by Aprovecho, in Appendix C, was then filled out in full [46].

Results

Results from testing have shown an inverse relationship between firepower and thermal efficiency, regardless of the cookstove. This relationship, holding true for all three cookstoves, can partly be explained because the performance of all of the cookstoves is dictated by the flame regime in which each stove falls over. This dominates

over other features such as cookstove geometry. By increasing this flame turbulence, cookstoves can achieve higher thermal and combustion efficiencies. The guiding equations to calculate firepower and thermal efficiency are shown in Appendix D [43]. Figure 19 shows the results from testing of all three stoves using the WBT and LEMS.

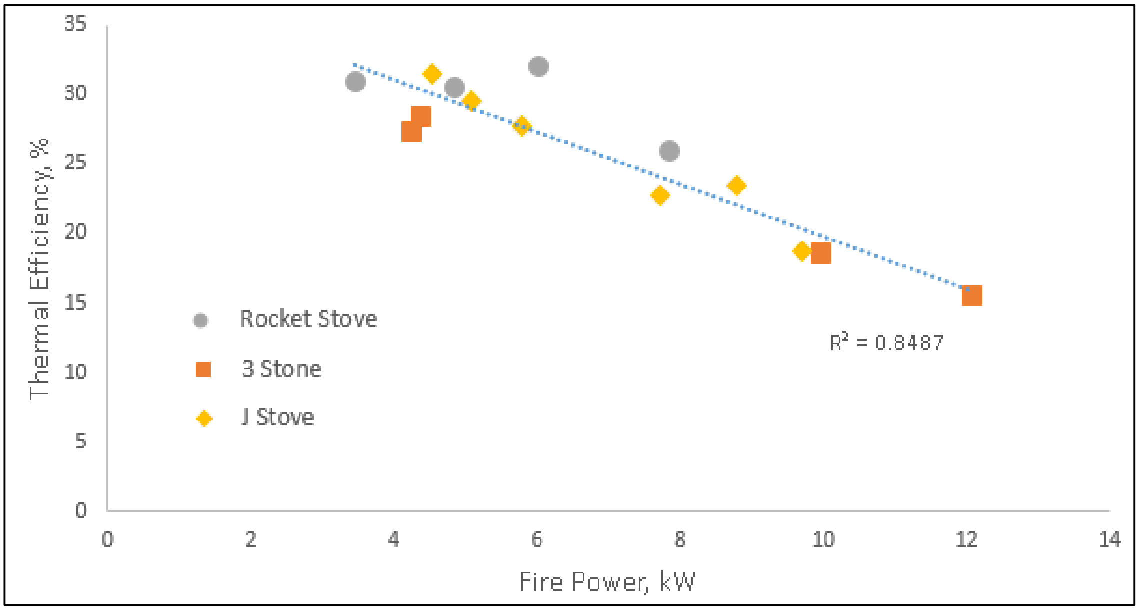

Figure 19. Testing revealed an inverse relationship between firepower and thermal efficiency, regardless of cookstove. These results show how the flame regime in which all three cookstove falls dominates over other features that may affect thermal efficiency such as cookstove geometry. By increasing flame turbulence biomass cookstoves can achieve higher thermal and combustion efficiencies.

To explain the inverse relationship between firepower and thermal efficiency the hypothesis that as firepower increases, the amount of heat that gets transferred to the cooking vessel decreases, thus decreasing the thermal efficiency was made. In order to test this hypothesis, velocity measurements below the cooking vessel were recorded in order to create a convective heat gain model. The equations used to determine the convective heat gain are shown in Appendix E [47]. To date, only three tests tracked the velocity of the flue gases resulting in very preliminary results, shown in Figure 20.

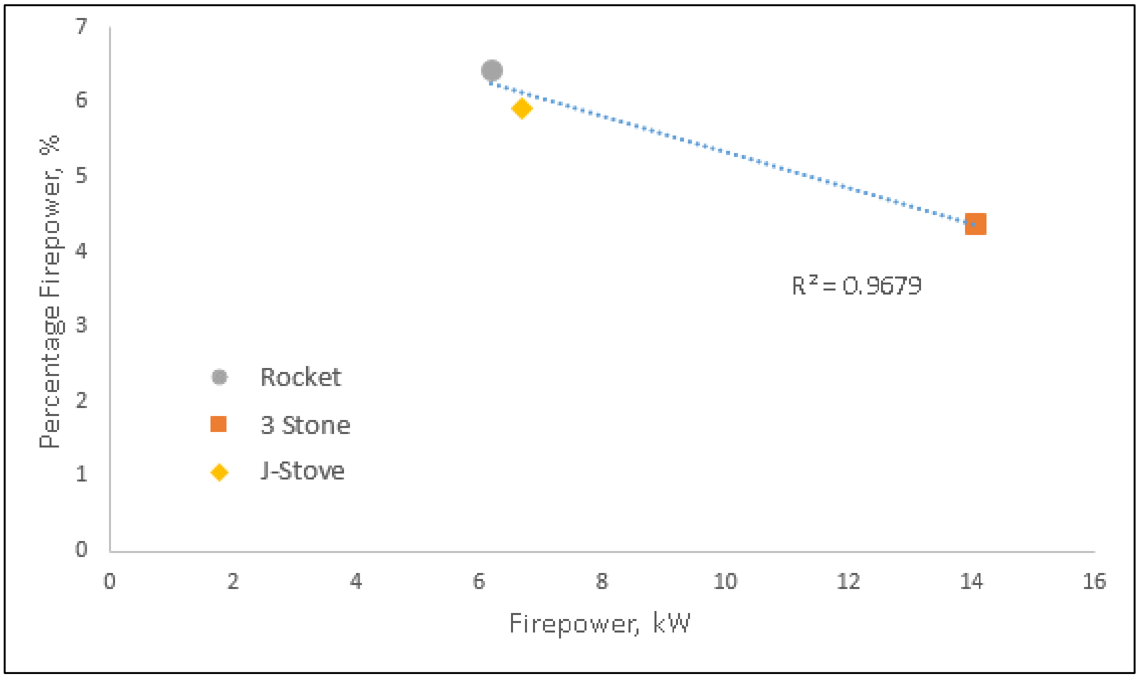

Figure 20. Initial results suggest that the percentage of average convective heat gain versus the firepower display an inverse relationship, supporting the hypothesis that increasing the firepower results in increased heat loss to the surrounding environment. Further testing must be completed to confirm these results.

Discussion

The results showed that cookstove thermal efficiency was dependent on the firepower of the test, not the cookstove. This inverse correlation is important for several reasons. Most literature today focuses on how three stone cookstoves are less thermally efficient than clean cookstoves, disregarding the importance of tending practices. As 2-3 billion people will continue to use biomass cookstoves for years to come, improving tending practices may be a simpler way to address the issues, namely deforestation and excess amount of time spent collecting firewood, that surround three stone cookstoves in contrast to supplying improved stoves to every home.

A better understanding of this relationship between firepower and thermal efficiency can also aid in improved cookstove designs. Reducing the size of feed chambers in cookstoves reduces the amount of fuel that can be added at one time which, in turn, results in lower firepower and higher thermal efficiency. For example, the rocket

stove that was used for testing was able to achieve a maximum firepower of 7.86 kW so far because the feed chamber limited the amount of fuel that could be added at a time. Implementation of similar designs could further help to improve efficiencies and reduce the amount of deforestation and time spent collecting firewood in the future.

Recommendations

Going forward there are several recommendations for future testing. The relationship between firepower and thermal efficiency should continue to be investigated. If this correlation continues to show consistent results, there could be a switch to a new focus on increasing thermal efficiency and reducing biomass fuel use through improved tending practices. Further testing should also include flue gas velocity measurements in order to build a more complete convective heat transfer model to help explain why increasing firepower results in decreased thermal efficiency. Upon calibration of the CO and CO_2 sensors in the lab, WBT results should include comparisons between firepower and total emissions. In addition to CO and CO_2, PM should also be factored into the comparison once the moisture is removed from the filters to improve the PM mass accuracy.

While the current testing focused on firepower and thermal efficiency, future testing should include experimentally proving the well-stirred combustion hypothesis that increasing flame turbulence results in increased combustion efficiency and decreased emissions. In this manner, the results from cookstove testing would touch on both reducing toxic emissions and reducing the amount of fuel needed for biomass stove users through practices that can be implemented with all biomass cookstoves.

Chapter IV. Conclusions

As over a quarter of the world’s population will continue to rely on biomass fuels to cook for decades to come, new ideas surrounding the way in which food is prepared must be examined. Current biomass cookstove practices that are used in developing countries result in incomplete combustion, releasing toxic chemicals such as CO, NO_x, and soot into homes, elevating the risk for disease and death from inhalation. Three stone cookstoves and the low thermal efficiencies associated with them require users to burn mass amounts of fuel to cook resulting in increased deforestation and time spent collecting firewood for women and children.

As organizations such as the Global Alliance for Clean Cookstoves continue to push for implementation of clean cookstoves in the developing world to improve upon traditional cookstoves, results found from testing could point to an easier alternative. The establishment of an inverse relationship between firepower and thermal efficiency, regardless of the cookstove, opens up a new route to reduce biomass fuel consumption in which tending practices become the main focus over cookstove type. This result could aid in future cookstove designs that limit the amount fuel that can be added at one time, reducing firepower and increasing thermal efficiency. Better tending of cookstove fires may be a simpler solution to dealing with many issues typically associated with three stone cookstoves.

Although rocket stove and J-stove designs have limited the user to the amount of fuel that can be burnt at one time ensuring better biomass thermal efficiency, it appears that these stoves are not able to improve upon their combustion regime. Future research can transcend non-premixed combustion into well-stirred or pre-mixed combustion which would lower the temperature of the reaction and improve combustion efficiency, thus reducing emissions and the amount of fuel needed to cook. Well-stirred or pre-mixed combustion in conjunction with better tending practices have the potential to improve human health, reduce deforestation, and improve upon social issues associated with firewood collection. Though the use of biomass cookstoves for years to come may be certain, new cookstove research, as revealed in this thesis, will continue to bring new hope for a healthier and more sustainable tomorrow.

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Appendix A. Rocket Barn Results

The following work details some of the testing that was completed during the summer of 2016 at Rocket Works.

During the process of building the rocket barn, various tests were run to help verify the barn design. The theoretical fuel to dried tobacco ratio was calculated in order to compare the Rocket Works' rocket barn to traditional drying equipment seen in Malawi. Using 334.4 kg as the theoretical amount of tobacco cured in one batch and assuming an 8 kg/hour feed rate, the fuel to dried tobacco ratio calculated was 4.1:1. This is a significant improvement from the 7:1 ratios often times seen in Malawi and on the low end of fuel to dried tobacco ratios seen in rocket barns currently implemented in the field [H]. Additionally, temperature measurements were taken during a gasifier burn test to monitor the temperatures produced in different parts of the gasifier structure. Temperatures were collected from four zones: the secondary air inlet, the air to the barn, diffuser air, and temperatures achieved inside the chimney as illustrate in Figure 21.

Figure 21. Temperatures collected from four zones: secondary air inlet, air to barn, diffuser air, and chimney (right to left) helped to verify the Rocket Works' gasifier design.

Figure 22 below illustrates the temperatures achieved during this burn test in comparison to the temperature needed to cure tobacco.

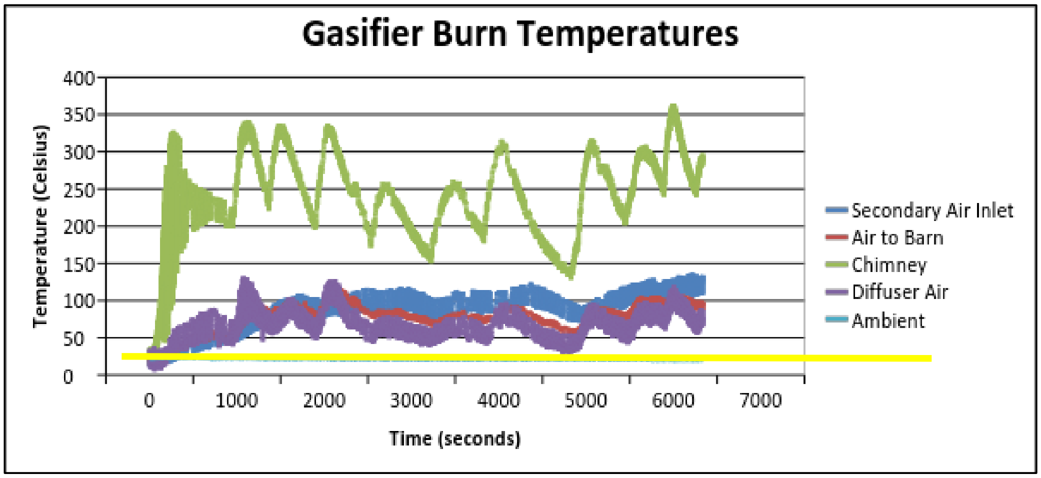

Figure 22. Maximum temperatures were achieved from the gasifier when fuel was added or the fire was stoked. The graph illustrates the need for a better feed system emphasizing smaller batch loads fed more frequently in order to reduce temperature variance. The maximum temperatures were seen in the chimney reaching just over 350˚C at its peak proving that the gasifier design would be sufficient in providing proper temperatures inside the barn. The temperature needed to cure tobacco is 70˚ C as shown with the yellow line.

The gasifier produced a significant amount of heat purely from biomass. Maximum temperatures were achieved within the various zones of the gasifier structure when fuel was added or whenever the fire was stoked. Additionally maximum temperatures were seen inside the chimney with max temperatures reaching just over 350˚C. The average temperatures achieved inside the diffuser were between 70˚C and 75˚C, right inside the temperature range needed to cure tobacco. Both the theoretical to dried tobacco ratio and the temperature readings collected helped in verifying that Rocket Works' gasifier design was capable of reducing the amount of fuel needed while still providing enough heat to the barn. The temperature graph also helped point out improvements that could be made with the feed system. The peaks and valleys in the readings were a result of adding large batches of fuel over longer time intervals. By implementing a feed system that provides small batch fed loads to the gasifier at shorter time intervals, temperature variance can be reduced.

Appendix B: WBT Worksheet

Created by Erin Peiffer and Sari Mira

STAGE 1	**Initial Readings**			
Pot without water				
Pot + Water		g		
Filter Readings Before				
1		g		
2		g		
3		g		
4		g		
5		g		
6		g		
7		g		
8		g		
9		g		
10		g		
AVG.		g		
Empty Stove		g		
Wood 1		g		
Kindling		g		
Paper		g		
Air Temp		C		
Water Temp Start		C		

STAGE 2	**Testing**			
	Time (sec)	Fuel (g)	Temp (C)	
Cyclone On				
Fire Started				
Additional Kindling				Lighting Time
Additional Paper				
Fire Lit				
Wood 2				
Pot on (J-stove only)				
Wood 3				
End Test				Test Time
STAGE 3	**Final Readings**			
Pot + Water		g		
Stove + Charcoal		g	Total Fuel Added	
Wood Remaining		g		g
Filter Readings			Net Fuel	
1		g		g
2		g		
3		g		
4		g		

5		g		
6		g		
7		g		
8		g		
9		g		
10		g		
AVG.		g		
PM Total				

Appendix C: WBT Processing Worksheet

(Worksheet can be found at http://aprovecho.org/software/ [46]).

HELL FOUNDATION HEH PROJECT WATER BOILING TEST

DATA AND CALCULATION FORM (the form can be used with stoves that cook between one and four pots)*

Shaded cells require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	
Test Number	
Date	
Stove type/model	
Location (Hood)	
Fuel species	
Cold/hot	

*Note, if you are testing a multi-pot stove, the data entry places in the simmering test for pots other than the primary pot are left blank intentionally because the simmering test can not account for pots other than the primary pot.

Magnahelic

Full Flow:	
K	2.16E-05
m3/M	0

Initial Test Conditions

Data	value	units	label	Data	value	l
Air temp		°C		Dry weight of Pot # 1 (grams)		P1
Average dimensions of fuel		cm x cm x cm		Dry weight of Pot # 2 (grams)		P2
Gross calorific value (dry fuel)	20,634	kJ/kg	HHV	Dry weight of Pot # 3 (grams)		P3
Net calorific value (dry fuel)	19,314	kJ/kg	LHV	Dry weight of Pot # 4 (grams)		P4
Wood moisture content (% - wet basis)		%	MC	Weight of stove (grams)		k
in the fuel)	17,279	kJ/kg	EHV	Local boiling point		T_b
Net calorific value charcoal (dry fuel)	29,400		LHV			
Fuel type (enter "W","K","G",or "C")	W	W = wood, K = kerosene, G = LPG, C = coal and charcoal				

Miscellaneous parameters:

Temperature of air, end cold start		Wood batch	
Temperature of air, end simmer		Fuel type	
Kindling type		Weight of empty stove (final)	
Firestarter type		Light Time	
Initial mass of cold start firestarter			
Initial mass of cold start kindling			
Pot letter			
Air pressure			
Mass of ash after cold start (enter 0 if not separate			
Mass of ash after simmer (enter 0 if not separated)			

Gravimetric

Enter filter info for each phase

Or enter total filter info if only 1 filter was used for the entire test

	cold start	hot start	simmer	total	
Filter Number					
Tare Filter Mass				0.000	g
Gross Filter Mass				0.00000	g
Net PM Mass					g
Average PM concentra					ug/m3

BASIC TEST DATA

		HIGH POWER TEST (COLD START)			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time	hh:mm:ss		t_{ci}		t_{cf}
Weight of fuel	g		f_{ci}		f_{cf}
Water temperature, Pot # 1	°C		$T1_{ci}$		$T1_{cf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g		$P1_{ci}$		$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+stove	g				c_c

		COLD START		HOT START	
Calculations/Results	Units	data	label	data	label
Fuel consumed (moist)	g	-	f_{cm}	-	f_{hm}
Net change in char during test	g	-	Dc_c	-	Dc_h
Equivalent dry wood consumec	g	-	f_{cd}	-	f_{hd}
Water vaporized from all pots	g	-	w_{cv}	-	w_{hv}
Effective mass of water boiled	g	#DIV/0!	w_{cr}	#DIV/0!	w_{hr}
Time to boil Pot # 1	min	-	Δt_c	-	Dt_h
Thermal efficiency	--	0.0%	h_c	-	h_h
Burning rate	g/min	-	r_{cb}	-	r_{hb}
Specific fuel consumption	g/liter	#DIV/0!	SC_c	#DIV/0!	SC_h
Temp-corr sp consumption	g/liter	#DIV/0!	c	#DIV/0!	SC^T_h
Temp-corr sp energy consump	kJ/liter	#DIV/0!	c	#DIV/0!	SE^T_H
Firepower	watts	-	FP_c	-	FP_h

HOT START, COLD START, AND SIMMER TESTS

Appendix D: Firepower and Thermal Efficiency Calculations

(Equations based off of WBT 4.3.2 [43])

$$Firepower = \frac{f_{cd} LHV}{\Delta T_c 60}$$

ΔT_c = time to boil

F_{cd} = dried fuel consumed

$$F_{cd} = dry\ fuel - fuel\ to\ evaporate\ H_2O - fuel\ in\ char$$

$$dry\ fuel = f_{cm}(1 - MC)$$

F_{cm} = fuel consumed moist

MC = moisture content

$$fuel\ to\ evaporate\ H_2O = \frac{\Delta E_{H2O,c}}{LHV}$$

LHV = net calorific value

$$\Delta E_{H2O,c} = f_{cm} MC (C_p (T_b - T_a) + \Delta h_{H2O,fg})$$

C_p = 4.186 kJ/kgK

T_b = local boiling point

T_a= ambient temperature

$\Delta h_{H2O,fg}$ = specific enthalpy of vaporization = 2,260 kJ/kg

$$fuel\ in\ char = \frac{\Delta E_{char,c}}{LHV}$$

$$\Delta E_{char,c} = \Delta C_c + LHV_{char}$$

ΔC_c = net change in char

$$f_{cd} = \frac{f_{cm}(lHV(1 - MC) - MC(4.186(T_b - T_a) + 2260) -= \Delta C_c + LHV_{char}}{LHV}$$

$$\boldsymbol{Firepower} = \frac{\boldsymbol{f_{cm}(lHV(1-MC)-MC(4.186(T_b-T_a)+2260)-=\Delta C_c+LHV_{char}}}{\boldsymbol{\Delta T_c 60}}$$

$$Thermal\ Efficiency = \frac{\Delta E_{H2O,heat}+\Delta E_{H2O,evap}}{E_{released,c}}$$

$$\Delta E_{H2O,heat} = m_{H2O} C_p \Delta T$$

C_p = 4.186 kJ/kgK

$$m_{H2O} = P1_{ci} - P1$$

$P1_{ci}$ = mass of pot and water before test

P1 = mass of empty pot

$$E_{H2O,evap} = w_{cv} \Delta h_{H2O,fg}$$

w_{cv} = mass of water vaporized

$\Delta h_{H2O,fg}$ = specific enthalpy of vaporization for water = 2,260 kJ/kg

$$E_{released,c} = f_{cd} LHV$$

$$\boldsymbol{Thermal\ Efficiency} = \frac{\boldsymbol{4.186\left(T1_{cf}-T1_{ci}\right)(P1_{ci}-P1)+2260w_{cv}}}{\boldsymbol{f_{cd}LHV}}$$

Appendix E: Convective Heat Gain Equations

(Equations based off of “Heat Transfer Efficiency of Biomass Cookstoves” [47])

For air @ 850K

ρ = 0.4097 kg/m^3

V = velocity m/s

L_D = characteristic length (Diameter of Rocket Stove and J-Stove Chimney = 0.1m, 3 Stone Cookstove = 0.16m)

μ = 384.3e-7 Ns/m^2

Pr =0.716

K_{fluid} = 59.6e-3 W/mK

A = surface area of bottom of pot (0.07065m^2)

dT = temperature of gases – temperature of water in pot

Solve for Reynold’s Number

$$Re = \frac{\rho V L_D}{\mu}$$

Stagnation Point Nusselt Number

$$Nu = 0.565 sqrt\big((\mathrm{Pr})(Re)\big)$$

Solve for h

$$Nu = \frac{hL_D}{K_{fluid}}$$

Solve for Q_{conv_gain}

$$Q_{conv\_gain} = hAdT$$

Appendix F: Graphs from WBT

The following graphs are results from the various WBT completed.

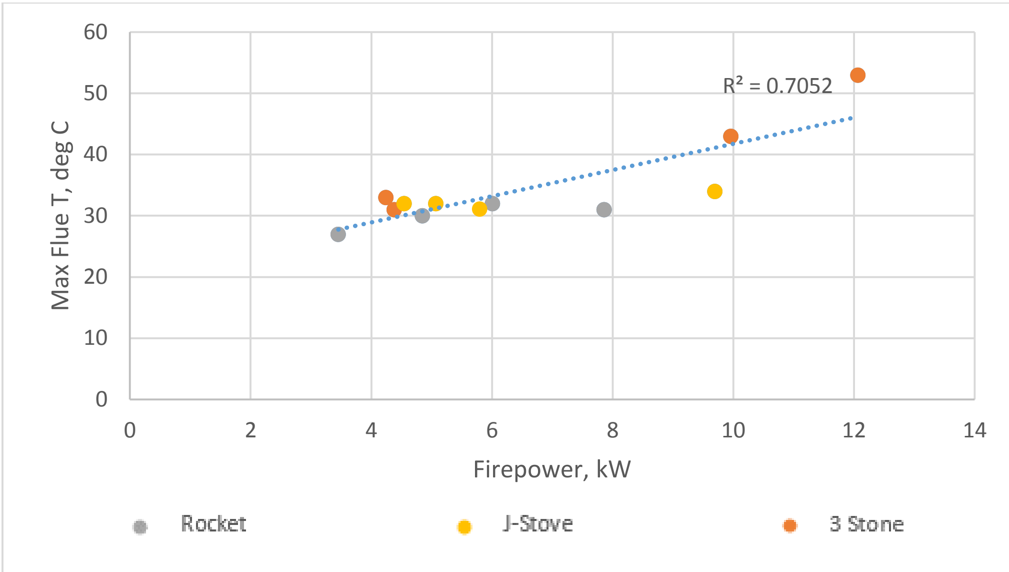

Figure 23. Positive correlation between firepower and max flue temperature, as expected.

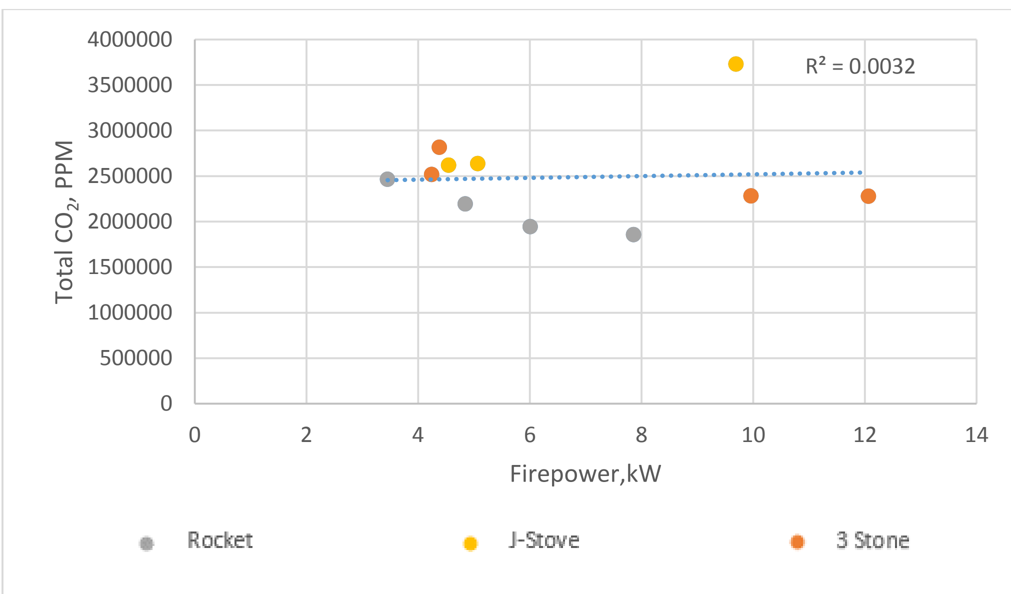

Figure 24. Very weak correlation between firepower and total CO_2 (sensor not calibrated. Graph just shows general trends in testing).

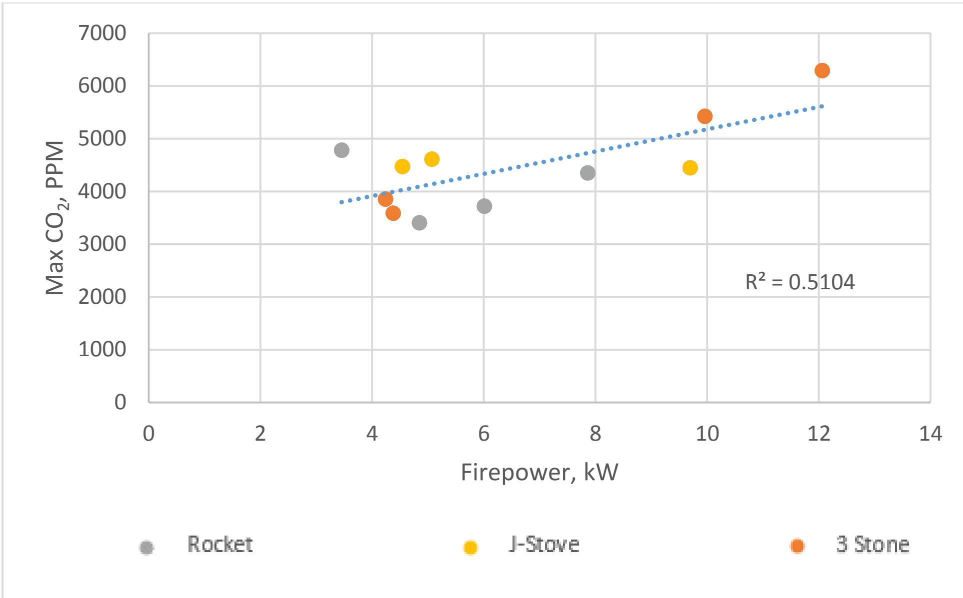

Figure 25. Positive correlation between firepower and max CO_2 (sensor not calibrated. Graph just shows general trends in testing).

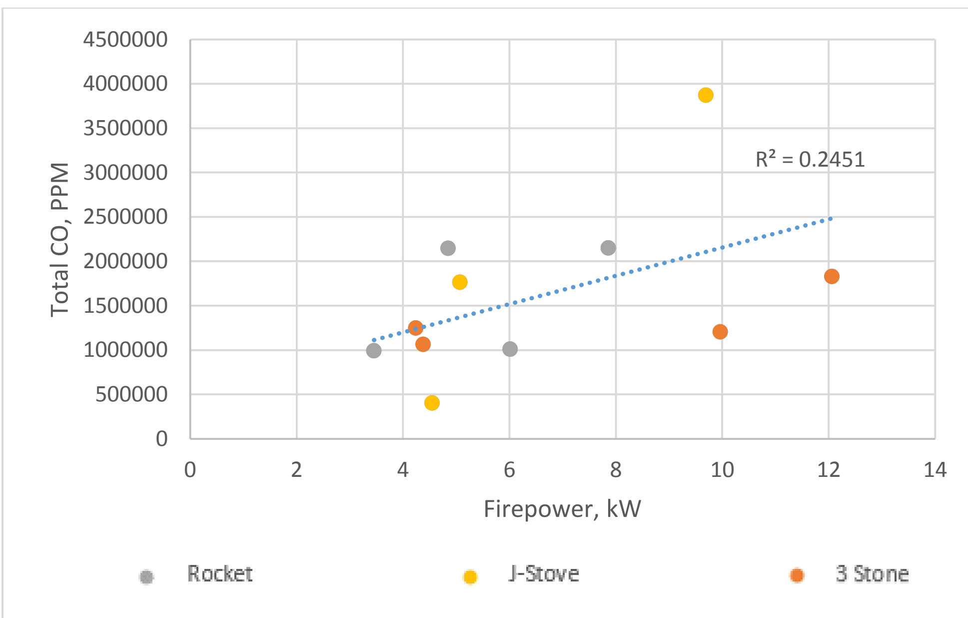

Figure 26. Weak positive correlation between firepower and total CO (sensor not calibrated. Graph just shows general trends in testing).

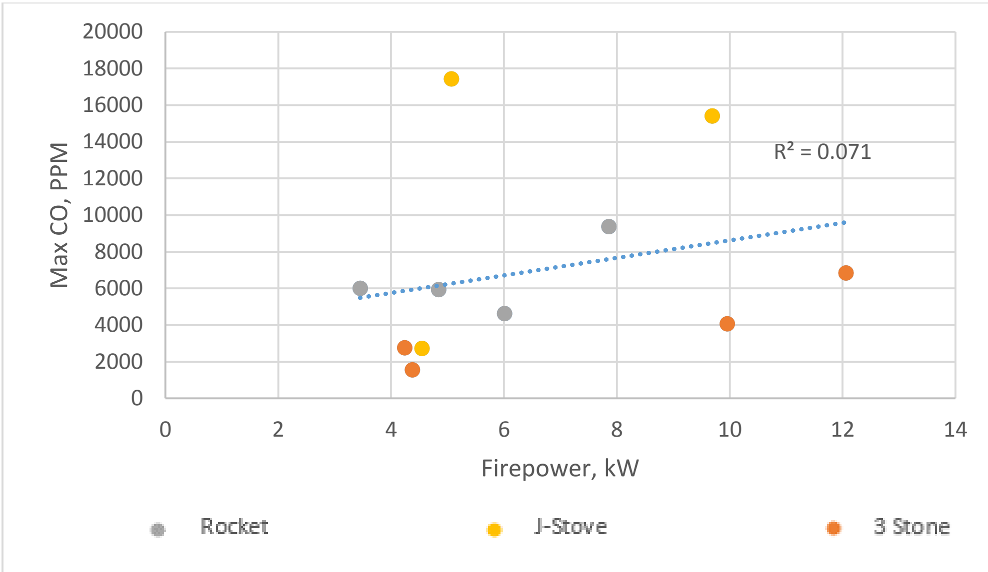

Figure 27. Very weak correlation between firepower and max CO (sensor not calibrated. Graph just shows general trends in testing).

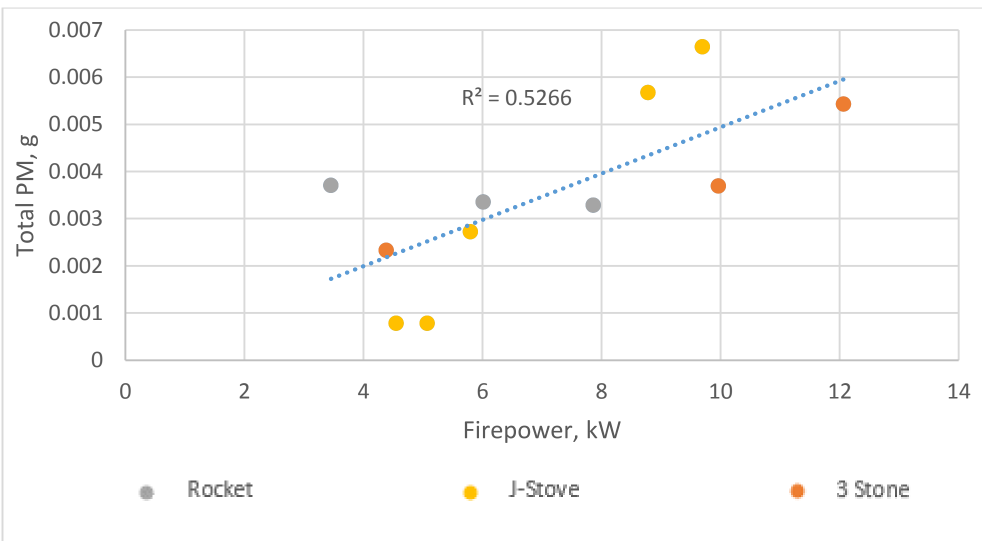

Figure 28. Positive correlation between firepower and total PM (including moisture mass on filter).

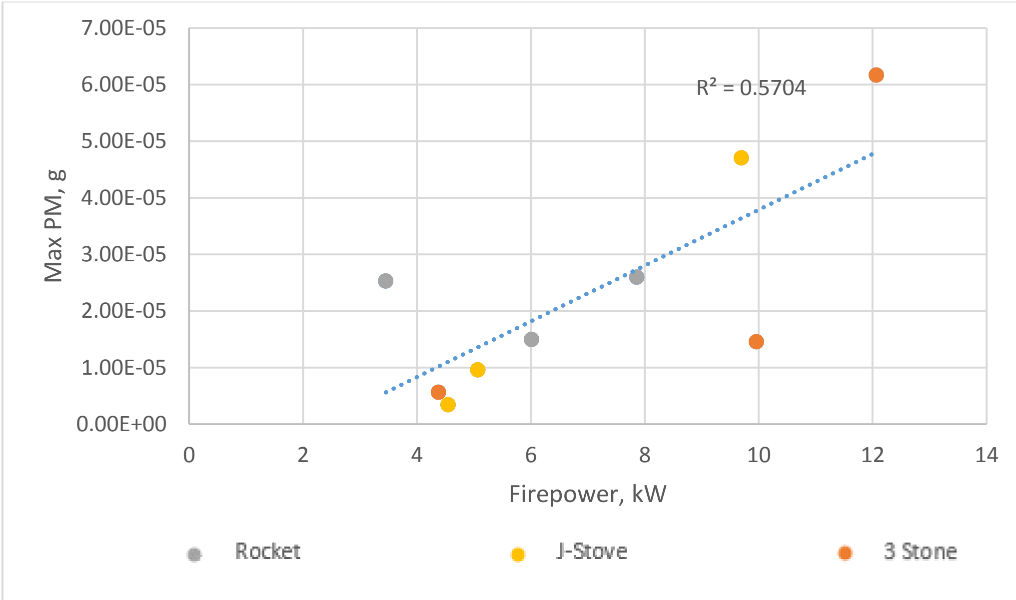

Figure 29. Positive correlation between firepower and max PM (normalized from PM filter including moisture mass).

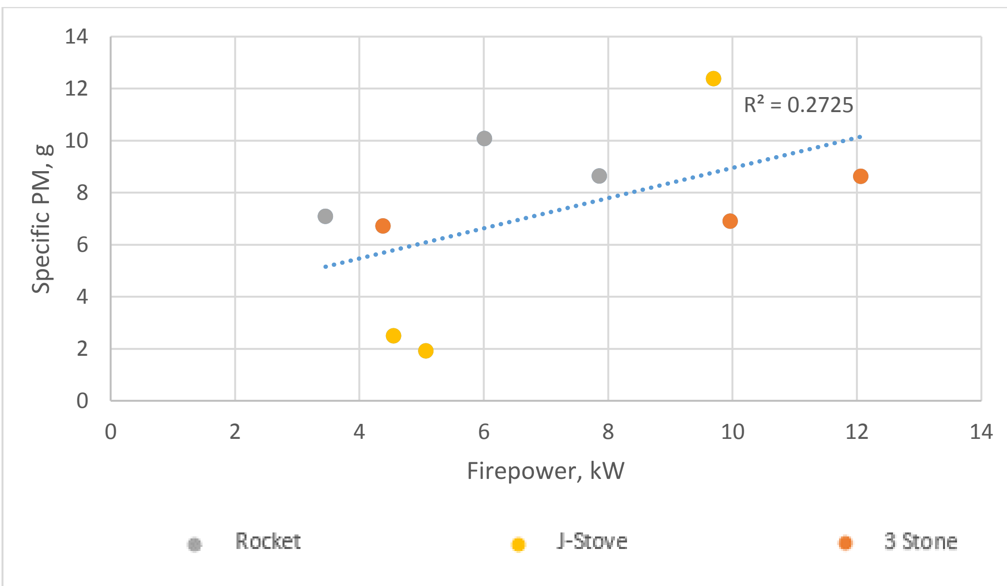

Figure 30. Weak correlation between firepower and specific PM (including moisture mass from filter).

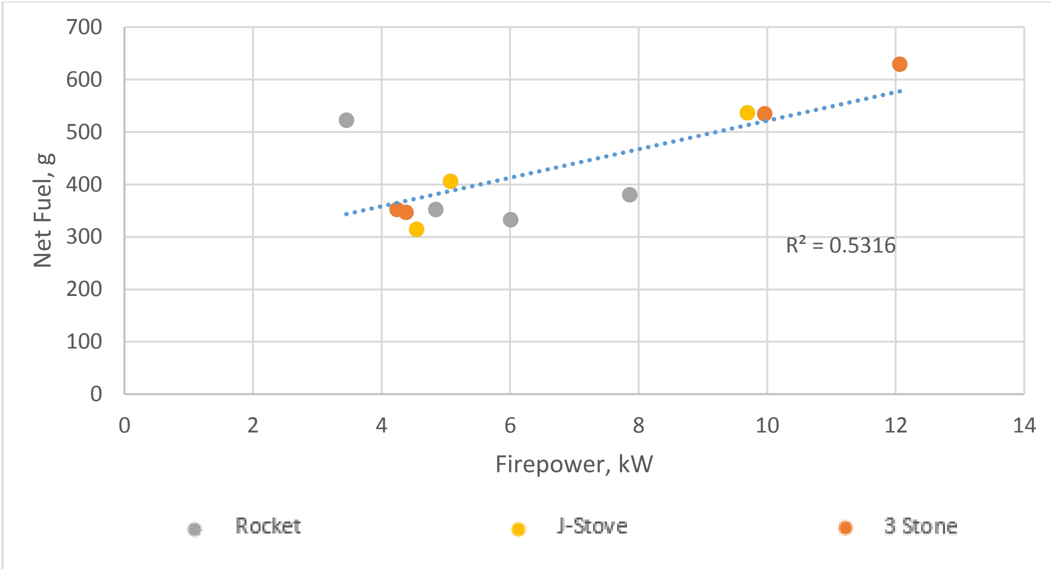

Figure 31. Positive correlation between firepower and net fuel use.

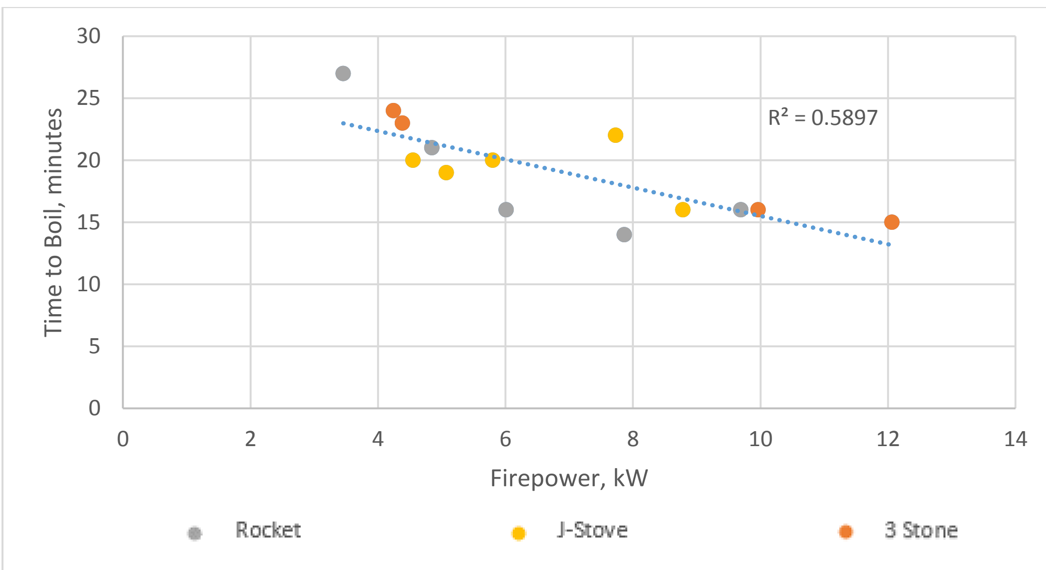

Figure 32. Inverse correlation between firepower and time to boil.