Assessment and Expansion of Laboratory-Based Testing of Biomass Cookstoves

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Assessment and Expansion of Laboratory-Based Testing of Biomass Cookstoves

Cameron M. Quist

A dissertation submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy

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ABSTRACT

Assessment and Expansion of Laboratory-Based Testing of Biomass Cookstoves

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Doctor of Philosophy

Biomass cookstoves are a significant source of various pollutants, such as CO₂, CO, and particulate matter (PM). To mitigate the issues surrounding cookstoves, significant research has been undertaken on improved cookstoves (ICS). This research can be performed in a laboratory setting, in the field, or a combination of both. This work concentrates on the purely laboratory testing. Laboratory testing has both advantages and disadvantages when compared to field testing (e.g. decreased cost and increased consistency). However, field applications are variable, environments can be significantly different (for example wind and ambient temperature can be very different in the field vs. a controlled lab environment) and the personal preferences of the users of the cookstove can also be difficult to predict when only using laboratory testing. It is typically preferable to narrow down the possible cookstove choices by using laboratory results before heading to the field.

This work concentrated on assessing the limitations of laboratory testing of cookstoves as presently constituted, as well as finding new ways to improve and expand upon the testing methodologies. Sources of error during testing was considered, leading to recommendations on how to adjust testing to decrease that error. Of note, it was found that higher thermal efficiencies led to increased propagated errors, which complicates the comparison of this efficiency among cookstoves. Additionally, a method for estimating the transient thermal efficiency was developed. Further, the effects of changing some of the key testing parameters were explored and the results showed that the overall thermal efficiency was minimally affected by parameter variations within the WBT or ISO 19867-1 guidelines. Finally, two methods were explored and compared for finding kinetic parameters associated with transforming food from the uncooked state to the cooked state. It was found that physical testing was more effective for samples that started in a harder physical state, whereas DSC testing was more effective with samples that had lower water content. This analysis was done with the intention of using transformation kinetics in future applications of cookstove models so that researchers could gain additional insights into which stoves may be best for their target market.

Keywords: biomass cookstove, cookstove, thermal efficiency, specific consumption, water boiling test, WBT, ISO 19867-1
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1 Introduction

Cooking food is essential to human survival. In developed countries, people cook generally using gas ranges, electric stoves and ovens, microwaves, bread makers and other modern appliances that are safe and efficient. For the billions of people in developing areas these appliances are not available, and neither is the infrastructure to support them. Approximately four billion people still use wood and other biomass fueled fires for their cooking (Clean Cooking Alliance, 2021). Though biomass is often the least expensive option for people in these areas, it can be very hazardous to their health, and emissions (most especially black carbon and soot particulates) from biomass cookstoves play a significant role in global climate change (DeAngelo, Schneider, & Moss, 2010; Kopp & Mauzerall, 2010; USAID, 2010).

When using biofuels for cooking, incomplete combustion leads to many pollutants, especially carbon monoxide and particulate matter (N. MacCarty, Still, & Ogle, 2010). These pollutants have been linked to many health problems for those who use biomass cookstoves (such as respiratory infection) (Perez-Padilla, Schilmann, & Riojas-Rodríguez, 2010), most especially among women and children. To improve this situation, many improved cookstoves have been designed and implemented over the past 40 years (J. Jetter et al., 2012; N. MacCarty et al., 2010). While there have generally been engineering improvements over a simple campfire, with few exceptions adoption rates have been low (Mobarak, Dwivedi, Bailis, Hildemann, & Miller, 2012). There are many reasons for the low adoption rates, including cost, designs that are not adaptable to local cooking styles, lower heating rates than expected, lack of training, designs
not rugged enough for long-term use, and in some cases the practice of cookstove stacking (using both the improved cookstove and the original cookstove) (Ruiz-Mercado, Masera, Zamora, & Smith, 2011). These cookstoves are intended to improve many possible performance aspects of cookstoves from energy efficiency and the time required to reach cooking temperature to the amount of carbon dioxide released per unit of food cooked. As people look to continue to improve on these designs, it is important that information relating to these metrics can be conveyed accurately by laboratory-based tests for design iteration purposes.

To improve overall cookstove efficiency, it is important to investigate the two efficiencies which typically are used to characterize cookstoves. Combustion efficiency is based on how completely the biomass burns and is usually based on the modified combustion efficiency defined as the amount of CO\(_2\) produced divided by the total CO and CO\(_2\) produced. The thermal efficiency (\(\eta_{th}\)) is based on how much of the energy released by the wood that is burned is transferred to the water in the pot. Even in a simple three-stone fire, modified combustion efficiencies can be well over 90% (J. Jetter et al., 2012). However, \(\eta_{th}\) values are extremely low – even as low as 10%. While a carefully constructed rocket stove with a pot skirt and a meticulously tended fire can reach \(\eta_{th}\) of approximately 40%, many improved cookstoves have thermal efficiencies only a few percentage points higher than a three-stone fire. This makes \(\eta_{th}\) the more natural efficiency to concentrate on when improving cookstoves.

The relatively small range of \(\eta_{th}\) means that it is especially important to be accurate when reporting and comparing values, both in the efficiency measured and its associated uncertainty. It is therefore important to know the sources of uncertainty in \(\eta_{th}\) especially for the dominant testing protocol which is the Water Boiling Test (WBT). The WBT is a test that characterizes a cookstove by measuring many variables (including water mass loss, wood burned and optionally
pollutant data) and using these variables to calculate various performance metrics such as \( \eta_{th} \). The error of these measurements and how they affect the uncertainties in the metrics needs to be well defined. An additional issue that has been identified in the WBT protocol is that the WBT only tests boiling style cooking, but in the field there are many different styles such as frying and baking (P. Bailis, Ogle, Maccarty, & From, 2014).

The purpose of this work is to aid in the design of cookstoves by improving methodologies for assessing thermal analysis of cookstoves via the WBT and expanding methods for comparing cookstoves beyond the WBT. This will be accomplished through four specific tasks. Task 1 will apply statistical methods to determine the uncertainty associated with reporting \( \eta_{th} \). Task 2 will develop a method to assess \( \eta_{th} \) with time since \( \eta_{th} \) is currently only evaluated at the endpoints of testing. Task 3 will test the effects of choices made on parameters used in the WBT (e.g. initial water mass, burning rate, etc.) to assess how variations on these parameters can affect \( \eta, \eta_{th}, SC, \) and time to temperature. Task 4 will compare two methods for finding kinetic parameters that may be used to augment existing cookstove computer models and help to determine required heating rates and minimum temperatures when designing or choosing a cookstove for a specific geographic area. The first two tasks focus on improving the WBT efficiency analysis, the third task focuses on improving the utility of the WBT results through understanding what effects a researcher’s experimental preferences have on cookstove. The final task adds another tool to help researchers choose and develop cookstoves according to their area of interest.
2 Literature Review

Improved cookstove literature includes a wide range of topics, including cookstove testing, design, modeling, and field usage. Improved cookstoves began to be studied using more formal and academic methods in the 1970s, and the literature has continued to expand and improve since then. Given the billions of people who will likely continue to use this technology in the next few decades, it is unlikely that this area of research will be abandoned soon. This work will focus on improving the Water Boiling Test (WBT), and so the focus of this review will be on the WBT and its place in cookstove testing.

2.1 Testing

Several tests exist to investigate the efficiency differences between improved and traditional cookstoves. There are many questions that should be answered when doing cookstove testing, and each test tries to answer at least a few of these questions. One of the main questions is the level of improvement of the cookstove over a traditional cooking method (e.g. a three stone fire or traditional design) in areas such as $\eta_{th}$, CO/CO$_2$ ratio and other emissions characteristics, and time to boil. Other important requirements for cookstoves can be more qualitative (e.g. how suitable is the stove design for a popular local dish) or quantitative (e.g. how much can your average family afford to spend on an improved cookstove, or is there a significant return on investment should the improved cookstove be purchased?). Many of the quantitative questions
and requirements can be tested using laboratory testing, whereas other quantitative and nearly all the qualitative questions and requirements are best studied in the field.

### 2.2 Varieties of Tests

Testing of cookstoves can be done in a laboratory by researchers, in a laboratory by users, in the field by researchers, or in the field by users. Currently, there are defined tests for researchers to perform in the laboratory, and for users to perform in both the laboratory and the field. The Water Boiling Test (WBT) is the most common of all laboratory tests, and it has several derivatives (Lewis & Pattanayak, 2012). The other main laboratory test, which is performed by users, is the Controlled Cooking Test (CCT). There are many possible field tests to be done (typically customized to a specific project), and historically the most frequently used is the Kitchen Performance Test (KPT).

#### 2.2.1 The Water Boiling Test, ISO 19867-1, and Derivatives

The WBT is “intended to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced while cooking” (P. Bailis et al., 2014). The WBT is designed to compare cookstoves, primarily based on $\eta_{th}$ and mass of emissions created, and ensure that cookstoves meet the performance requirements set out by various government and non-government agencies. The WBT consists of three phases: cold-start high-power, hot-start high-power, and simmer. The cold-start high-power phase is defined as bringing the water to a boil from when the cookstove starts at room temperature. Hot-start high-power is the phase
when the water is brought to a boil after the cookstove is already hot from the end of the cold-start high-power phase. During the simmer phase, the water is kept simmering at a few degrees lower than boiling for 45 minutes.

The WBT is the most common method of testing and is generally used as the initial test to assess cookstove effectiveness. There have been many studies done with the WBT to compare cookstoves and iterate on designs (Kshirsagar & Kalamkar, 2014; Manoj, Sachin, & Tyagi, 2013). However, there are many known issues with the WBT. The authors of the WBT include several thoughts and warnings in the WBT including the need for additional protocols to account for differing uses, improving the correlation to field testing results, settling the importance of the use of a lid, accounting for the lack of measurement of the charcoal after the cold-start phase, answering questions about wood choice, adding other possible useful metrics, accounting for humidity in the ambient air, and many other possible improvements (P. Bailis et al., 2014).

While the WBT does have several known flaws, it is still considered useful and has been used many times to compare cookstove performance (J. J. Jetter & Kariher, 2009; N. MacCarty et al., 2010; Tryner, Willson, & Marchese, 2014). The WBT measures cookstove performance using several metrics, including $\eta_{th}$, time to boil, specific consumption, combustion efficiency and emissions-related metrics involving CO and PM 2.5 or 10.

One of the most commonly reported metrics is $\eta_{th}$. Many studies have been performed on defining and improving cookstove $\eta_{th}$. To understand the details of cookstove $\eta_{th}$, it is important to know where the energy from the fire can flow as shown in Eq. 2-1 and Figure 2-1.

$$q_T = q_{pot} + q_{walls} + q_{flue} + q_{other}$$  \hspace{1cm} \text{Eq. 2-1}

where $q_T$ is the total energy generated from the combustion of the fuel and is measured using the amount of mass the wood or other fuel loses during the test, $q_{pot}$ is the energy transferred to the
water in the pot, $q_{\text{walls}}$ is the energy transferred through the cookstove walls, $q_{\text{flue}}$ is the energy that leaves the stove through the flue, and $q_{\text{other}}$ is other forms of energy not accounted for such as the energy that flows out other parts of the cookstove or lost through the pot walls.

**Figure 2-1:** A simple diagram showing heat transfer through the stove. The $q_{\text{other}}$ term is not represented as it includes energy flowing to several places, such as into the ground or into the walls of the pot (and not the water in the pot).

In the water boiling test, $\eta_{\text{th}}$ is defined as:
\[ \eta_{th} = \frac{q_{pot}}{q_T} \]  

Eq. 2-2

It should be noted that \( \eta_{th} \) can vary with time, but researchers calculate \( \eta_{th} \) based on the final value of the terms in Eq. 2-2 at the end of a given phase of the testing process. The three phases are the cold start high power (room temperature stove with a fast feed rate), hot start high power (stove is hot from cold start phase use, same feed rate as cold start), and simmer (the water is kept just below boiling temperature with a slow feed rate). It is important to note that the WBT only includes calculation of \( q_{pot} \) and \( q_T \). Additional analysis is required to assess the individual heat losses associated with Eq. 2-1 (Baldwin, 1987; Manoj et al., 2013).

As mentioned above, controlled experimental testing of cookstoves is centered around cooking by boiling, such as the WBT and its derivatives. Using a boiling-based task as a method to characterize cookstove performance is one way to get reasonably consistent, useful data. Unfortunately, there are a great many styles of cooking implemented by cookstove users, so boiling-based tests may not cover the whole range of experiences. Additional methods of testing, such as with cookstoves used for frying, are needed to gain a greater understanding of cookstove characteristics, especially since boiling may not be as efficient as some other methods such as frying (Bates, Clear, Friday, Hazas, & Morley, 2012). In fact, one of the most widely used books on the subject of biomass cookstoves specifically mentions that non-water heating stoves were not considered in the study (Baldwin, 1987). Current analysis methods across cooking styles (boiling, frying, baking, etc.) have centered around modern cooking appliances and there is not any evidence of similar efforts for biomass cookstoves (P. Bailis et al., 2014).

One alternative to the WBT is the Heterogeneous Testing Protocol (HTP) (Robinson, Pemberton-pigott, Makonese, & Annegarn, 2009). This test seeks to improve the utility of
laboratory testing by testing cookstoves under conditions more closely resembling field use. Many of the metrics used in the HTP are named and defined similarly to the more popular WBT metrics, and like the WBT it is a task-based test. Some of the important differences include the addition of more varieties of fuel, the addition of a medium power level, and a requirement to use multiple varieties of pots. Though in the WBT literature no significant difference was found when using different pot sizes (Makonese, Robinson, Pemberton-pigott, & Annegarn, 2010), the HTP shows a difference in specific fuel consumption and in the emissions factors. This may be due to the wider range of variation in test parameters specified in the HTP.

Recently both the HTP and WBT have been replaced by ISO 19867-1 (International Organization for Standardization, 2018). ISO 19867-1 covers a wider range of aspects of cookstoves than the HTP or WBT and is now used as the primary laboratory cookstove test. However, the method for testing efficiency remains largely unchanged from the WBT and so work regarding WBT efficiency remains relevant.

### 2.2.2 The Controlled Cooking Test

The CCT is a somewhat less used test. This may be at least in part because of the difficulty of finding local users to do cooking in a laboratory when compared to paying (or finding volunteer) researchers to do tests in a laboratory. The CCT is another lab test, but it is performed by a local person who is familiar with both the meal being prepared and the stove being tested (R. Bailis, 2004). After a meal is selected and the necessary preparations are made, the local user cooks the meal. The following measurements are required for CCT analysis: total weight of food cooked, weight of char remaining, equivalent dry wood consumed, specific fuel
consumption (mass of food cooked/mass of fuel used), and total cooking time. Questions can also be asked of the person testing to help understand user response to the design (Adkins, Tyler, Wang, Siriri, & Modi, 2010) This allows stoves to be compared against each other in a situation that is closer to real use than the WBT, but is also less reproducible than the WBT.

2.2.3 The Kitchen Performance Test

The Kitchen Performance Test (KPT) “is the principal field–based procedure to demonstrate the effect of stove interventions on household fuel consumption.” (P. Bailis et al., 2014)(see also Granderson, Sandhu, Vasquez, Ramirez, & Smith, 2009; Kishore & Ramana, 2009). The KPT is used to determine two things: the benefits perceived by the users and the actual difference in fuel consumption after cookstove adoption. As a field test, the results are highly variable and require more data than the others to be significant. It is also not a purely quantitative test as it requires two surveys as well as fuel consumption measurements. The word measurements here is also used very loosely, as in at least some cases complicated estimations are required (Kishore & Ramana, 2002). These tests are very important, however, especially as they can reveal discrepancies between lab testing and field use. For example, it is possible that an improved cookstove may have better emissions characteristics when tested in the lab, but then only have better emissions in the field under certain conditions such as during the higher power phases of cooking (Sahu, Peipert, Singhal, Yadama, & Biswas, 2011).
2.2.4 Summary of Notable Laboratory Studies

The various metrics of many cookstoves have been studied under various operating conditions. In one study, 22 different stoves were tested (J. Jetter et al., 2012). Based on $\eta_{th}$, Jetter’s evaluation showed that many improved cookstoves did not actually show improvements over a three-stone fire. Further, it was unclear from the study which design modifications, such as construction materials or combustion chamber geometry, were the most important and how they affected the operation of the cookstove. However, Jetter did suggest a number of improvements for cookstove testing and analyzed the effects of biomass vs. coal fuels.

In a major study by MacCarty including 50 cookstoves, several observations on cookstove efficiency are important (N. MacCarty et al., 2010). One important note is that improvements in cookstove efficiency do not necessarily lead to improvements in cookstove emissions. The rocket-style stoves were shown to decrease average fuel use by 33%, and pot skirts were shown to reduce fuel use by 25-30% as well. An additional important note was that the variability between tests at the same laboratory can vary by 5-25%. It would be beneficial if some of the causes of this variation could be identified and improved.

2.3 Known Effects of Cookstove Modifications

A few studies have been done on the effects of individual modifications to cookstoves. Andreatta and Wohlgemuth (Andreatta & Wohlgemuth, 2010) have done extensive studies on skirts around pots, and found that operating at the optimal skirt distance increased the $\eta_{th}$ from 20.7% in the no-skirt case to 28.7%. In another study, bulk flow rates of all gases through the
cookstove from Agenbroad’s model (Agenbroad, 2010) were used by Zube (Zube, 2010) in his heat transfer analysis of L-shaped cookstoves. Zube explored four scenarios to determine their effects on heat transfer:

1. Adjustment of Pot Gap
2. Changing of Fluid Flow Geometry
3. Finned Cooking Surfaces
4. Premixed vs. Diffusion Flames

A study of each of these parameters showed that the largest $\eta_{th}$ gains could be made with finned cooking surfaces and proximity to flame. Pot gap adjustment and fluid flow geometry changes were shown to have small positive effects but premixed and diffusion flames showed no significant impact on heat transfer.

Baumgartner et. al. (Baumgartner et al., 2011) showed that ventilation during cooking, cookstove maintenance, and kitchen structure had significant impact on PM 2.5 level exposure (related to combustion efficiency) for cooking with biomass. Another study by Bhattacharya (Bhattacharya, Albina, & Khaing, 2002) showed the effects of several variables on both emissions and $\eta_{th}$. This study used an improved Indian stove, a traditional Vietnamese stove, and an improved Thai stove and found that moisture content increased CO while decreasing efficiency and NOx. Fuel size did not affect $\eta_{th}$ but did affect the PM levels detected. Pan or pot size had no discernable effect on CO, NOx, PM, or $\eta_{th}$. CO and NOx were also found to decrease if the fire was started from the top of the fuel pile rather than the bottom (Bhattacharya et al., 2002).
2.4 Design

Cookstoves use a variety of fuels, can have a variety of configurations, and can be made with a variety of materials. Some examples of fuels include wood, charcoal, dung, leaves, and reeds. Configurations can include anything from a simple ground campfire to a rocket stove or advanced designs with fans, chimneys, or heat-based electrical chargers. Materials can be earth-based, such as rocks, clay, and dirt or either custom made or recycled metals. An in-depth analysis of these factors has been discussed both in books and published journal articles (Baldwin, 1987; Manoj et al., 2013).

2.5 Modeling

Over the past approximately 30 years there have been several computational models developed for cookstoves or individual aspects of those cookstoves (N. A. MacCarty & Bryden, 2015). These cookstoves range from simple 3-stone fires to fully enclosed stoves along with individual stove characteristics (such as the gap distance between a pot and the pot skirt). Some of the findings of these studies are summarized below.

Some of the earliest modeling done in the 1980s concentrated on the effects of geometry using standard heat transfer models that can be found in engineering textbooks (Baldwin, 1987; N. A. MacCarty & Bryden, 2015). Here it was found that the size of the gap between a pot skirt and the cookstove has a significant effect on firepower, airflow, and efficiency. The height of the pot skirt was also found to be important, not in helping the heat transfer but in allowing for greater firepower. In this idealized version of a cookstove, the shape of the stove was found to favor wider, shorter pots over taller, narrow ones.
In the field of fluid flow, Gupta and Mittal (Gupta & Mittal, 2010) modeled a rocket stove and the buoyant flow associated with heated gases. In their study, the stove was modeled as an axisymmetric object with the combustion reaction occurring in two zones. The combustion within each zone was assumed to be uniform. The heat released in each zone determined the buoyant flow through the stove. The most important findings of the study were the optimal spacing between the stove and the cooking vessel (10-15mm) and that a “diffuser-like shape” in the combustion zone increases mass flow rate.

Agenbroad modeled the fluid flow through an L-shaped rocket stove (Agenbroad, 2010). The method involved a coupled 1-d problem. At the joint of the L, a point-source heat addition term was used to approximate the change in density. The model was then able to account for both buoyancy effects and the chimney effect. The model was validated and tested on two sizes of cookstoves, both with and without a cooking vessel on top. The model worked well for predicting bulk flow rate and excess air ratio. Another interesting result was a non-dimensional set of equations that may be useful in modeling stoves of other geometries.

While both of the fluid flow-based models have been able to give some useful data, they are also inherently limited. Gupta and Mittal (Gupta & Mittal, 2010) did not fully account for an actual stove geometry, and treated the fire as a uniform heating source. While this allowed for faster calculations, it also made it difficult to apply the findings to real cookstoves. Agenbroad’s model did not predict accurate temperatures, CO levels, or particulate matter emissions (Agenbroad, 2010).

Andreatta and Wohlgemuth (Andreatta & Wohlgemuth, 2010) performed CFD modeling of the flow after the exit of the cookstove. The main thrust of the modeling work was determining the effects of a skirt on heat transfer. To calibrate the model, data from real stoves
were used to determine an exit flow rate, which was then approximated as though it were coming out of a tube and around the pot. In a personal communication with Dale Andreatta, it was mentioned that because natural gas flames were used in the validation, the radiative heating was too low and the convective heating too high. There was a suggestion that liquid fuels could be used to address this problem.

2.6 Contribution to Literature

As noted above, many studies have been performed to assess $\eta_{th}$ and other important cookstove characteristics. However, it is difficult to compare results within or between labs or find results that can be applied to field conditions. If a lab employs more than one person in the testing process, small differences between how the individuals run the test (e.g. burning rate) can result in surprising differences in results. Of note, the way in which the stoves are used by those testing it may also vary significantly from those for whom it is meant as a product. Additionally, when looking at results reported in studies, error ranges are often omitted. Just as important is the fact that different labs may use slightly different protocols for their own tests. To this point, relatively few studies have been performed that involve uncertainty analysis. Most studies that have been done on cookstoves that include statistical analyses are more concerned with emissions, time to boil, or other factors rather than $\eta_{th}$ (Honkalaskar, Bhandarkar, & Sohoni, 2013; Roden et al., 2009; Wang et al., 2014). Statistical studies on cookstove performance have generally been centered around quantifying the variance between runs and the number of experiments required to reach statistical significance, not on the accuracy of the individual reported values of $\eta_{th}$. One exception is that of Taylor (Taylor, 2009), who performed a propagation of error on the ash content of the wood. This work has been valuable, but errors associated with equipment and reported values used in the $\eta_{th}$ equation (such as lower heating
value) have not been addressed. This provides an impetus to address statistical errors associated with key parameters that relate to $\eta_{th}$ which is the motivating factor for the first task of this study.

This study is being conducted to improve the $\eta_{th}$ comparison and utility of the Water Boiling Test for cookstoves. The first task of the study will be to quantify the accuracy, using propagation of error, of calculated $\eta_{th}$ based on data taken from four cookstove tests involving an original cookstove and three modified configurations. Once the accuracy and repeatability of the equipment have been verified, transient analysis can begin. This second task is aimed at gaining new tools to use in assessing cookstove data. It is hoped that these new tools, such as measuring $\eta_{th}$ with time, can bring insight into the performance of the cookstove and help discover some of the limitations of the WBT. The third task will involve investigating how important it is to keep some of the controllable experimental variables constant in an effort to improve cookstove comparisons between labs and to provide some data about some of the possible differences between the WBT and its derivatives, specifically investigating the effects of firepower, pot size, lid presence, and initial mass of water. Improving comparisons between labs will be done using a two-tiered full factorial study. This is critical because several labs use different experimental testing variables and it is difficult to compare $\eta_{th}$ between such studies. The final task for this study is to examine a possible addition to the WBT: a method for obtaining food reaction rate data (with the possibility that this data could then be used to improve the applicability of the WBT analysis and cookstove modeling to field use). The goal of cooking food is to affect changes in food, of which heating is only one effect. Chemical changes are also a very important part of food preparation, and the WBT may not be reaching its full potential in testing for those scenarios. Many foods experience a structural change that is in some way related to the chemical changes that occur during the cooking process (Lemmens et al., 2009; Peng, Tang, Barrett,
Sablani, & Powers, 2014). It is therefore possible to assess the relative cooking level of a food by measuring physical characteristics of the food.

In summary, there have been many studies done on the behavior of biomass cookstoves in the past, and the methodologies for testing have been continuously improving. This study aims to aid in this effort primarily by answering five questions: 1) how accurate does the instrumentation need to be, 2) what can be learned from transient analysis of $\eta_{th}$, 3) which protocol decisions matter, 4) how can the WBT lab test be altered to better reflect real-world performance, and 5) what methods are best for a cookstove researcher to use for estimating the kinetics of food used in their region of interest. It is hoped that researchers looking to improve their use of the WBT will find these results useful.
3 Uncertainty Analysis and Design Guidelines of Biomass Cookstove Thermal Efficiency Studies

3.1 Introduction

The hazards of using biomass cookstoves on a daily basis are well documented, including the potential of asthma, cancer, carbon monoxide poisoning, and others (Abeliotis & Pakula, 2013; Chowdhury, 2012; Hawley & Volckens, 2013; Mueller, Pfaff, Peabody, Liu, & Smith, 2011). In addition to the personal risk of using biomass cookstoves, there are significant environmental effects. The pollutants released are greenhouse gas emissions, and the particulate matter can increase global climate change (Bond et al., 2013). Despite these health risks and the environmental damage, those living in developing regions often have no option other than the continued use of biomass to cook and to heat their homes.

Beginning in the mid-1980s, many organizations have made efforts to mitigate the health and environmental hazards by engineering and distributing more efficient, cleaner burning biomass cookstoves (Baldwin, 1987). Improved cookstove designs have ranged from wood burning rocket stoves to cookstoves specializing in the use of farming waste. Assessment of the performance of improved cookstoves has been conducted using the Water Boiling Test (WBT) or a variant thereof (P. Bailis et al., 2014; J. Jetter et al., 2012; Kshirsagar & Kalamkar, 2014; Manoj et al., 2013). Two commonly reported values from these tests are the modified
combustion efficiency (MCE), often observed above 90%, and the thermal efficiency ($\eta_{th}$) which is often shown to be below 50% (J. Jetter et al., 2012). This work focuses on $\eta_{th}$.

Recent efforts to improve $\eta_{th}$ have involved modeling the heat transfer, in whole or in part, and then improving the cookstove design (Agenbroad, 2010; Andreatta & Wohlgemuth, 2010; N. A. MacCarty & Bryden, 2015; Wohlgemuth, Mazumder, & Andreatta, 2009). However, physical tests are still required for model validation and for comparing $\eta_{th}$ of cookstoves based on changes to cookstove designs. Usually, the average $\eta_{th}$ for a number of test replicates (and sometimes standard deviation or confidence interval) is reported in the literature to compare various cookstoves or to assess design changes. To effectively compare $\eta_{th}$ between cookstoves or to assess the effects of a design change on $\eta_{th}$, it is important to understand how the uncertainty in $\eta_{th}$ depends on measurements, input data (manufacturing specifications, literature values, etc.), and test conditions.

The uncertainty associated with measurements, input data, and test conditions can be a result of uncertainties in the models and input parameters, variability in the equipment used in testing, and random changes in operating conditions such as wind speed, ambient temperature, the method in which wood is stacked within or the method in which fuel is fed into the cookstove. Valid, unbiased comparison of cookstove performance can only be made if variations in conditions in which the tests were performed and the uncertainties in measurements and input data are reported. Unfortunately, variations can also occur both with different testers and the same tester (Zube, 2010). Fortunately, measurement and input data uncertainties can be quantified with a propagation of uncertainty analysis based upon the equations used to calculate $\eta_{th}$. The focus of this work is to address the uncertainty of $\eta_{th}$ associated with measurements and input data. Although uncertainty of $\eta_{th}$ associated with various testing conditions is not the
focus of this work, it is important to reemphasize the need to report testing conditions to adequately compare $\eta_{th}$ reported in the literature.

3.2 Materials and Methods

3.2.1 Testing Chamber and Cookstove

As shown in Figure 3-1A, a cinderblock structure (1.4 m long x 0.8 m wide x 0.7 m high) was built on a rolling metal cart. The cookstove was placed in the cinderblock housing on a 6.4-mm thick metal plate. Underneath the plate was a 10 cm deep container of sand used to imitate an in-home cookstove placed on the ground. The cinderblock housing was topped by a hood through which the exhaust flowed through a fan and a flue at an approximate flow rate of 16 L/min.

Figure 3-1. (A) Cookstove testing chamber with a traditional Peruvian brick channel stove resting atop a metal plate. The hood vented to a chimney augmented by a fan that can be seen directly above the apex of the hood. (B) The wood was arranged in a ‘log-cabin’ configuration made of sticks measuring 2 cm x 2 cm x 13 cm. There were 4 layers of sticks, with each layer containing 2 sticks.
The cookstove used for this study simulated a basic channel cookstove used in many Peruvian households in the Piura region. The basic design of this cookstove is simply two small, parallel walls of bricks that are placed far enough from each other to maximize the fire while still holding the cooking pot above the fire (similar to figure 2-1). The brick walls used in these experiments were 2.5 bricks high and 2.5 bricks long, which resulted in a wall 14 cm tall by 56 cm long and 10 cm wide. The walls were set approximately 15 cm apart. The effects of three modifications to the channel cookstove on $\eta_t h$ were investigated. First, a grate was included by adding one additional layer of bricks (adding an additional 5.5 cm to the height) and placing the grate between the lower and middle layers of brick. The intent of this modification was to reduce heat loss to the ground and to improve the combustion efficiency by increasing airflow into the combustion zone. Second, a pot skirt made of bent metal sheets to conform to the sides of the pot was added to increase heat transfer to the pot. Third, the combined effects of the grate and skirt were investigated. The basic cookstove design was tested seven times, the grate addition six times, the skirt addition nine times, and the grate/skirt addition five times.

3.2.2 Experimental Protocol

For each test, a 15-liter pot (25 cm high, and 25 cm diameter) filled with 2.5 liters of water was placed on the cookstove. The temperature of the water was continuously measured using a k-type thermocouple. Douglas fir was cut into uniform sticks (2 cm x 2 cm x 25 cm) for each experiment. The wood was dried in a dehydrator for approximately 24 hours before testing to maintain consistency in the moisture content. The wood moisture content was measured at the beginning of each run using a wood moisture meter (MMD4E The Seeker, General Tools, New York City, NY). For all runs, the moisture content was below the detectable limit of the meter.
(5%). While using a moisture meter is not the preferred method for determining moisture content in the WBT protocol, it is mentioned as an option and is an inexpensive and fast method. For this study, moisture meter measurement error was used to provide a worse-case scenario as to the contribution of this measurement error to $\eta_{th}$ analysis.

The WBT was performed during each run to obtain $\eta_{th}$. The wood was arranged in a ‘log-cabin’ configuration at the beginning of each cold start phase as shown in Figure 3-1B. For the log-cabin, the sticks were cut in half and four layers of sticks were stacked, with each layer containing two sticks. The cold start is where the cookstove begins at ambient temperature. Newspaper and splintered wood were placed in the center as starter and kindling and the fire was started. At each four-minute interval following the start of the fire, an alternating pattern of three wood sticks and then two wood sticks were added to the existing fire until the water boiled. At this point, the fire was extinguished by removal from the cookstove and smothering. The amount of remaining wood and charcoal were measured using a digital scale with an accuracy of ± 0.5 g. The charcoal was obtained by both removing the charcoal in the combustion chamber and by shaving off the charcoal from the remaining wood with a file. After the cold start analysis, all charcoal and wood were removed from the cookstove and the process described for the cold start was repeated with a fresh pot again filled with 2.5 liters of water. The only difference was that the cookstove was now warm at the beginning of the burn. This phase is called the hot start phase. Once the water boiled in the hot start phase, the fire was extinguished and the remaining wood and charcoal were weighed. Then, additional hot start phases were continued. Only runs involving the hot start phase were analyzed in this work to reduce variability in the analysis.
3.2.3 Calculation of the Thermal Efficiency, $\eta_{th}$

As previously defined (P. Bailis et al., 2014), $\eta_{th}$ is the ratio of the energy transferred to the water in the pot ($E_{pot}$) to the energy available in the fuel ($E_{fuel}$):

$$\eta_{th} = \frac{E_{pot}}{E_{fuel}} \quad \text{Eq. 3-1}$$

Monitoring the temperature of the water in the pot, measuring the mass of water that evaporated, and determining the amount of wood consumed are some of the key aspects needed to determine $\eta_{th}$ (P. Bailis et al., 2014; Poudyal et al., 2015).

The amount of energy transferred to the pot is calculated according to

$$E_{pot} = C_p w * m_{water,i} * \Delta T + \Delta h_{H2O,fg} * \Delta m_{water} \quad \text{Eq. 3-2}$$

where $C_p w$ is the specific heat of water, $m_{water,i}$ is the initial mass of water in the pot, $\Delta T$ is the final temperature of water minus the initial temperature of water in the pot, $\Delta h_{H2O,fg}$ is the heat of vaporization of saturated water at the ambient pressure (often approximated as the heat of vaporization at $P_{amb}=1$ atm or $T=100$ °C), and $\Delta m_{water}$ is the change in mass of water in the pot. In Eq. 3-2, the first term accounts for the energy used to heat the water and the second term accounts for the energy used in water evaporation.

The energy in the fuel is approximated as

$$E_{fuel} = f_{cd} * LHV_{wood} \quad \text{Eq. 3-3}$$

where $f_{cd}$ is the equivalent dry weight of wood consumed and $LHV_{w}$ is the lower heating value of the wood consumed on a dry basis. $f_{cd}$ is a way to group variables for calculating $\eta_{th}$ and is defined as,

$$f_{cd} = f_{cm} * (1 - MC) - f_{cm} * MC * y - \frac{LHV_c}{LHV_{wood}} * m_c \quad \text{Eq. 3-4}$$
where $f_{cm}$ is the mass of the fuel consumed during the test including the moisture in the fuel, $MC$ is the initial moisture mass fraction of the wood (g/g), $LHV_c$ is the lower heating value of the charcoal obtained from burning the wood, $m_c$ is the mass of the charcoal remaining, and $y$ is the ratio of energy used to remove moisture from the wood relative to energy available in the dry wood. Specifically,

$$y = \frac{\left[C_p \ast (T_{\text{boil}} - T_{\text{amb}}) + \Delta h_{H_2O fg}\right]}{LHV_{\text{wood}}}$$  \hspace{1cm} \text{Eq. 3-5}

where $T_{\text{boil}}$ is the boiling temperature of water (based on ambient pressure) and $T_{\text{amb}}$ is the ambient temperature during the test. In Eq. 3-4, the first term describes the energy released from the moisture-free burned wood, the second term describes the energy used to volatilize the moisture in the wood and the third term describes the energy remaining in the charcoal after the test is completed.

### 3.2.4 Uncertainty of $\eta_{th}$

The maximum uncertainty in $\eta_{th}$, due to uncertainties in both measurements and input data, is denoted as $\delta_{th}$. The maximum uncertainty in $\eta_{th}$ was calculated for each experiment based on the propagation of uncertainty (Bethea and Rhinehart, 1991) according to

$$\delta_{th} = \sum_i \left( \left| \frac{\partial \eta_{th}}{\partial x_i} \right| \delta_i \right)$$  \hspace{1cm} \text{Eq. 3-6}

Here, $x_i$ represents each measurement and input data parameter in Eqs. 3-2 through 3-4 that is used to calculate $\eta_{th}$ and $i$ is the total number of parameters (see Table 3-2 for $x_i$ parameters). $\delta_i$ is the maximum uncertainty associated with each $x_i$. Thus, $\delta_{th}$ is found by summing the product of $\delta_i$ and the partial derivative (or sensitivity) of the thermal efficiency with respect to $x_i$ evaluated at the average value of each $x_i$. 
The fractional contribution, $f_i$, of each parameter to $\delta_{\text{th}}$ is defined as

$$f_i = \left| \frac{\partial \eta_{\text{th}}}{\partial x_i} \right| \frac{\delta_i}{\delta_{\text{th}}}$$  \hspace{1cm} \text{Eq. 3-7}$$

The fractional contribution is useful in determining the relative importance of the uncertainty in each parameter to $\eta_{\text{th}}$.

In addition to calculating the maximum uncertainty of $\eta_{\text{th}}$, the propagated standard deviation of $\eta_{\text{th}}$ was also calculated to enable the calculation of confidence intervals for $\eta_{\text{th}}$ based on measured and input data uncertainties. In general, a 99% confidence interval would have a smaller interval than the maximum uncertainty interval since the maximum uncertainty assumes that all uncertainty for each parameter $x_i$ would propagate at the maximum uncertainty. A maximum uncertainty actually occurring is also very unlikely to be observed in practice. The propagated standard deviation ($\sigma_{\text{th}}$) is calculated according to

$$\sigma_{\text{th}} = \sqrt{\sum_i \left( \frac{\partial \eta_{\text{th}}}{\partial x_i} \sigma_i \right)^2}$$  \hspace{1cm} \text{Eq. 3-8}$$

where $\sigma_i$ is the standard deviation of the measured or input data parameter $x_i$.

A more intriguing form of Eqs. 3-6 through 3-8 is obtained by multiplying and dividing the right side of Eq. 3-6 by $\eta_{\text{th}}$ to obtain:

$$\delta_{\text{th}} = \sum_i \left( \frac{\partial \eta_{\text{th}}}{\partial x_i} \right) \frac{\delta_i}{\eta_{\text{th}}} = \eta_{\text{th}} \sum_i \left( \frac{\partial \eta_{\text{th}}}{\partial x_i} \right) \frac{\delta_i}{\eta_{\text{th}}} = \eta_{\text{th}} \sum_i \phi_i$$  \hspace{1cm} \text{Eq. 3-9}$$

where $\phi_i$ is a new variable that represents the contribution of each parameter $x_i$ to $\delta_{\text{th}}$. Here, the summation of $\phi_i$ provides information on the value of $\delta_{\text{th}}$ relative to $\eta_{\text{th}}$. Similarly, substituting the definition of $\phi_i$ shown in Eq. 3-9 into Eq. 3-7 gives

$$f_i = \phi_i \frac{\eta_{\text{th}}}{\delta_{\text{th}}}$$  \hspace{1cm} \text{Eq. 3-10}$$
Also, substituting the definition of $\phi$ shown in Eq. 3-9 and $\sigma_i = \delta_i / 2.57$ (based on the maximum uncertainty for parameter $i$ being in the 99th percentile) into Eq. 3-8 gives

$$\sigma_{th} = \frac{n_{th}}{2.57} \sqrt{\sum_i \phi_i^2}$$  \hspace{1cm} \text{Eq. 3-11}

An advantage of using $\phi$ is that this term is less complex than the partial derivatives enabling $\delta_{th}, f_i$, and $\sigma_{th}$ to be quickly obtained from knowledge of $\eta_{th}$ and the value of each $\phi$.

3.3 Results

Table 3-1 shows the mass of fuel consumed ($f_{cm}$), the mass of water evaporated ($\Delta m_{water}$), the change in water temperature ($\Delta T$), and mass of charcoal remaining ($m_c$) at the end of each test for the basic stove, stove with skirt, stove with grate, and stove with both a skirt and grate.

| Table 3-1. Summary of measured data for each cookstove configuration. |
|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|
| **Basic stove (n=9)**                           | **skirt (n=9)**                                 | **grate (n=5)**                                 | **Skirt and grate (n=5)**                        |
| $f_{cm}$ (g)                                     | $\Delta m_{water}$ (g)                          | $\Delta T$ (K)                                  | $m_c$ (g)                                       |
| average                                         | 566.6                                           | 70.4                                            | 52.0                                            |
| std dev                                         | 89.7                                            | 1.2                                             | 7.3                                             |
| std dev/average                                 | 0.16                                            | 0.02                                            | 0.14                                            |
| **skirt (n=9)**                                 | **grate (n=5)**                                 | **Skirt and grate (n=5)**                       |
| average                                         | 385.7                                           | 70.5                                            | 43.0                                            |
| std dev                                         | 24.0                                            | 1.3                                             | 8.3                                             |
| std dev/average                                 | 0.06                                            | 0.02                                            | 0.19                                            |
| average                                         | 502.0                                           | 70.7                                            | 37.8                                            |
| std dev                                         | 106.9                                           | 2.5                                             | 9.8                                             |
| std dev/average                                 | 0.21                                            | 0.04                                            | 0.26                                            |
| average                                         | 366.0                                           | 69.9                                            | 37.4                                            |
| std dev                                         | 42.7                                            | 1.4                                             | 4.4                                             |
| std dev/average                                 | 0.12                                            | 0.02                                            | 0.12                                            |
As expected, $f_{cm}$ for each test varied significantly. The basic design used the most wood, and the least wood was consumed when the skirt and grate/skirt were used. $f_{cm}$ for both configurations that included skirts was statistically less (99% confidence) than the basic stove. Since $f_{cm}$ for the grate configuration was also significantly greater (90% confidence) than the skirt and significantly greater (95% confidence) than the grate/skirt configuration, this showed that the simple skirt significantly reduced fuel consumption.

The amount of water vaporized and the change in water temperature were very similar among all configurations with a maximum difference in water vaporized of 4.3 g (approximately 20 g of water was vaporized in each test) and a maximum difference in temperature changes of 0.82 °K (each $\Delta T$ was approximately 70 °K). This was expected since the initial water temperature for all runs was similar and the boiling temperature varied only slightly among testing days due to the slight variation in atmospheric pressure. Values of $\Delta T$ were consistent because the initial water temperature was easily controlled while the other three measured parameters ($f_c$, $\Delta m_{water}$, $m_c$) could not be directly controlled. On the other hand, the mass of the remaining charcoal varied among each type of modified cookstove. The average for each configuration ranged from 32.4 g to 52.0 g, with the grate and grate/skirt showing the least amount of charcoal. The basic cookstove showed significantly more charcoal formation (95% confidence) compared to all configurations with a skirt and/or grate. This finding suggests that the grate and/or skirt can be effective for reducing charcoal.

After each experiment, $\eta_{th}$ was calculated using Eqs. 3-1 through 3-5. Then, $\phi$ was evaluated for each $x_i$ parameter and subsequently $\delta_{th}, f_i$, and $\sigma_{th}$ were calculated using Eqs. 3-9 through 3-11. According to the definition of $\phi$ shown in Eq.9, $\delta_i$ is required to evaluate $\phi$. Table 3-2 shows $\delta_i$ for each key parameter $x_i$ in Eqs. 3-2 through 3-5, literature values for some
$x_i$, and the source for each $\delta_i$. It should be noted that $\delta_{\Delta T}$ is twice the uncertainty of the thermocouple used because the term is derived from two temperatures subtracted from each other. Similarly, $f_{cm}$ and $\Delta m_{water}$ are twice the uncertainty of the measurement scale because these parameters are derived from two mass values subtracted from each other. Where literature values were used, the ratio of $\delta_i$ to the literature value ranged from about 0.01 to 0.10. Thus, some parameters can potentially have more impact on uncertainty contributions than other parameters.

Table 3-2. Uncertainty estimates of all measured and input parameters of $\eta_{th}$ (Eqs. 3-1 through 3-5). Starred values indicate that the value is twice that of the instrument because it is a calculated difference.

<table>
<thead>
<tr>
<th>$x_i$</th>
<th>Value</th>
<th>$\delta_i$</th>
<th>Units</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{water,i}$</td>
<td>0.5</td>
<td>g</td>
<td></td>
<td>Salter® scale. <a href="http://www.salterusa.com/salter_us/catalog-us/kitchen-scales/aquatronic-high-capacity-scale-with-touchless-tare.html">http://www.salterusa.com/salter_us/catalog-us/kitchen-scales/aquatronic-high-capacity-scale-with-touchless-tare.html</a></td>
</tr>
<tr>
<td>$\Delta T$</td>
<td>1.0*</td>
<td>°K</td>
<td></td>
<td>K-type thermocouple after calibration.</td>
</tr>
<tr>
<td>$H_{vap,Pamb}$</td>
<td>2260</td>
<td>0.4</td>
<td>kJ/kg</td>
<td>Heat of vaporization of saturated water at ambient pressure which is assumed to be 1 atm. <a href="http://www.iapws.org/relguide/Advise1.pdf">http://www.iapws.org/relguide/Advise1.pdf</a></td>
</tr>
<tr>
<td>$\Delta m_{water}$</td>
<td>1.0*</td>
<td>g</td>
<td></td>
<td>Salter® scale. (Same as above)</td>
</tr>
<tr>
<td>$f_{cm}$</td>
<td>1.0*</td>
<td>g</td>
<td></td>
<td>Salter® scale. (Same as above)</td>
</tr>
<tr>
<td>$MC$</td>
<td>2.5</td>
<td>%</td>
<td></td>
<td>General Tools® moisture meter <a href="http://www.generaltools.com/MMD4E--Pin-type-LCD-Moisture-Meter_p_636.html">http://www.generaltools.com/MMD4E--Pin-type-LCD-Moisture-Meter_p_636.html</a></td>
</tr>
<tr>
<td>$LHV_{water}$</td>
<td>19314</td>
<td>965</td>
<td>kJ/kg</td>
<td>Variation in literature shows approximately 5%</td>
</tr>
<tr>
<td>$LHV_c$</td>
<td>29500</td>
<td>2950</td>
<td>kJ/kg</td>
<td>The WBT worksheet assumes this value in the absence of other data. Assumed 10% uncertainty since data was not readily available and this value can vary significantly across tree species, though it can be determined with good accuracy through several methods as discussed in the body of this work.</td>
</tr>
<tr>
<td>$m_c$</td>
<td>0.5</td>
<td>g</td>
<td></td>
<td>Salter® scale. (Same as above)</td>
</tr>
<tr>
<td>$T_{amb}$</td>
<td>0.5</td>
<td>K</td>
<td></td>
<td>K-type thermocouple after calibration.</td>
</tr>
</tbody>
</table>
Of particular interest was the quantification of \( \delta_i \) for both values of LHV. The LHV of an individual species of wood can vary from tree to tree and by location within the tree. Values found in literature for Douglas fir range from 19.5 MJ/kg (J. J. Jetter & Kariher, 2009) to 21.1 MJ/kg (Kuhns and Schmidt). Using the average of these values as the value of the wood burned in this study, the maximum variance is 0.8 MJ/kg or about 4% of the value. Additionally, the values within a single tree can also vary significantly. If the lower heating value of wood used in cookstove combustion is bounded by the lower heating values of the stem (i.e. trunk) and the branches, using data from Singh and Kostecky, the average stem LHV was 19.122 for the softwoods and 18.396 hardwoods studied and the average branch LHV was 20.649 and 19.545 (Singh & Kostecky, 1986). Using the average of stem and branch LHV values as the value of the burned wood, this would give a maximum variance of +/- 4% of the value for softwoods and +/- 3% for the hardwoods. On the other hand, measurements of the LHV (such as using a bomb calorimeter) for processed fuels can lead to a very low \( \delta_i \).

Even more difficult is identifying \( \delta_i \) and the literature value of LHV of the charcoal remaining from the wood as these values can vary from wood species to species and there is very little data available at that level of specificity. Taylor showed significant variance (values ranged from 22.6 MJ/kg to 31.0 MJ/kg) from the WBT’s currently assumed (in the absence of user defined data) char LHV value of 29.5 MJ/kg for all wood-derived char (P. Bailis et al., 2014; Taylor, 2009). It is important to have a value assumed for the case where a researcher is for some reason unable to get the data necessary, and so it is also important to know how much variance may be added by using this assumption. It should be noted that researchers can use various
methods (such as bomb calorimetry) to measure LHV and thereby decrease the error significantly from what is used in this study.

Eqs. 3-12 through 3-18 show $\phi_i$ for all $x_i$ parameters in Table 3-2 except for $C_p, m_{\text{water},i}$, $H_{\text{vap},i}, T_{\text{amb}}$, and $T_{\text{boil}}$. The $\phi_i$ for these parameters are not shown since the sum of the fractional contribution ($f_i$) of each of these parameters to $\delta_{th}$ accounted for less than 1% in the experimental studies.

\[
\Phi_{LHV_{\text{wood}}} = \frac{\delta_{LHV_{\text{wood}}}}{LHV_{\text{wood}}} \left[ \frac{1}{1 - \left( MC \left( \frac{LHV_c}{LHV_{\text{wood}}} \right) \right)} \right] = \frac{\delta_{LHV_{\text{water}}}}{LHV_{\text{wood}}} \cdot [\text{mod}_{LHV_{\text{wood}}}] \quad \text{Eq. 3-12}
\]

\[
\Phi_{\Delta T} = \frac{\delta_{\Delta T}}{\Delta T} \left[ \frac{1}{1 + \left( \frac{\Delta m_{\text{water}}}{m_{\text{water},i}} \right) \left( \frac{\Delta h_{H2O,fg}}{C_p \Delta T} \right)} \right] = \frac{\delta_{\Delta T}}{\Delta T} \cdot [\text{mod}_{\Delta T}] \quad \text{Eq. 3-13}
\]

\[
\Phi_{MC} = \frac{\delta_{MC}}{MC} \left[ \frac{1}{1 + \left( MC \left( \frac{LHV_c}{LHV_{\text{wood}}} \right) \right)} \right] = \frac{\delta_{MC}}{MC} \cdot [\text{mod}_{MC}] \quad \text{Eq. 3-14}
\]

\[
\Phi_{LHV_c} = \frac{\delta_{LHV_c}}{LHV_{c}} \left[ \frac{1}{1 - \left( MC \left( \frac{LHV_c}{LHV_{\text{wood}}} \right) \right)} \right] = \frac{\delta_{LHV_{c}}}{LHV_{c}} \cdot [\text{mod}_{LHV_{c}}] \quad \text{Eq. 3-15}
\]

\[
\Phi_{mc} = \frac{\delta_{mc}}{mc} \left[ \frac{1}{1 - \left( MC \left( \frac{LHV_c}{LHV_{\text{wood}}} \right) \right)} \right] = \frac{\delta_{mc}}{mc} \cdot [\text{mod}_{mc}] \quad \text{Eq. 3-16}
\]

\[
\Phi_{f_{cd}} = \frac{\delta_{f_{cd}}}{f_{cd}} \left[ \frac{1}{1 - \left( MC \left( \frac{LHV_c}{LHV_{\text{wood}}} \right) \right)} \right] = \frac{\delta_{f_{cd}}}{f_{cd}} \cdot [\text{mod}_{f_{cd}}] \quad \text{Eq. 3-17}
\]

\[
\Phi_{\Delta m_w} = \frac{\delta_{\Delta m_{\text{water}}}}{\Delta m_{\text{water}}} \left[ \frac{1}{1 + \left( \frac{\Delta m_{\text{water},i}}{\Delta m_{\text{water}}} \right) \left( \frac{\Delta h_{H2O,fg}}{C_p \Delta T} \right)} \right] = \frac{\delta_{\Delta m_{\text{water}}}}{\Delta m_{\text{water}}} \cdot [\text{mod}_{\Delta m_{\text{water}}}] \quad \text{Eq. 3-18}
\]
As seen, each $\phi_i$ has two essential elements. The first element is a ratio between the parameter uncertainty ($\delta_i$) and the corresponding value of the parameter. The second element is a modulation factor that may amplify or attenuate $\phi_i$ and can lead to some experimental guidelines as discussed later. When looking at the modularity terms in Eqs. 3-12 through 3-18, the modularity terms in Eqs. 3-12 and 3-14 through 3-17 will always amplify $\phi_i$ and the modularity terms in Eqs. 3-13 and 3-18 will always attenuate $\phi_i$.

Figure 3-2 shows the relationship between $\delta_{th}$ and $\eta_{th}$ where the units are % efficiency. The highest $\eta_{th}$ of 15% corresponds to a $\delta_{th}$ of 2.18% (which is 15% of $\eta_{th}$), and the lowest $\eta_{th}$ of 6.2% corresponds to a $\delta_{th}$ of 0.76% (which is 12% of $\eta_{th}$). Interestingly, $\delta_{th}$ has an upward linear correlation with $\eta_{th}$ with an intercept at the origin. The reason for the linear correlation is outlined in the discussion section. It should also be noted that there is no cookstove configuration involving a skirt that has a thermal efficiency below 11%. All cookstoves with skirts showed $\eta_{th}$ ranging from 11.7% to 14.6%. Of the tests with a cookstove configuration lacking a skirt, there is one (grate only) with $\eta_{th}$ of 15%. This point has been determined to be an outlier (it is well outside the 99% confidence interval of the other values). However, this outlier is still consistent with the linear relationship. None of the other tests without a skirt reached a $\eta_{th}$ greater than 10.3%. The $\eta_{th}$ for both configurations with a skirt were significantly greater (99% confidence) than the configurations without a skirt. The average efficiencies (standard deviation) for the basic, skirt, grate, and both configurations were 8.9% (1.8%), 12.8% (0.8%), 8.6% (1.5%), and 13% (1.4%) respectively. This again shows that the skirt is critical to increasing the thermal efficiency by ensuring that more of the thermal energy released by the fuel is transferred to the water in the pot. This is consistent with the findings in Table 3-1 where less wood was used with a skirt.
Figure 3-2. Propagated Maximum Error ($\delta_{th}$) vs. $\eta_{th}$. Both axes are in units of % efficiency. The squares, triangles, circles, and diamonds represent data from the basic cookstove, the cookstove with a grate added, the cookstove with a skirt added, and the cookstove with both a grate and a skirt added, respectively.

Figure 3-3 shows $f_i$ for the top four parameters contributing to $\delta_{th}$ for each cookstove configuration. Each bar represents the average $f_i$ for all studies involving a given cookstove configuration, with the error bars representing one standard deviation. Interestingly, the average $f_i$ associated with $LHV_{wood}$ was around 0.44 (44%) for all configurations. Thus, a more accurate value of $LHV_{wood}$ would reduce $\delta_{th}$. The average $f_i$ for $\Delta T$ was near 0.10 (10%) for all cookstove configurations. The average $f_i$ for $MC$ was near 0.26 (26%) and the average $f_i$ for $LHV_c$ was around 0.14 (14%) for all cookstove configurations. For each cookstove configuration, the top four parameters accounted for approximately 93% of $\delta_{th}$. 
Figure 3-3. Fraction contribution to uncertainty ($f_i$). The figure shows $f_i$ (Eq. 10) for the top four most contributing parameters in Eqs. 3-1 through 3-5. The solid, slanted lined, circle filled, and empty columns represent data from the basic cookstove, the cookstove with a grate added, the cookstove with a skirt added, and the cookstove with both a grate and a skirt added, respectively.

It is interesting to note that for each cookstove configuration, the $f_i$ values appear to be independent of the cookstove configuration. Based on the four parameters contributing the most to $\delta_{th}$, the independence is expected since $LHV_{\text{wood}}$ and $LHV_c$ are based on literature values and $\Delta T$ and MC are controlled variables. Also of interest is that when $f_i$ for $\Delta T$ increases or decreases, the $f_i$ contribution for $LHV_c$ changes in the opposite direction. In general, more accurate LHV values, thermocouples, and moisture analysis than was used in this study would be beneficial.

Figure 3-4 shows $\sigma_{th}$ versus $\eta_{th}$ for all studies (diamonds) where a linear correlation is again observed. Regression results in $\sigma_{th}=0.029\times\eta_{th}$ with an $R^2$ value of 0.96. The 95% confidence interval of the linear fit (dotted lines) is also shown. The confidence interval
demonstrates a very tight fit around the line such that the line is a very accurate representation of \( \sigma_{th} \) versus \( \eta_{th} \) for this study.

**Figure 3-4.** Propagated Standard Deviation (\( \sigma_{th} \)) vs. \( \eta_{th} \). Both axes are in units of % efficiency. The data for all cookstove configurations is shown as diamonds, with a solid trendline for the fit. A 95% confidence interval of the linear fit is also shown as a dotted line.

In cookstove studies, the standard deviation associated with a group of experiments is often reported. The difficulty of only reporting the standard deviation is that it does not necessarily include all uncertainties (a differing LHV value based on different literature sources, for instance, would result in a bias in the observed values that could not be accounted for with a simple standard deviation of the data) although it does include error associated with testing conditions that are not explicitly included in the calculation of \( \sigma_{th} \). Testing conditions would include parameters such as wind speed, ambient temperature, atmospheric pressure, and relative
humidity, which would require further investigation as to their effects. Thus, comparison of $\sigma_{th}$ using propagation of uncertainties in measurements and input data with the uncertainty calculated using the standard deviations of the results of a group of experiments is informative. Therefore, Figure 3-5 includes the average $\eta_{th}$ and associated standard deviation (symbols) of the group of experiments for each cookstove configuration with a line representing the regression curve from Figure 3-4. The average $\eta_{th}$ (and $\sigma$) for the basic stove, skirt, grate, and both grate and skirt configurations were 8.9 (±1.8), 12.8 (±0.8), 9.7 (±2.9), and 13 (±1.4) % respectively. The line was extrapolated to 40% assuming that the linear relationship between $\sigma_{th}$ and $\eta_{th}$ was still valid over this extended range. Based on the four parameters above that contribute the most to the propagated uncertainty, the assumption of linearity over this range is likely valid if the same equipment were used in all experiments. Further validation of the linearity is discussed below. Additionally, the extremely consistent data and tight confidence interval shown in Figure 3-4 suggests that this extrapolation is also valid.

As can be seen in Figure 3-5, the averaged results for each cookstove configuration gives a higher standard deviation than can be accounted for by just $\sigma_{th}$. This result clearly indicates that in the low $\eta_{th}$ range, standard deviations associated with $\eta_{th}$ are dominated by variability in ambient conditions (e.g. wind speed, humidity, etc.) and testing procedures (e.g. method and rate of feeding wood, using unprocessed versus processed fuels, etc.) that are not directly part of the efficiency equation and are much more difficult to control. However, measurement uncertainty can potentially become more important as $\eta_{th}$ increases as shown in Figure 3-5. Thus, it would be beneficial when comparing cookstoves to address the contributions of measurement and input data uncertainties. In some instances, measurement uncertainty (e.g. temperature and percent moisture) can depend upon the equipment used. In contrast, literature data uncertainty due to the
LHV values depend upon the literature value used and the associated uncertainty of the value. Thus, cookstove results should report all input data (e.g. \( LHV_{wood} \)).

![Figure 3-5. Standard Deviation (\( \sigma \)) vs. \( \eta_{th} \). Both axes are in units of \% efficiency. The unfilled squares, triangles, circles, and diamonds represent standard deviations associated with each group of experiments for the basic cookstove, the cookstove with a grate added, the cookstove with a skirt added, and the cookstove with both a grate and a skirt added, respectively. The solid line represents the propagated standard deviation regressed from Figure 3-4 and is extended to 40\% efficiency.](image)

3.4 Discussion

Analyzing the modulation factors in Eqs. 3-12 through 3-18 leads to some insight into the behavior of the uncertainty associated with these parameters. For example, Eq. 3-12 indicates that decreasing the moisture content (MC) of the wood will increase the denominator of the modulation factor and therefore reduce the \( LHV_{wood} \) contribution to \( \delta_{th} \). A low ratio of charcoal produced to fuel burned (\( m_{ce}/f_{cm} \)) will also reduce the \( LHV_{wood} \) contribution to \( \delta_{th} \), though this is a characteristic of the stove and cannot be changed through changes in the protocol. Wood with
higher $LHV_{wood}$ will also lead to lower uncertainty. Thus, studies using dry, hard woods will generally experience less uncertainty than studies using more moist woods and/or soft woods. However, it is important to use wood that is appropriate for the stove design and to know how that will affect uncertainty.

Interestingly, Eq. 3-13 shows that bringing the ratio of $\Delta m_w$ to $m_{wi}$ to its maximum value of unity would be the protocol change that would most reduce the uncertainty contribution from $\Delta T$. This is unrealistic since boiling to completion takes a significant amount of time. If 15% of the water is boiled ($\Delta m_{water}/m_{water,i} = 0.15$), the $\Delta T$ uncertainty contribution would be 50% of the contribution compared to when no water is boiled, and if 50% of the water is boiled, the contribution of the uncertainty in $\Delta T$ decreases to 29%. This calculation was based on a $\Delta T$ of 80 K, which is a typical value for cookstove tests. However, implementing this strategy for reducing the uncertainty in $\eta_{th}$ would dramatically increase the time required to perform a test which would likely not be practical. Additionally, a higher $\Delta T$ also leads to a lower contribution such that starting with a colder water and approaching boiling could be another option for reducing the uncertainty contribution from $\Delta T$. However, there are physical limitations since $\Delta T$ is bound by realistic operating conditions between ambient temperature and boiling. It is, therefore, best to control the uncertainty due to temperature measurements by either calibrating thermocouples or using more accurate devices to measure temperature such as an RTD.

Eqs. 3-14 through 3-17 also indicate that low $MC$ and low $m_{eff,cm}$ will minimize the contribution of the uncertainty in $MC$ and $LHV_c$ to the uncertainty in $\eta_{th}$. Thus, similar to the findings in Eq. 3-12, dry wood would be the best to use to reduce measurement uncertainty. However, dry wood is often not found in the field and some stoves do not perform as well with dry wood. In situations where moist wood is needed, it would be important to pay more
particular attention to minimizing measurement uncertainty of moisture content. Additionally, minimizing the formation of charcoal by increasing airflow would be beneficial.

Eq. 3-18 shows similar design guidelines found in Eq. 3-13. For instance, a large $\Delta T$ can help mitigate the uncertainty associated with $\Delta m_{\text{water}}$. However, Eq. 3-18 is not affected by the ratio of $m_{\text{water},i}$ to $\Delta m_{\text{water}}$, but rather is affected individually by $m_{\text{water},i}$ and $\Delta m_{\text{water}}$. Both a large $m_{\text{water},i}$ and $\Delta m_{\text{water}}$ will mitigate this uncertainty. This would imply using the largest amount of water and boiling it to completion. However, using a large amount of water may decrease the relevancy of the results as the stove should be tested under conditions as similar to field use as possible. Considering that $f_i$ of $\Delta m_{\text{water}}$ is very small (and therefore $\phi_{\Delta m_{\text{water}}}$ is very small), and the possibility of less useful results, this method of reducing uncertainty is not worth the time and cost for most studies.

Another interesting result is that the summation of each $\phi_i$ explains the linearity of the uncertainty as shown in Figures 3-2 and 3-4. In Eqs. 3-12 through 3-18, all of the parameters in the modulation terms except $m_c/f_{cm}$ can be controlled and remain the same between experimental studies, even if cookstove configurations change significantly as was done in this study. Additionally, $m_c/f_{cm}$ is usually less than 0.1. Focusing on the four most significant parameters (Eqs. 3-12 through 3-15) shown in Figure 3-3, since $f_i$ for each parameter was constant, then the $\phi_i$ was also constant according to Eq. 3-10. Therefore, Eq. 3-9 shows that ratio of $\delta_{th}/\eta_{th}$ is constant which is consistent with Figure 3-2. Similarly, Eq. 2-11 also shows then that ratio of $\sigma_{th}/\eta_{th}$ is constant which is consistent with Figure 3-4.

It should be noted that the actual values of the contributions reported in this study are specific to this set of experimental parameters, equipment, and testing protocols. However, Eqs.
3-12 through 3-18 can be readily used in any cookstove study that uses the same definition for \( \eta_{th} \) to calculate \( \delta_{th}, f_i, \) and \( \sigma_{th} \) associated with measurement and input data at any given \( \eta_{th}. \)

### 3.5 Conclusions

This study showed how to quickly determine propagated values of \( \delta_{th} \) and \( \sigma_{th} \), as well \( f_i, \) from a given \( \eta_{th} \) based on uncertainties associated with measured and input data associated with the efficiency equation. This allows for an understanding of how significant \( \delta_{th} \) and \( \sigma_{th} \) are in comparison to \( \eta_{th}. \) Additionally, this analysis is important because it helps assess how these values can compare to population standard deviations for a set of experiments and provides some guidance as to the importance of measurement and input value uncertainties. As shown, \( \delta_{th} \) becomes increasingly important as \( \eta_{th} \) increases. Thus, rigorous assessment of the relative impact of all measured and input parameters on cookstove performance metrics, such as \( \eta_{th}, \) is critical. In addition, the fractional contribution \( (f_i) \) of each parameter to \( \delta_{th} \) indicates which parameters are important to focus on for reducing measurement and input value uncertainties.

For this study \( LHV_{water}, LHV_{ch}, \Delta T, \) and \( MC \) were the critical parameters such that more accurate LHV values, thermocouples, and moisture analysis would be beneficial. It should also be noted that, while not part of this study, the effects of error in separating wood and char values can be very important. These effects can be found in Taylor’s work, where it was suggested that it is better to err on the side of counting char as fuel rather than the other way around (Taylor, 2009).

Another valuable aspect of this study is that it provided guidance on experimental procedures to minimize measurement and input data uncertainty contributions to \( \eta_{th}. \) The results of this study indicate that reducing the moisture content of the wood, reducing the ratio of the
mass of the char to the mass of wood, using wood with a large heating value, boiling off a reasonable fraction of the water (e.g. 15%) in the pot, and starting with relatively cold water will reduce the uncertainty in the measured thermal efficiency. However, these recommendations may have large costs associated with them (e.g. time to boil water), may have physical limitations (e.g. $\Delta T$ is bound by the freezing and boiling temperatures), and/or may be limited by the operational guidelines of the cookstove (e.g. moisture content, fuel type, etc.).

On the other hand, the $\delta_i$ associated with each parameter $x_i$ is much easier to decrease. For LHV values, as previously stated it may not be possible to significantly reduce the uncertainty in wood LHV values when using cut wood unless a more processed fuel such as wood pellets is used. However, the LHV of the char may be significantly easier to estimate as the char can be easily ground into a powder and either measured by bomb calorimetry or estimated through various means (e.g. by analyzing the chemical makeup of the char and Thornton’s rule or proximate analysis). By comparison with LHV values, thermocouples are much easier to improve through calibration. The WBT protocol suggests a minimum accuracy of +/- 0.5 °C, which improves the uncertainty from thermocouples compared to uncalibrated thermocouples which can be on the order of +/- 2.0 °C based on manufacturer specifications. Another important observation is that moisture content ($MC$) can be much more accurately obtained through the oven-drying method, which suggests that the moisture meter may not be the optimal choice although the meter is much simpler and quicker to use.

It should be noted that the above conclusions address issues associated with parameters directly expressed in the $\eta_{th}$ definition (Eqs. 3-1 through 3-5). The above method can be applied to any study to assess the impact of measurement uncertainty using reasonable values for that study. It is important to characterize and report measurement uncertainty associated with the
parameters to provide insights on which measurements contribute the greatest amount to uncertainty and the degree to which measurement error contributes to overall uncertainty which also includes effects of indirect parameters (such as shape of fuel, wind speed, humidity, etc.). Particularly, reporting the LHV value and its associated uncertainty is highly valuable. It is also beneficial that all literature data and test conditions be reported to enable better comparisons between cookstoves. Once the confidence in these values can be assessed, it is useful to investigate further uses of the data gathered during the testing process.

This chapter is based off of a published article (Quist, C. M., Jones, R. B., Jones, M. R., & Lewis, R. S., 2016). I hereby confirm that the use of this article is compliant with all publishing agreements.
4 Transient Thermal Efficiency Estimation

4.1 Introduction

Biomass cookstoves are commonly used for cooking throughout the developing world. Unfortunately, use of biomass cookstoves creates emissions that can be hazardous to users and the environment. These emissions increase the threat of asthma, release cancer causing agents and can lead to carbon monoxide poisoning (Abeliotis & Pakula, 2013; Chowdhury, 2012; Hawley & Volckens, 2013; Mueller et al., 2011). The environmental effects of these cookstoves range from release of gases that contribute to climate change to release of particulate matter that may have an effect on glacial melting (Bond et al., 2013).

These issues with biomass cookstoves have been the impetus for continually growing efforts to improve cookstoves. This effort has produced a large number of well-engineered cookstoves, but comparison and selection continues to be an issue (J. J. Jetter & Kariher, 2009; N. MacCarty et al., 2010). Many cookstoves are built with different purposes in mind, such as cooking a stew vs. cooking a flatbread. Other cookstoves use different kinds of fuel, including wood, leaves, or dung. Compounding these issues is that the metrics that are important in comparing cookstoves are not completely settled or characterized (Kshirsagar & Kalamkar, 2014; Taylor, 2009). Some of the metrics that have been used in cookstove comparison and selection have included thermal efficiency, fuel economy, emissions, and high and low power fuel rates (J. Jetter et al., 2012; Taylor, 2009). These metrics may or may not be comparable for
stoves of different feeding rates, fuel types, etc. and so it is important to understand how various experimental parameters affect the performance metric used for comparison.

One of the most commonly used metrics is that of thermal efficiency. Average thermal efficiency ($\eta_{avg}$) typically obtained at the end of a cookstove test is defined as the total amount of heat that goes into the water in the pot divided by the total energy potentially available to the pot during the test. There are many challenges associated with using $\eta_{avg}$ as a metric for comparing biomass cookstoves. Some of these challenges originate from the fact that all the data points that are used in its calculation are based on measurements taken at the beginning and end of the test and so are an average of the efficiency over the course of the whole test. Unfortunately, not every test uses the same endpoints.

Assessment of $\eta_{avg}$ has typically been obtained using the Water Boiling Test (WBT) (P. Bailis et al., 2014; J. Jetter et al., 2012; Kshirsagar & Kalamkar, 2014; N. MacCarty et al., 2010; Manoj et al., 2013). Recently, the WBT has been superseded by ISO 19867-1 (International Organization for Standards, 2018). While both of these protocols call for the water to actually boil, some researchers prefer to finish tests at 90 °C (P. Bailis et al., 2014; Defoort, Orange, Kreutzer, & Lorenz, 2009). This study was made using the WBT definitions and procedures, but the concepts contained apply to both methods. How $\eta_{avg}$ depends on the methods used within the protocol or how fire placement affects $\eta_{avg}$ during the course of the experiment is not yet fully defined. For instance, $\eta_{avg}$ may be effectively evaluated long before boiling occurs, which would significantly reduce the time required to test a stove. In addition, differences between a cold start analysis and a hot start analysis of the WBT needed to be quantified more rigorously. The cookstove is at ambient temperature at the beginning of a cold start test, while a hot start test
begins shortly after a cold start test finishes and must be started while the cookstove is still significantly above the ambient temperature. The designers of the WBT are aware of the many challenges inherent in the current testing protocol and so it is important to be familiar with the limitations of the test (P. Bailis et al., 2014).

The objective of this research is to demonstrate that analysis of the time-dependent behavior of $\eta_{avg}$ (denoted as $\eta_t$) overcomes some of these challenges and enables at least some comparison of results of tests with different endpoints. Additionally, comparing $\eta_t$ predictions obtained during cold and hot starts provides significant insights.

4.2 Materials and Methods

4.2.1 Testing chamber and cookstove

A modified Peruvian-style channel cookstove was used for all tests as shown in Figure 4-1. The Peruvian-style channel cookstove in its most basic form is simply two rows of bricks stacked parallel to each other. The cookstove used in these experiments included a grate between the first and second layer of bricks and a pot skirt (see Figure 4-1). The brick walls used in this cookstove were 3.5 bricks high and 2.5 bricks long, which resulted in a wall 19.5 cm tall by 56 cm long and 10 cm wide.

This cookstove was placed inside a cinderblock structure that was built on a metal cart. The cinderblock structure measured 1.4 m long, 0.8 m wide, and 0.7 m tall. Within the cinderblock structure, the cookstove was placed on a 6.4 mm thick metal plate that was placed on a 10 cm deep container of sand. The container of sand was used to simulate typical conditions in which the cookstove is on the ground. An exhaust hood was attached to the top of cinderblock
structure. The flue and exhaust hood fan combined to give the hood a flow rate of approximately 16 L/min, which was used for safety only and not emissions data collection.

![Figure 4-1](image)

**Figure 4-1.** (A) Cookstove testing chamber with a traditional Peruvian brick channel cookstove resting atop a metal plate. A skirt surrounds the pot that sits on top of the stove. The cookstove is placed in a hood vented to a chimney that is augmented by a fan. (B) The wood is arranged in a ‘log-cabin’ configuration made of sticks measuring 2 cm x 2 cm x 13 cm. There are 4 layers of sticks, with each layer containing 2 sticks.

### 4.2.2 Experimental protocol

The WBT protocol (P. Bailis et al., 2014) was followed and the measured values were used to calculate $\eta_{avg}$. The wood used in these experiments was Douglas fir cut into 2 cm x 2 cm x 25 cm uniform sticks. The wood was dried in a dehydrator for approximately 24 hours before testing to minimize the moisture content. The moisture content was consistently below the detectable limit of 5% (dry basis) for all experiments as measured using a General Tools wood
moisture meter (MMD4E The Seeker, General Tools, New York City, NY) and was dried with a profile that was shown to lead to approximately a 2.5% moisture content (dry basis). Figure 4-2 shows the mass loss of wood as it is dried in both a dehydrator and in an oven. The mass percent water of the sticks dried in the dehydrator was about 2.1% remaining, assuming that the mass of the sticks dried in the oven are fully dried out sticks. The oven drying method is the method suggested in the WBT protocol for determining percent water mass. At this low of a percent moisture, the effects of even a 100% increase or decrease in water mass on the efficiency of the cookstove used in these experiments is minimal.

![Figure 4-2](image.png)

**Figure 4-2.** Mass loss of drying wood in a dehydrator and in an oven. The oven-based final mass is considered the dry mass of the wood.

The water was placed in a 25-cm high by 25-cm diameter (15 liter) pot. Four cold-start experiments were conducted in which the pot was initially filled with 2.5 liters of water. Three hot-start experiments were conducted in which the pot was initially filled with 2.5 liters of water whereas the remaining four hot-starts were conducted using 5.0 liters of water. The difference in
water volume was used to assess its impact on $\eta_{avg}$. The temperature of the water was measured every two seconds using a k-type thermocouple.

A log-cabin configuration of wood was used at the beginning of each test to start the fire (Figure 4-1B). The log-cabin structure was formed from four layers of two sticks where the sticks were half of the original length. Small pieces of wood and two full-length strips (~3 cm wide) of torn newspaper were placed in the middle of the log cabin as a starter. Once the fire was started, full-length sticks were added at four-minute intervals. Bundles of two and three sticks were alternately added to the fire, and this pattern continued throughout the experiment. Some experiments ended when the water reached a particular state (90 °C, boiling, etc.) and others ended at a specified time. At the end of the test, the fire was pulled out from within the cookstove and smothered. The masses of the remaining wood and charcoal (both in the chamber and removed from charred wood) were weighed using a digital scale with an accuracy of ± 0.5 g. Both the cold start and hot start experiments used this method, with an additional requirement for the hot starts that a hot start phase be started immediately following either a cold start or another hot start.

### 4.2.3 Estimation of average thermal efficiency ($\eta_{avg}$) with time

The thermal efficiency ($\eta$) of a biomass cookstove is given by

$$\eta = \frac{E_{pot}}{E_{fuel}} = \frac{C_{Pw}*m_{water, i}*\Delta T + \Delta h_{H2O,fg}*\Delta m_{water}}{f_{cm}*(1-MC)*LHV_{wood} - f_{cm}*(MC+y)*LHV_{wood} - LHV_c + m_c}$$

Eq. 4-1

where $E_{pot}$ is the heat transferred to the water in the pot and $E_{fuel}$ is the energy theoretically available to the pot if the fuel completely combusts. For the WBT, the measured parameters in Eq. 4-1 were recorded at the beginning and end of the test leading to an average thermal
efficiency for the entire test where \( \eta = \eta_{\text{avg}} \). Note that Eq. 4-1 does not differ from the expression originally used in the WBT protocol as it is only a rearrangement of terms (P. Bailis et al., 2014). The two terms in the numerator represent the sensible and latent heat transferred to the water. Here, \( C_{p_w} \) is the heat capacity of water at 100 °C, \( m_{\text{water},i} \) is the initial mass of water, \( \Delta T \) is the change in temperature over the course of the test, \( \Delta h_{H_2O,fg} \) is the heat of vaporization at the ambient pressure (assumed to be one atmosphere), and \( \Delta m_{\text{water}} \) is the mass of the water that was vaporized during the test. The three terms in the denominator represent the energy in the dry wood that is used, the energy needed to remove moisture from the wood, and the energy remaining in the charcoal after the burn. The latter two terms are subtracted from the first term so that \( E_{\text{fuel}} \) represents the available energy. Here, \( f_{cm} \) is the mass of the fuel consumed during the test, \( MC \) is the initial percent moisture of the wood, \( LHV_{\text{wood}} \) is the lower heating value of the wood, \( LHV_{c} \) is the lower heating value of the char from the wood, \( m_c \) is the mass of char remaining at the end of the test, and \( y \) is a factor to account for the energy lost to evaporation of the moisture in the wood, which is defined as,

\[
y = \frac{[C_{p_w}(T_{\text{boil}}-T_{\text{amb}})+\Delta h_{H_2O,fg}]}{LHV_{\text{wood}}} \tag{4-2}
\]

where \( T_{\text{boil}} \) is the boiling temperature at one atmosphere of pressure and \( T_{\text{amb}} \) is the ambient temperature.

While most of the terms in these equations stay constant throughout the experiment, to calculate \( \eta_t \) (the time-dependent average) there are four terms in Eq. 1 that need to be measured or calculated as functions of time. The four terms are \( \Delta T \), \( \Delta m_{\text{water}} \), \( f_{cm} \), and \( m_c \). The initial moisture content of the wood, \( p_m \), also varies with time. However, the wood is initially well dried, so variations in \( p_m \) are neglected. Of these four terms, \( \Delta T \), \( f_{cm} \), and \( m_c \) are simple to
measure or approximate with time. A thermocouple can be used to measure the temperature at any time, so \( \Delta T \) can be measured at any time. In contrast, total \( f_{cm} \) and \( m_c \) are measured at the end of the test and it was assumed that these parameters varied linearly with time since an approximately constant consumption of wood \( (f_{cm}) \) could be observed from data (Bussman, 1988) in previous studies (though this observation was not noted by Bussman), even with wood added in batches throughout the experiment.

The key to the analysis of \( \eta_t \) is the temperature data taken during each experiment. The thermocouples used were k-type thermocouples with data points taken every two seconds. To estimate \( \Delta m_{water} \) with time, a mass balance of the water on the pot was used since the only data obtained was \( \Delta m_{water} \) at the end of the experiment, which is typical of the WBT. The mass balance for water, assuming a well-mixed system, is

\[
\frac{dm}{dt} = -k \cdot A \cdot (P_i^s - P_{w}^a)
\]

Eq. 4-3

where \( m \) is the mass of water in the pot, \( t \) is time, \( k \) is the mass transfer coefficient characterizing water loss from the pot based on a partial pressure driving force, \( A \) is the surface area of the water exposed to the atmosphere (which may be combined with \( k \) to create a single constant), \( P_i^s \) is the partial pressure of water vapor at the water surface, and \( P_{w}^a \) is the partial pressure of water in the atmosphere which is associated with the humidity. Because the system is at low pressure, \( P_i^s \) can be approximated using Raoult’s Law which shows that \( P_i^s = x_i \cdot P_i^* \) where \( x_i \) is the mole fraction of water in solution (which is unity) and \( P_i^* \) is the vapor pressure of water at its current temperature. Thus, \( P_i^s \) is equivalent to \( P_i^* \) evaluated at the water surface temperature. For this study, the surface temperature was approximated to be equal to the temperature of water in the
pot (which changes with time). $P^a_w$, which is constant, was obtained from relative humidity data at the ambient temperature.

Assuming a constant time-averaged value of $k$, integrating Eq. 4-3 gives

$$\Delta m_{water} = k \cdot A \int_0^t (P^s_w - P^a_w) dt$$  \hspace{1cm} \text{Eq. 4-4}

It is important to note that $k$ is not truly constant over the course of the experiment, and especially when the water approaches boiling the assumption of constancy is no longer valid. Over the course of the entire experiment, the temperature of the water is measured with time. Therefore, $P^s_w$ at each temperature can be calculated from the Riedel Equation (Riedel, 1954; Sandler, 2006; Vetere, 2006) and therefore $(P^s_w - P^a_w)$ as a function of time can be generated. The time-averaged value of $k$ is then obtained by dividing the measured $\Delta m_{water}$ at the end of the experiment by the water surface area and the area under the $(P^s_w - P^a_w)$ curve. Once $k$ is determined, $\int_0^t (P^s_w - P^a_w) dt$ may be evaluated at any time such that Eq. 4-4 then provides an estimate of $\Delta m_{water}$ at any time. Now that the four terms, $\Delta T$, $\Delta m_{water}$, $f_{cm}$, and $m_c$, are either measured or estimated as functions of time, $\eta_t$ is determined using Eq. 4-1. The results and discussion section provide details regarding the validation of this approach.

4.3 Results and Discussion

Table 4-1 shows a summary of measured and calculated values for each cold start (CS), hot start (HS), and validation (VAL) experiments. As can be seen, there was variation in the tests. Some of this variation was controlled during the experiment ($m_{water,i}$, $\Delta T$, Final T, and whether boiling occurred) and some variation ($\Delta m_{water}$, %lost, and $\eta_{avg}$) was a consequence of
the testing process. For instance, the percent of the initial water that was lost during the experiment (due to vaporization or boiling) ranged from 1.1% to 24.8%. Similarly, there was a wide range in ΔT from 21.1 to 72.7 K. These types of uncontrolled or controlled variations can lead to variations in $\eta_{avg}$. This leads to the question as to whether $\eta_{avg}$ can be compared between tests when such variations occur. For instance, the CS experiments showed $\eta_{avg}$ varying from 11-17%. In the literature, there is also a fair amount of variation in cookstove testing between different types of cookstoves. The remaining results demonstrate how $\eta_t$ can be assessed, resulting in valuable insights when comparing cookstove tests even in the presence of uncontrolled or controlled variations with varying test endpoints.

**Table 4-1:** Summary of measured and calculated values for each experiment. $m_{water,i}$ is the mass of initial water in the pot, $\Delta m_{water}$ is the mass lost over the course of the experiment, % lost is the percent of the initial mass that was lost over the course of the experiment, ΔT is the temperature difference from the beginning to the end of the test, Final T is the temperature of the water at the end of the test, the Boiled column indicates whether or not the water boiled during the test, and $\eta_{avg}$ is the average thermal efficiency at the end of the test.

<table>
<thead>
<tr>
<th>Test</th>
<th>$m_{water,i}$ (g)</th>
<th>ΔT (K)</th>
<th>Final T (°C)</th>
<th>Boiled</th>
<th>$\Delta m_{water}$ (g)</th>
<th>% lost</th>
<th>$\eta_{avg}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>2468</td>
<td>21.1</td>
<td>94.8</td>
<td>Y</td>
<td>611</td>
<td>24.8</td>
<td>16.5</td>
</tr>
<tr>
<td>CS2</td>
<td>2505</td>
<td>72.7</td>
<td>95.0</td>
<td>Y</td>
<td>319</td>
<td>12.8</td>
<td>15.5</td>
</tr>
<tr>
<td>CS3</td>
<td>2490</td>
<td>64</td>
<td>90.9</td>
<td>N</td>
<td>87</td>
<td>3.5</td>
<td>14.3</td>
</tr>
<tr>
<td>CS4</td>
<td>2449</td>
<td>69.2</td>
<td>90.2</td>
<td>N</td>
<td>144</td>
<td>5.9</td>
<td>11.3</td>
</tr>
<tr>
<td>HS1</td>
<td>4910</td>
<td>68.2</td>
<td>89.8</td>
<td>N</td>
<td>144</td>
<td>2.9</td>
<td>18.5</td>
</tr>
<tr>
<td>HS2</td>
<td>4916</td>
<td>71.4</td>
<td>91.2</td>
<td>N</td>
<td>172</td>
<td>3.5</td>
<td>17.6</td>
</tr>
<tr>
<td>HS3</td>
<td>4943</td>
<td>69.9</td>
<td>90.4</td>
<td>N</td>
<td>156</td>
<td>3.2</td>
<td>16.3</td>
</tr>
<tr>
<td>VAL1</td>
<td>2524</td>
<td>35.5</td>
<td>62.2</td>
<td>N</td>
<td>40</td>
<td>1.6</td>
<td>15.2</td>
</tr>
<tr>
<td>VAL2</td>
<td>2492</td>
<td>71.5</td>
<td>94.3</td>
<td>Y</td>
<td>125</td>
<td>5.0</td>
<td>18.0</td>
</tr>
<tr>
<td>VAL3</td>
<td>2481</td>
<td>70.5</td>
<td>94.9</td>
<td>Y</td>
<td>351</td>
<td>14.2</td>
<td>16.7</td>
</tr>
<tr>
<td>VAL4</td>
<td>4918</td>
<td>41</td>
<td>63.7</td>
<td>N</td>
<td>55</td>
<td>1.1</td>
<td>17.2</td>
</tr>
</tbody>
</table>
The time-dependent temperature profile (solid line) shown in Figure 4-3 (from CS2) is representative of the measured temperature profiles for cold start tests. The water temperature was measured every two seconds. Each experiment showed similar trends. There is a short lag time at the beginning of the experiment where the fire has not reached its steady-state burning. Once the fire begins to approach a steady burning rate, the water heats up in a nearly linear manner until it approaches the boiling temperature. As it approaches the boiling temperature, the rate at which water evaporates increases, and the rate at which the temperature of the water changes decreases. When the experiment reaches the boiling temperature, the water temperature stays constant as expected.

Figure 4-3. Temperature and efficiency with time of water in the pot for a cold start (CS4). This data is from an individual cold start that reached boiling. Included are the temperature profile (solid line), total efficiency (alternating dashes and dots), efficiency due to temperature increase (dotted line), and efficiency due to water evaporation (dashed line). $\eta_t$ was calculated based on Eq. 1.
Figure 4-3 also shows the prediction of $\eta_t$ for CS2. The figure includes total $\eta_t$ (dashes and dots), the portion of $\eta_t$ resulting from water heating which is the first term in the numerator of Eq. 4-1 (dots), and the portion of $\eta_t$ resulting from water loss through vaporization which is the second term in the numerator of Eq. 4-1 (short dashes). As expected, $\eta_t$ associated with water vaporization becomes more important as the water temperature approaches the boiling point due to the non-linear effect of vapor pressure with temperature. With this non-linear effect, $\Delta m_{\text{water}}$ increases non-linearly according to Eq. 4-4. The distinction between the total $\eta_t$ and the $\eta_t$ due to water heating increases significantly as the water heats up. The percentage of $\eta_t$ due to water evaporation reaches a value near 50% at the end of the experiment shown. Early on (before 400 seconds with this study), the percentage of $\eta_t$ due to water evaporation is below 10% such that its contribution is not as critical during the early stages. The contribution due to water heating (middle line) decreases near boiling since the $\Delta T$ term in the numerator of Eq. 4-1 remains constant while the denominator continues to increase due to the burning of wood. The distinction of $\eta_t$ information in Figure 4-3 is valuable, especially when seeking to compare results from studies in which the pot was covered with studies in which the pot was uncovered. For instance, having a lid will decrease the contribution associated with water vaporization, but it is unclear how the total $\eta_t$ would be affected. Comparisons will be more applicable if $\eta_t$ information is available since $\eta_{\text{avg}}$ provides less comparison information.
Figure 4-4. Mass transfer coefficients \( (k) \) calculated for each experiment which characterizes water lost from the post. Values of \( k \) were calculated using Eq. 4-4. The \( k \)-values are separated into non-boiling (solid bars) and boiling (horizontally-lined bars).

The \( k \) values calculated for the experiments of this study are shown in Figure 4-4. The values of \( k \) are shown according to experiments where the water did not reach the boiling temperature by the end of the experiment and where the water did reach the boiling temperature. As is evident, \( k \) values are very consistent among the non-boiling experiments (except two values, VAL1 and VAL4, that are nearly three times as high as the other values) and similarly consistent, but different, among the boiling experiments. For VAL1 and VAL4, these studies stopped at a much lower ending temperature (~63 °C) than the other non-boiling experiments (ending above 90°C) and a plausible explanation and analysis is presented in the discussion section. With removal of these two high values, the averages and standard deviations of the non-boiling and boiling experimental \( k \) values were 0.9 ± 0.1 and 1.3 ± 0.2 mg m\(^{-2}\) Pa\(^{-1}\) min\(^{-1}\),
respectively. These values are statistically different at the 99% confidence level. It was expected that boiling studies would have slightly higher $k$ values than the non-boiling studies since boiling can increase the time-averaged mass transfer coefficient. An increased value of $k$ due to boiling can over predict $\Delta m_{\text{water}}$ with time during the early stages of the experiment. However, this over prediction would minimally impact $\eta_t$ predictions since, as previously shown in Figure 4-3, the $\eta_t$ term related to water mass loss is a small fraction (<10%) of $\eta_t$ during the initial stages of water heating. It should be noted that the $k$ values were consistent even when the time and type (hot start vs cold start and 2.5 liters vs 5.0 liters) of experiments varied, further demonstrating the validity in estimating $k$ values for $\Delta m_{\text{water}}$ predictions with time.

**Figure 4-5.** Average thermal efficiency ($\eta_t$) predictions with time and validation experiments for hot starts. Each hot start is represented by a line, while the four validation runs are represented by symbols. The standard deviations of each experiment are based on propagated error analysis (Bethea & Rhinehart, 1991).

Figure 4-5 shows the prediction of $\eta_t$ for the three hot starts (HS1, HS2, and HS3) having 5 liters of water in the pot. The standard deviations shown at the end of the run are based on
propagated error analysis (Bethea & Rhinehart, 1991). The general shape of $\eta_t$ for these experiments shows a slight delay (30 s or less) followed by a steep increase that levels out to a constant value. All hot start tests showed that $\eta_t$ reached near-steady state at close to 400 s into the experiment, however before that time there is significant noise in the prediction because of minor variations in the temperature reading. At the end of the test, the hot start replicates reached an average $\eta_t$ value of 17.6% (standard deviation of 1.4 %) which is equivalent to $\eta_{avg}$ that would be obtained with the WBT.

In addition, four $\eta_{avg}$ values were calculated for three hot starts (VAL1, VAL2, and VAL3) using 2.5 liters of water and one hot start (VAL4) using 5.0 L of water to validate the predictions of $\eta_t$. $\eta_{avg}$ does not require any predictions with time so a $k$ value is not needed. The error bars are also based on the same propagated error analysis noted above. As shown, the $\eta_{avg}$ for all validation experiments were within the range of $\eta_t$ predictions for the hot starts. Although not part of this study, the validation experiments showed that water amount may not be significant for hot start analysis although further experiments need to be conducted to assess this finding. On another note, and referring back to Figure 4-4, both outlier $k$ values (VAL1 and VAL4) were obtained when the experiment stopped long before boiling. Fortunately, since $k$ is only used to predict $\Delta m_{water}$ with time and that this term in Eq. 4-1 is not significant early in an experiment due to little vaporization, the $\eta_{avg}$ for VAL1 and VAL4 agrees well with the time predicted $\eta_t$ for the longer hot start studies.

From the hot start studies, two significant conclusions were identified. First, the predictions for $\eta_t$ at a given time were consistent with values of $\eta_{avg}$ which validates the time predictions. Second, $\eta_t$ leveled off very early in the experiment (at about seven minutes where
the water temperature was ~63 °C) such that the $\eta_{avg}$, typical of the WBT, can be predicted long before boiling.

Figure 6 shows the results of four cold starts (CS1, CS2, CS3, and CS4) having 2.5 liters of water in the pot. Two of the four cold starts (CS3 and CS4) have significantly different ending points compared to the two cold starts (CS1 and CS2) where $\eta_{avg}$ is similar to $\eta_{avg}$ of the hot starts. However, $\eta_t$ increases more rapidly for hot starts than for cold starts. If CS1 and CS2 had been stopped much earlier, the $\eta_{avg}$ would be much lower than the hot start $\eta_{avg}$. Thus, if cold start and hot start $\eta_{avg}$ data is averaged to evaluate stove $\eta_{avg}$, it is important that cold starts are run long enough.

Interestingly, CS3 and CS4 show $\eta_t$ data that are different from CS1 and CS2, the latter which approach the hot start $\eta_t$ at the end of the experiment. One of the cold starts (CS4) has similar $\eta_t$ behavior as CS1 and CS2 until 500 s and then the $\eta_t$ essentially levels off at approximately 12%. If only average analysis was performed, an erroneous conclusion could be that the CS4 test was completely different than CS1 and CS2. With $\eta_t$ data, the additional information shows that CS4 was similar to CS1 and CS2 and then something happened experimentally to change the behavior of the stove. When the temperature profile from CS4 was investigated, it was found that there were two distinct linearly increasing temperature regions. The first region had a slope very close to that of CS1 and CS2, while the slope of the second region decreased to about half of that rate. This indicates that heating to the pot was significantly disrupted at this point, perhaps due to some disruption in the fire pattern. Video recordings at this time point could help identify possible reasons. Thus, $\eta_t$ analysis can provide important insights to help understand deviations in $\eta_{avg}$ so that erroneous conclusions do not occur.
Similarly, CS3 had a significant delay in $\eta_t$ but it can be seen that the $\eta_t$ starts approaching the $\eta_t$ of CS1 and CS2 at later times. Thus, depending upon when an experiment stops, $\eta_{avg}$ may seem the same or different. Again, the above analysis points to the value of estimating transient $\eta_t$ data. As can be seen, the cold start data is significantly less consistent among the four experiments but $\eta_t$ analysis provides some clarity for comparison.

![Figure 4-6](image)

**Figure 4-6.** Average thermal efficiency ($\eta_t$) predictions with time and validation experiments for cold starts. The standard deviations of each experiment are based on propagated error analysis (Bethea & Rhinehart, 1991).

To obtain $\eta_t$ predictions, two key assumptions were made. First, it was assumed that the $k$ value in Eq. 4-4 was independent of time. As previously discussed with Figure 4-4, the difference in $k$ values between the experiments that ended at 90 °C and those that boiled was expected although the variations in $k$ likely did not affect $\eta_t$ predictions. However, the two high $k$ values for the non-boiling studies were not expected. Interestingly, these two high $k$ values were obtained for the experiments that stopped at 63 °C, far below the boiling temperature. One
hypothesis that was explored was the potential of a thermal boundary layer forming around the sides of the pot due to the skirt increasing the heat transfer rate to the walls of the pot. The increased temperature of the water at the wall relative to the bulk temperature would result in a higher effective $P_w$ than predicted by just using the bulk temperature—this effect would be more pronounced at lower temperatures. A higher $P_w$ would lead to a lower prediction for $k$. However, subsequent analysis by measuring temperature profiles near the wall showed that the boundary layer was too small to fully justify this reasoning.

Although the $k$ predictions were higher at 63 °C, the effect of $\Delta m_{water}$ predictions for estimating $\eta_t$ are not as critical for experiments at these temperatures which stop far below the boiling point since the value of $\Delta m_{water}$ on $\eta_t$ has a smaller effect. As shown in Figure 4-3, the fraction of $\eta_t$ attributed to $\Delta m_{water}$ (noted as mass loss in the figure) is 11.2% at 63 °C whereas the fraction increases to 30% at boiling and further to 48.6% by the end of the test. Similarly, in Figure 4-4, $\eta_{avg}$ taken at 63 °C (VAL 1 and VAL 4) showed good agreement with $\eta_t$ predictions. This again shows that the effect of $\Delta m_{water}$ predictions at the lower temperatures does not contribute as strongly to the prediction of $\eta_t$. Therefore, while the predicted $\eta_t$ curves are based on several assumptions, the general trends are not largely affected by perturbations in the assumptions nor in the variability of $k$ values obtained from ending at significantly lower temperatures.

The second key assumption in predicting $\eta_t$ is the linear nature of the wood mass loss ($f_{cm}$) and charcoal formation ($m_c$) used in Eq 4-1. In the early 1980s, a group at the University of Eindhoven conducted a series of experiments on biomass cookstoves, including some experiments in which the fuel bed was placed on a balance (Bussman, 1988). A graph of the mass of the cookstove with time showed that the mass loss with time was approximately linear.
even when the wood was added at various intervals during the study. It is more linear in nature as the number of required wood batches increase. It also showed an approximately linear increase in coal formation. This supports the idea that both the mass loss and the charcoal creation can be approximated as linear for $\eta_t$ predictions when the feeding rate is consistent.

As shown in Figure 4-6, there is value in estimating $\eta_t$. This was most evident with the cold start data where for two of the experiments the $\eta_t$ was either delayed (CS3) or unexpectedly suppressed (CS4). These observations could only be determined with predictions of $\eta_t$ and it is clear that such predictions can help understand $\eta_{avg}$ deviations within testing of the same cookstove or can also help provide insights when comparing between cookstoves. Unlike $\eta_{avg}$ analysis, which is the norm for the WBT, trends in $\eta_t$ analysis can provide insights into testing protocols even when testing parameters vary as much as shown in Table 4-1. For instance, for the hot start studies $\eta_t$ began to level off between 400 and 500 seconds into the experiment. This corresponded to a $\Delta T$ of between 20 and 30 °C, meaning that $\eta_t$ stabilized by the time that the originally 20 °C water has reached somewhere between 40 and 50 °C. This is significantly below the boiling time. Some question has arisen as to whether the WBT should go to boiling or not (P. Bailis et al., 2014; Defoort et al., 2009) and this study supports the idea that one could stop the WBT long before boiling occurs during a hot start. This could potentially decrease the amount of time and wood required for each experiment significantly when emissions data is not being used or collected.

Shortening the cold start phase, however, may not be as feasible. As was shown in Figure 4-6, the cold start phase reached steady state $\eta_t$ much later than the hot start phase. In fact, when using 2.5 L of water for this cookstove during the cold start, the steady state $\eta_t$ didn't occur until just before boiling occurred. Therefore, to more fully capture the cold start phase it may be best
to run a long test that boils for at least some time or use larger quantities of water. Because of this finding, when testing cookstoves it may be desirable to perform one cold start followed by several hot starts. The performance of more than one hot start following a cold start phase and preceding the simmer phase, which is different than the WBT protocol, lends itself to several advantages. First, it allows for more consistent data to be obtained in a shorter time. A cold start requires a cold stove, and so once a test is performed it is necessary to wait until the stove has cooled to begin anew. A hot start, however, should be able to be repeated one after another without significantly affecting $\eta_t$ as shown in this study. This leads to a better statistical analysis. It is important to note that the hot start and cold start phases should have a similar final $\eta_t$ (which is equivalent to $\eta_{avg}$ from the WBT) for experiments that achieve steady state efficiency. This is consistent with other observations as the percent of heat loss to the cookstove body have been observed to be low (Tryner et al., 2014). Second, the current method of the WBT does not measure the charcoal remaining at the end of the hot start phase. Instead, the charcoal remaining is assumed to be the same as the preceding cold start phase. If multiple hot starts are performed, the charcoal remaining from all of the hot starts except for the last one can be measured. Combining this with the fact that hot starts may be able to be shortened significantly would lead to a greater amount of data for statistical purposes.

On another note, many styles of cooking that have been tested in the field require a longer cooking time than is required to accomplish the WBT tasks (Chowdhury, 2012; Commodore et al., 1994), and so $\eta_{avg}$ may be closest to what happens in the field for long cooking times. However, the ability to predict $\eta_t$ would allow for $\eta_{avg}$ to be estimated for shorter cooking styles, increasing the versatility of the comparison to field use. The WBT currently attempts to more closely approximate field use by having different phases. The typical
WBT includes a cold start, hot start, and simmer phase in order to approximate cooking on a cooled stove, cooking on a hot stove (e.g. cooking a meal soon after finishing another), and the cooking of foods that require a long time such as legumes. These phases help to close the gap between lab testing and field testing performance, but the challenges with this comparison are well documented (P. Bailis et al., 2014; Taylor, 2009). It is therefore important to know when to stop a test.

Any cookstove will have some transient time before it reaches its steady state \( \eta_t \). To maximize the amount of information gathered in any individual test it is important that \( \eta_t \) approaches steady state as much as possible by the end of the test. Using the data from Figure 4-5, it is clear that this can require different times for cold and hot start phases. A stove with a high thermal mass will also require more time to reach a steady state \( \eta_t \) than a stove with low thermal mass. The cold start phase curve of the \( \eta_t \) for a stove with extremely low thermal mass should approach the hot start phase curve. One way to estimate the minimum time required to reach steady state \( \eta_t \) would be to run a test until the water is in a rolling boil state for both the cold start and hot start phases and graph \( \eta_t \) with time. This would allow the researcher to see the whole curve and make a determination based off of that information. However, the results of this study also suggest that at least for the hot start phase this time could be significantly reduced. It is possible that the high thermal mass of this stove is the cause of the longer length of time required to reach the steady state \( \eta_t \) for the cold start. If this is true, then a lighter stove should reach its steady state efficiency more quickly for a cold start and so the 30 °C temperature rise required for the hot starts observed in Figure 4-6 should also be sufficient for a cold start. Predicting \( \eta_t \) can provide insights needed for adjusting protocols and comparing cookstoves with varying protocols. It is also recommended that once a final time or temperature has been selected,
predicting $\eta_t$ will allow one to confirm whether or not $\eta_{avg}$ has stopped changing. If a curve, such as the lowest curve in Figure 4-6, is observed, the steady state of $\eta_t$ has not been reached and the test needs to be longer to obtain an accurate steady state value of $\eta_t$. While WBT provides only an average value of thermal efficiency for the entire test ($\eta_{avg}$), $\eta_t$ analysis will allow for cookstoves to be compared at various points of operation.

Finally, when comparing cookstoves at earlier points of operation it is important to be careful that noise is not a significant factor. In the early part of the test the water heating is extremely dominant and the temperature difference has not become large enough to overcome noise in the thermocouple readings. This is evident for the $\eta_t$ predictions below 100 seconds in Figure 4-6. Sudden temperature reading changes within the accuracy of the thermocouple in the first 30 seconds of the test can sometimes even give physically impossible values of $\eta_t$. If repeated runs are averaged over the same time then the extreme variability of the early part of the test is corrected, the false negatives are no longer an issue, and the curve becomes smooth.

4.4 Conclusions

$\eta_t$ of a cookstove was modeled using the equations and assumptions outlined in this work. These assumptions included linear mass loss of wood, linear increase of charcoal mass, and a mass transfer coefficient that is independent of time and temperature. To verify the accuracy of the prediction, four validation experiments based on the standard WBT protocol were conducted and the calculated $\eta_{avg}$ for each validation experiment were compared with $\eta_t$ predictions. All of the $\eta_t$ predictions had similar values compared to $\eta_{avg}$ at the given time, leading to validation of the predictions.
Analysis of $\eta_t$ resulted in several insights not available from the traditional $\eta_{avg}$ using the WBT protocol. First, the amount of time and temperature increase required to get an accurate view of the $\eta_{avg}$ of a hot start may be significantly shorter than the time required to accomplish the task outlined in the WBT protocol. It may therefore be possible to measure $\eta_{avg}$ with much smaller temperature differences than are currently recommended although this may interfere with other uses of the WBT. This could decrease the time and wood requirements of biomass cookstove testing. Second, the experimental time may vary between the cold and hot start phases to obtain steady state $\eta_t$ values. At least for the high thermal mass stove used in these experiments, there is a significant difference in the amount of time required for $\eta_t$ to reach steady state for a cold start phase versus a hot start phase. Third, determining $\eta_t$ provides validation as to if and when $\eta_{avg}$ has reached steady state. Fourth, determining and comparing $\eta_t$ changes between experimental runs lead to some valuable experimental findings. Investigation of the curve of the $\eta_t$ showed the causes of the two lowest cold start $\eta_{avg}$ measurements were 1) a physical change in the system and 2) not running the test for long enough. These findings would not have been obvious with a traditional WBT. Using predicted curves of $\eta_t$ can therefore be very useful for researchers who wish to find ways to more efficiently compare cookstoves and simultaneously improve the consistency of the testing of an individual cookstove. Just a small modification of measuring temperature with time in the WBT test allows one to predict beneficial $\eta_t$ information in contrast to just obtaining $\eta_{avg}$.

Further, there are still some questions about the effects of various choices in the protocol, such as the amount of water used and how different the behavior of the stove is when using a lid. In this test, the amount of water did not have a measureable effect on efficiency, though the data sample was small. Additionally, especially for hot starts where the water may not need to be
brought to high temperature, the lid may not have a strong effect. However, once the water is close to boiling the effects of using a lid may be stronger. These kinds of choices and possible interactions between these protocol decisions need to be investigated.

This chapter is based off of a published article (Quist, C. M., Jones, M. R., & Lewis, R. S., 2016). I hereby confirm that the use of this article is compliant with all publishing agreements.
5 Effects of Variations in Testing Parameters on Water Boiling Test Performance Metrics

5.1 Introduction

Biomass cookstoves have been studied extensively for several decades (Baldwin, 1987; Kshirsagar & Kalamkar, 2014; Lewis & Pattanayak, 2012; N. A. MacCarty & Bryden, 2015; Manoj et al., 2013; Poudyal et al., 2015; Quist, Lewis, & Jones, 2014). Generally, these studies have been motivated by a need to improve assessment capabilities and accelerate the development of improved cookstoves (ICS). With over 2 billion daily users, biomass cookstoves have a significant impact on air quality and on global climate change. ICS mitigate 1) health risks to cookstove users, 2) climate change, 3) deforestation, and 4) glacial retreat (Mueller et al., 2011; Chowdhury, 2012; Abeliots & Pakula, 2013; Bond et al., 2013; Hawley & Volckens, 2013). These effects can be very impactful, especially in local areas (Rehman, Ahmed, Praveen, Kar, & Ramanathan, 2011). Designing new ICS requires testing methods with appropriate performance metrics that can define and identify improvements in cookstoves. To that end, several testing protocols have been developed, including the recently established ISO 19867-1 laboratory testing standard, (a testing sequence for emissions and performance, safety, and durability of cookstoves used primarily for cooking or water heating), the Water Boiling Test (WBT) and its derivatives, as well as the Controlled Cooking Test and the Kitchen Performance Test (https://www.cleancookingalliance.org/technology-and-fuels/testing/protocols.html).
The WBT has been the most common laboratory test and it has been used in many studies to compare multiple cookstove designs (Bailis et al., 2014; MacCarty et al., 2010; Jetter et al., 2012). The WBT involves evaluating the cookstove performance for heating water during three phases. The cold-start phase is for evaluating a cookstove under high power and is initially at room temperature. The hot-start phase is for evaluating a cookstove under high power that is still warm after completion of the cold-start phase. The simmer phase is for evaluating a cookstove during prolonged low power use, such as when making a soup.

In the WBT, metrics such as the time to boil, total fuel consumed and emissions of particulate matter (PM), CO, and CO₂ are measured. These measured metrics are used to calculate pollutant-based metrics such as specific emission rates and energy-based metrics such as thermal efficiency and specific consumption. Some studies have focused on additional aspects of these metrics such as transient estimations of thermal efficiency and uncertainty analysis (Quist, Jones, & Lewis, 2016; Quist, Jones, Jones, & Lewis, 2016). In addition to the pollutant and energy metrics, some other items of user interest include safety (for which there are additional protocols), and ease of use (e.g. time between adding wood) (Ruiz-Mercado et al., 2011).

When performing the WBT, it is important to understand how a given cookstove testing parameter or a combination of cookstove testing parameters affect measured or calculated metrics, especially since changes in multiple testing parameters may have competing effects on a given metric. Several cookstove studies have focused largely on assessing how variations in testing parameters such as wood geometry, wood moisture content, pot size, and cookstove material affect thermal efficiency and, in some cases, emissions characteristics (Bhattacharya et al., 2002; L’Orange, DeFoort, & Willson, 2012; Yuntenwi, MacCarty, Still, & Ertel, 2008).
Through a design-of-experiments approach, the present work expands upon the previous work by addressing the effects of variations in testing parameters that include pot size, initial mass of water, presence or absence of a lid, firepower, and experimental ending point on the measured metric of time to 90 °C and the calculated metrics of thermal efficiency and specific consumption. Although the WBT protocol excludes lids and has an ending point associated with boiling, this study sought to address how lids affected various metrics and also looked at a 90 °C ending point since boiling temperature is affected by the altitude of the testing location. Additionally, the relationship between thermal efficiency and specific consumption is explored. Since specific consumption was previously identified as a preferred metric for WBT analysis (Jetter & Kariher, 2009; MacCarty et al., 2010), it is useful to further investigate the response of specific consumption to variations in testing parameters.

Different markets, testing preferences, or availability of cooking equipment may require adjusting WBT procedures, so it is important to assess the effects of these adjustments on measured or calculated metrics. These results will provide guidance for future testing protocols and also provide insights for comparing experimental results among cookstoves tested by different entities that used different testing protocols. Characterizing the interactive effects of testing parameter variations may give some confidence in the ability to compare cookstove performance metrics if different testing parameters of pot size, initial mass of water, presence or absence of a lid, firepower, and experimental ending point are used.
5.2 Materials and Methods

To appropriately assess the impact of variations in the above-stated testing parameters, a gas burner was used as the heat source since it was important to maintain a well-defined and controlled heat source. A controlled heat source provides a consistent heating rate and eliminates the effects of other variables associated with a wood heat source such as wood composition/moisture content, burning patterns, and wood geometry/placement that are difficult to control. The burner was a WKAF2B Low Pressure Burner (King Kooker, Jefferson, LA) with a diameter of six inches. The natural gas fuel, primarily methane, had a lower heating value of 43 kJ/g. A wire grate was placed above the burner to separate the top of the burner from the bottom of the pot. Two studies were conducted using a full factorial design to assess the impact of the specified testing parameters on the metrics of thermal efficiency ($\eta$), specific consumption (the mass of fuel required to complete the test per the initial mass of water used in the test, abbreviated to SC), and time to reach temperature. Testing parameter variations included covering (lid vs. no lid), firepower (770 W vs. 1400 W), pot size (small pot of 20-cm diameter and 18-cm height vs. large pot of 26-cm diameter a 22-cm height), initial mass of water (2.5 kg vs. 5.0 kg), and experimental ending point (90 °C, boiling, or 5-min post-boiling).

The first study was a 4-factorial design (experiments 1–16 shown in Table 5-1) assessing varied testing parameters of use of a pot lid, firepower, pot size, and initial mass of water at a fixed experimental ending point of water reaching 90 °C. There were five replicates for each experiment. For this study, the bottom of the pot was one cm above the burner. The second study was a 3-factorial design (experiments 17–24 shown in Table 5-2) assessing varied testing parameters of use of a pot lid, pot size, and experimental ending point (boiling vs. five-minutes post boiling) at a fixed firepower of 1400 W and initial mass of water of 2.5 kg. For the second
study, the bottom of the pot was 1.5 cm above the burner to allow for easier access to the gas burner during the startup process. There were three replicates for each experiment.

All studies were conducted using a protocol based on the WBT. In the WBT, the cold-start and hot-start phases are performed at a high firepower (i.e. fast fuel feeding rate) to reach the boiling temperature quickly. However, the cold-start phase occurs prior to heating the cookstove and the hot-start phase occurs after the cookstove is heated. Since for this study there was no significant cookstove mass to heat up, there was no appreciable difference between a cold-start phase or a hot-start phase. The simmer phase was not investigated. Firepower was kept constant within an individual test.

**Table 5-1:** Factorial design of first study at a fixed experimental ending point of water reaching 90 °C.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Covering</th>
<th>Firepower</th>
<th>Pot size</th>
<th>Initial Mass of Water (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>770 W</td>
<td>Small</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>770 W</td>
<td>Small</td>
<td>2.5</td>
</tr>
<tr>
<td>3</td>
<td>No</td>
<td>1400 W</td>
<td>Small</td>
<td>2.5</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>1400 W</td>
<td>Small</td>
<td>2.5</td>
</tr>
<tr>
<td>5</td>
<td>No</td>
<td>770 W</td>
<td>Large</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>Yes</td>
<td>770 W</td>
<td>Large</td>
<td>2.5</td>
</tr>
<tr>
<td>7</td>
<td>No</td>
<td>1400 W</td>
<td>Large</td>
<td>2.5</td>
</tr>
<tr>
<td>8</td>
<td>Yes</td>
<td>1400 W</td>
<td>Large</td>
<td>2.5</td>
</tr>
<tr>
<td>9</td>
<td>No</td>
<td>770 W</td>
<td>Small</td>
<td>5.0</td>
</tr>
<tr>
<td>10</td>
<td>Yes</td>
<td>770 W</td>
<td>Small</td>
<td>5.0</td>
</tr>
<tr>
<td>11</td>
<td>No</td>
<td>1400 W</td>
<td>Small</td>
<td>5.0</td>
</tr>
<tr>
<td>12</td>
<td>Yes</td>
<td>1400 W</td>
<td>Small</td>
<td>5.0</td>
</tr>
<tr>
<td>13</td>
<td>No</td>
<td>770 W</td>
<td>Large</td>
<td>5.0</td>
</tr>
<tr>
<td>14</td>
<td>Yes</td>
<td>770 W</td>
<td>Large</td>
<td>5.0</td>
</tr>
<tr>
<td>15</td>
<td>No</td>
<td>1400 W</td>
<td>Large</td>
<td>5.0</td>
</tr>
<tr>
<td>16</td>
<td>Yes</td>
<td>1400 W</td>
<td>Large</td>
<td>5.0</td>
</tr>
</tbody>
</table>
Table 5-2: Factorial design of second study at a fixed firepower of 1400 W and an initial mass of water of 2.5 kg.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Covering</th>
<th>Pot Size</th>
<th>End Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>17</td>
<td>No</td>
<td>Small</td>
<td>90 °C</td>
</tr>
<tr>
<td>18</td>
<td>Yes</td>
<td>Small</td>
<td>90 °C</td>
</tr>
<tr>
<td>19</td>
<td>No</td>
<td>Large</td>
<td>90 °C</td>
</tr>
<tr>
<td>20</td>
<td>Yes</td>
<td>Large</td>
<td>90 °C</td>
</tr>
<tr>
<td>21</td>
<td>No</td>
<td>Small</td>
<td>Boiling + 5 min</td>
</tr>
<tr>
<td>22</td>
<td>Yes</td>
<td>Small</td>
<td>Boiling + 5 min</td>
</tr>
<tr>
<td>23</td>
<td>No</td>
<td>Large</td>
<td>Boiling + 5 min</td>
</tr>
<tr>
<td>24</td>
<td>Yes</td>
<td>Large</td>
<td>Boiling + 5 min</td>
</tr>
</tbody>
</table>

As noted above, η and SC were two of the metrics evaluated in this study. For a biomass cookstove, η is defined as the energy used to heat and vaporize the water in a pot on a cookstove divided by the net amount of energy released from the biomass fuel that is consumed according to Eq. 5-1 (Quist, Jones, & Lewis, 2016)

\[
\eta = \eta_{\text{heat}} + \eta_{\text{vap}} = \frac{C_p w \times m_{\text{water,i}} \times \Delta T}{E_{f,\text{net}}} + \frac{\Delta h_{\text{H}_2\text{O,fg}} \times \Delta m_{\text{water}}}{E_{f,\text{net}}}
\]

Eq 5-1

The first term in Eq. 5-1 is the efficiency used to heat the water (\(\eta_{\text{heat}}\)) and the second term is the efficiency used to vaporize the water (\(\eta_{\text{vap}}\)). Here, \(C_p w\) is the heat capacity of water, \(m_{\text{water,i}}\) is the initial mass of water, \(\Delta T\) is the change in temperature of the water in the pot, \(\Delta h_{\text{H}_2\text{O,fg}}\) is the heat of vaporization of water at ambient pressure, \(\Delta m_{\text{water}}\) is the mass of water vaporized over the course of the test, and \(E_{f,\text{net}}\) is the net energy of the consumed fuel that was available to heat the water in the pot. The value of \(\eta\), but not \(\eta_{\text{heat}}\) or \(\eta_{\text{vap}}\), is widely reported in many cookstove studies to provide one point of comparison between cookstoves.

In contrast to \(\eta_{\text{heat}}\) and \(\eta_{\text{vap}}\), SC has been used as a metric for comparison in the past. Here, SC is defined as the net mass of fuel used to heat the water in the pot relative to the final amount of water that was heated according to:
\[ E_{f,\text{net}} = f_{cm} \times (1 - MC) \times LHV_f - f_{cm} \times MC \times [C_p w \times (T_{\text{boil}} - T_{\text{amb}}) + \Delta h_{H_2O,f_g}] - LHV_c \times m_c \]  
Eq. 5-2

In some cases, SC may also be corrected for temperature (Bailis et al., 2014).

5.3 Results

Fig. 5-1 shows the values of \( \eta_{\text{heat}} \) (gray) and \( \eta_{\text{vap}} \) (white) for both studies, with the first study comprised of experiments 1–16 and the second study comprised of experiments 17–24. As can be seen, the total \( \eta \) changed between 60% to 74% with varying testing parameters. The average value is 66%. Although \( \eta \) is higher compared to biomass cookstoves, \( \eta \) is consistent with other studies using burners with natural gas (Berkely Air Monitoring Group, 2012).

![Figure 5-1](image-url)  
**Figure. 5-1.** Thermal efficiency (\( \eta \)) associated with the experiments shown in Table 5-1 (Experiments 1–16) and Table 5-2 (Experiments 17–24). Gray bars indicate the portion of thermal efficiency from the energy stored in heating the water (\( \eta_{\text{heat}} \)) and the white bars indicate the portion of the efficiency from evaporation of water (\( \eta_{\text{vap}} \)).
All even-numbered experiments were performed with a lid. Comparing the studies in which the lid was the only experimental input variation (e.g. 1 vs. 2, 3 vs. 4, 5 vs. 6, etc.), the presence of a lid resulted in a value of $\eta$ that was slightly lower than the studies with an absence of a lid. In contrast to $\eta$, significant variations in $\eta_{\text{heat}}$ and $\eta_{\text{vap}}$ were observed for the studies with or without a lid. For the even-numbered experiments that had the presence of a lid in the first study, $\eta_{\text{vap}}$ was small, ranging from 1 to 6%. For the experiments that did not have a lid (odd numbered experiments), $\eta_{\text{vap}}$ was much more significant, ranging from 13 to 50%. For all studies, experiments 5, 13, 19, and 23 showed the most significant $\eta_{\text{vap}}$. In all cases in which the lid was the only parameter variation (e.g. 1 vs. 2, 3 vs. 4, 5 vs. 6, etc.), the presence of a lid resulted in a higher $\eta_{\text{heat}}$. If $\eta$ is the only efficiency metric of interest, the presence or absence of a pot lid does not make much difference. However, a pot lid can be used to minimize the evaporative component of efficiency if heating the water is the desirable attribute.

![Graph](image.png)

**Figure. 5-2.** Specific consumption (SC) associated with the experiments shown in Table 5-1 (Experiments 1–16) and Table 5-2 (Experiments 17–24).
Fig. 5-2 shows SC for all experiments. The experiments in the first study (experiments 1–16) had an average SC of 12 ± 2 g_{fuel}/kg_{water}. However, there were three SC values that were much higher than the others. Experiments 1, 5, and 13 had SC values of 13, 19, and 15 g_{fuel}/kg_{water}, respectively. As shown, the experiments in the second study (experiments 17–24) had much higher SC values than many of the experiments in the first study, with an average SC of 15 ± 3 g_{fuel}/kg_{water}. This is because the first study stopped at 90 °C, whereas the second study involved boiling which would require more fuel and would result in the loss of more water due to evaporation. The average SC for all experiments combined was 13 g_{fuel}/kg_{water}, with the lowest value of 10 g_{fuel}/kg_{water} (experiment 14) and the highest value of 20 g_{fuel}/kg_{water} (experiment 23). For all cases in which the lid was the only experimental variation (1 vs. 2, 3 vs. 4, 5 vs. 6, etc.), the presence of a lid (even numbered) always resulted in an SC value that was lower than in the absence of a lid (odd numbered).

Fig. 5-3 shows the time to reach 90 °C for all experiments. Time to reach 90 °C showed significant variation among all experiments. The times ranged from 13.4 min (Experiment 4) to 70.7 min (Experiment 13). Experiment 13 also had the second highest SC. These extremes were caused by the combined factors of a pot with no lid, low firepower, and a large pot. As expected, for all cases in which the lid was the only testing variation (1 vs. 2, 3 vs. 4, 5 vs. 6, etc.), the presence of a lid (even numbered) always resulted in a faster time than in the absence of a lid (odd numbered). Further, a pattern can be seen by the results of the first study (experiments 1–16). For the first four experiments with a small pot size and 2.5 kg of water, the time to reach 90 °C decreased from the first to the fourth experiment. The first experiment had no lid and the second experiment had a lid—both were at low firepower. As expected, the experiment with a lid took less time to reach temperature. The third and fourth experiments were at the higher
firepower with the third experiment having no lid and the fourth experiment having a lid. Interestingly, at the higher firepower, the presence or absence of the lid had a very small effect on the time to reach 90 °C. Thus, the higher firepower is the dominant factor in the faster time for this set of experiments. This same trend was observed for experiments 5–8 (large pot, 2.5 kg water), experiments 9–12 (small pot, 5.0 kg water), and experiments 13–16 (large pot, 5.0 kg water). In comparing experiments 1–4 with 5–8 (all having 2.5 kg of water), the first experiment in each of the groups showed a significant variation with each other whereas the second, third, and fourth experiments in each group were similar among the two groups. The same is true when comparing experiments 9–12 with 13–16 (all having 5.0 kg of water). Thus, for a similar amount of water, the pot size had a significant effect on the time to reach 90 °C only when there was no lid and low firepower.

![Figure 5-3](image_url)

**Figure. 5-3.** Minutes to reach 90 °C associated with the experiments shown in Table 5-1 (Experiments 1–16) and Table 5-2 (Experiments 17–24).
Statistical Analysis System (SAS Institute, Cary, North Carolina) was used to run a regression analysis (using the ‘glmselect’ method) of the data from each study to predict the performance metric based on variations in the testing parameters, including cross effects. The regression analysis resulted in an equation of the following form:

\[
y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{14} x_1 x_4 + \beta_{23} x_2 x_3 + \\
\beta_{24} x_2 x_4 + \beta_{34} x_3 x_4 + \beta_{123} x_1 x_2 x_3 + \beta_{124} x_1 x_2 x_4 + \beta_{134} x_1 x_3 x_4 + \beta_{234} x_2 x_3 x_4 + \\
\beta_{1234} x_1 x_2 x_3 x_4
\]

Eq. 5-4

Here, \( y \) is the predicted metric (\( \eta, \eta_{\text{vap}}, \text{SC}, \text{or Time to 90 °C} \)) based on \( x_i \) testing parameter variations. For the first study, \( x_1 \) had a value of 0 for no lid and 1 for a lid, \( x_2 \) had a value of 0 for 770 W and 1 for 1400 W, \( x_3 \) had a value of 0 for a small pot and 1 for a large pot, and \( x_4 \) had a value of 0 for 2.5 kg of water and 1 for 5.0 kg of water. \( \beta_0 \) is the predicted metric for the base case associated with no lid (\( x_1 = 0 \)), 770 W (\( x_2 = 0 \)), small pot (\( x_3 = 0 \)), and 2.5 kg of water (\( x_4 = 0 \)). For the second study, \( x_1 \) had a value of 0 for no lid and 1 for a lid, \( x_2 \) had a value of 0 for no boiling and 1 for boiling, \( x_3 \) had a value of 0 for a small pot and 1 for a large pot, and \( x_4 \) had a value of 0 for all cases since only three input parameters were studied. \( \beta_0 \) is the predicted metric for the base case associated with no lid (\( x_1 = 0 \)), no boiling (\( x_2 = 0 \)), and small pot (\( x_3 = 0 \)). \( \beta \) values are the parameter estimates for each specific study and include 2, 3, and 4-level cross effects.

Although the fitted \( \beta \) values for Eq. 5-3 are specific to each study, the statistical relevance of the \( \beta \) values can provide insights for assessing the impacts of variations in testing parameters (including cross effects) on the calculated or measured metric of interest. These insights can be important for comparing a given metric among cookstoves. Tables 5-3 and 5-4 show the
statistically relevant (99% probability) $\beta$ values for the first and second studies, respectively. The $\beta$ values that affect the $\beta_0$ (base case) value by more than 10% are highlighted in gray. A positive $\beta$ value means that testing parameter variations associated with the addition of a lid, a higher firepower (1400 W), a larger pot size, a larger amount of water (5.0 kg), or the allowance of boiling increase the metric relative to the base case. Conversely, a negative $\beta$ value means that the testing parameter variations decrease the metric relative to the base case. Positive $\beta$ values for $\eta$ and $\eta_{\text{heat}}$ and negative $\beta$ values for SC and the time to reach 90 °C are considered as beneficial.

Table 5-3: $\beta$ values for the first study (See Eq. 5-4).

<table>
<thead>
<tr>
<th>Experimental Inputs</th>
<th>Positive is beneficial</th>
<th>Negative is beneficial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\eta$ (%)</td>
<td>$\eta_{\text{heat}}$ (%)</td>
</tr>
<tr>
<td>$\beta_0$ (base case)</td>
<td>68.7</td>
<td>53.9</td>
</tr>
<tr>
<td>$\beta_1$: Effect of Adding Lid (1)</td>
<td>-1.9</td>
<td>+9.0</td>
</tr>
<tr>
<td>$\beta_2$: Effect of Increasing Firepower (2)</td>
<td>-4.0</td>
<td>+1.8</td>
</tr>
<tr>
<td>$\beta_3$: Effect of Increasing Pot Size (3)</td>
<td>-18.0</td>
<td>+5.3</td>
</tr>
<tr>
<td>$\beta_4$: Effect of Increasing Mass of Water (4)</td>
<td>+2.6</td>
<td>2.1</td>
</tr>
<tr>
<td>$\beta_{12}$: Cross effect of (1) and (2)</td>
<td>-2.9</td>
<td>+0.8</td>
</tr>
<tr>
<td>$\beta_{13}$: Cross effect of (1) and (3)</td>
<td>+18.2</td>
<td>-5.4</td>
</tr>
<tr>
<td>$\beta_{14}$: Cross effect of (1) and (4)</td>
<td>+1.2</td>
<td></td>
</tr>
<tr>
<td>$\beta_{23}$: Cross effect of (2) and (3)</td>
<td>+13.9</td>
<td>-4.5</td>
</tr>
<tr>
<td>$\beta_{24}$: Cross effect of (2) and (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{34}$: Cross effect of (3) and (4)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{123}$: Cross effect of (1), (2), and (3)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta_{124}$, $\beta_{134}$, $\beta_{234}$, and $\beta_{1234}$</td>
<td>-16.5</td>
<td>+5.3</td>
</tr>
</tbody>
</table>
Table 5-4: β values for the second study (See Eq. 5-4).

<table>
<thead>
<tr>
<th>Experimental Inputs</th>
<th>Positive is beneficial</th>
<th>Negative is beneficial</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>η (%)</td>
<td>η\text{heat} (%)</td>
</tr>
<tr>
<td>β₀ (base case)</td>
<td><strong>62.5</strong></td>
<td>54.5</td>
</tr>
<tr>
<td>β₁: Effect of Adding Lid (1)</td>
<td>-2.3</td>
<td>+4.5</td>
</tr>
<tr>
<td>β₂: Effect of Boiling (2)</td>
<td>+1.2</td>
<td>-14.3</td>
</tr>
<tr>
<td>β₃: Effect of Increasing Pot Size (3)</td>
<td>+1.7</td>
<td>-5.9</td>
</tr>
<tr>
<td>β₁₂: Cross effect of (1) and (2)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>β₁₃: Cross effect of (1) and (3)</td>
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<tr>
<td>β₂₃ and β₁₂₃</td>
<td>+6.3</td>
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The only difference between the base cases for the two studies is the low firepower for the first study and the high firepower for the second study. For the first study, y = β₀ = 68.7% for the base case when y represents the metric η. If an increase in the firepower was the only variation, then according to Eq. 5-3, y = β₀ + β₂ = 64.7%. This is consistent with η = 62.5% for the base case of the second study. When the first study is adjusted for a higher firepower, similar analysis for the other three metrics show η\text{heat} = 55.7% for the first study and 54.9% for the second study, SC = 12.1 g/kg for the first study and 13.8 for the second study, and Time to 90 °C = 15 min for the first study and 16 min for the second study. Thus, there was good consistency between the two studies.

Interestingly, for both studies, none of the β values associated with testing parameter variations affected the base case value of β₀ greater than 6% when y represents the metric η. In fact, no β values associated with cross effects were of statistical significance. Conversely, for both studies, many variations in testing parameters (single and/or cross effects) affected the base case value of β₀ at 10% or greater when y represents the metric η\text{heat}, SC, or Time to 90 °C.
5.4 Discussion

The question arises as to which metric(s) should be used for cookstove comparison. In many studies, a higher $\eta$ has been noted as one of the desired results of improved cookstoves and has been a basis for comparing cookstoves. As shown by the statistically significant $\beta$ values in Tables 5-3 and 5-4, the effects of adding a lid, increasing firepower, increasing pot size, increasing the amount of water, and allowing boiling had a relatively small effect on the value of $\eta$ (the overall efficiency)—and the effects were not coupled to each other (no statistically significant cross effects). Thus, for the ISO 19867-1 laboratory testing standard where $\eta$ is used as a metric, variations in testing parameters do not have a strong effect on this metric. Table 5-3 shows that not having a lid, having a lower firepower, and having a larger amount of water gives the highest $\eta$. One likely reason for this is that without a lid, steam will counterintuitively increases $\eta$. Additionally, a lower firepower means that the heated air going around the pot is slower. The slower air has more dwell time around the pot and can therefore transfer its energy more completely leading to higher efficiency. A larger amount of water will provide more surface area for hot gases to transfer heat to the liquid. However, the reason that $\eta$ is not statistically affected by the various cross effects in either study and appears to be only slightly affected by variations in the testing parameters may be a result of the two parts of the efficiency shown in Eq. 5-1. Fig. 5-1 shows that when $\eta_{\text{heat}}$ decreases, it is met by an approximately equal increase in $\eta_{\text{vap}}$. Basically, the small changes in $\eta$ due to variations in the testing parameters is beneficial if $\eta$ is the desired metric for comparison since it implies that studies for a given cookstove could provide a generally consistent value of $\eta$ that is not strongly dependent on the varying testing parameters. However, is $\eta$ the best metric for comparison?
Previously it was noted that η may not always be the best choice for comparison and may even mask some very important differences when seeking to compare cookstoves (MacCarty et al., 2010; Jetter et al., 2012). For example, the experiment with the highest η (#9) also showed one of the lowest SC values—both beneficial qualities since a lower SC means that less fuel is used. However, the water took 22 more min than average to boil which leads to a longer cooking time. The experiment with the second highest η (#13) had one of the higher SC values (which is not beneficial) and took nearly 40 min longer than average to boil. Each of these configurations did not include a lid. The highest η in which the experiment had a lid (#14) had the lowest SC value of all studies but still took nearly 14 more min than average to boil. It is clear that cookstove operation procedures (e.g. lid vs. no lid, heating rate, etc.) affect cookstove performance. Thus, the questions arise as to what testing parameters for cookstove operation play any significant role in cookstove performance, what measured or calculated metrics are the most valuable to use when assessing and comparing cookstoves, and what is the best way to provide consistency in the measurement of the metrics for cookstove comparison.

Evaluating the role of variations in testing parameters for cookstove analysis are critical for understanding the output metrics that are being evaluated. It is therefore helpful to compare η with other metrics, which for this chapter are η_heat, SC, and time to reach 90 °C. This allows cookstove conditions that improve η to be evaluated as to whether they also improve the other metrics. Also, there is an added benefit of providing some guidance on testing parameters (e.g. lid vs. no-lid) that are important to control when comparing cookstoves across studies.

Eq. 5-1 for η contains a portion due to the heating of the water (denoted as η_heat) as well as a portion due to evaporation. In contrast to η where the presence of a lid only reduces η by 1.9% (parameter β1, Table 5-3) in the first study, the presence of a lid alone increases η_heat by 9%.
to a value of 62.9%. Therefore, inclusion of a pot lid is beneficial for cooking processes where heating the water is the primary objective (e.g. cooking potatoes). From an efficiency perspective, the energy associated with evaporation is lost energy when the primary purpose is heating water. However, if other cooking process such as steaming or removing water to thicken a soup are the primary purpose, then the energy associated with vaporization is also beneficial. Thus, knowledge of $\eta_{\text{heat}}$, in addition to $\eta$, provides additional insights into the efficiency aspects related to the desired cooking process and inclusion of a pot lid is beneficial when a large $\eta_{\text{heat}}$ is desired.

With regards to variations only in pot size for the first study, $\eta$ is not affected but $\eta_{\text{heat}}$ is reduced by 18% (parameter $\beta_3$) relative to the base case to a value of 35.9%. Thus, in the absence of a lid, the pot size is important to consider in assessing $\eta_{\text{heat}}$. However, Eq. 5-4 leads to $\eta_{\text{heat}} = \beta_0 + \beta_1 = 62.9\%$ for a lid with a small pot and $\eta_{\text{heat}} = \beta_0 + \beta_1 + \beta_3 + \beta_{13} = 63.1\%$ for a lid with a large pot. Therefore, changing pot size does not greatly affect $\eta_{\text{heat}}$ if there is a lid. Similar analysis for the first study shows that when a lid is present, $\eta_{\text{heat}} = 64 \pm 3\%$ no matter the variations in pot size, firepower, and mass of water. This reduced variation is due to the cancelling of similar positive and negative effects of the $\beta$ values. For the second study in the presence of a lid, $\eta_{\text{heat}}$ only varied from 59.0% to 59.4% when the pot size was changed. However, boiling always reduced $\eta_{\text{heat}}$ since once the water reaches boiling temperature, all energy added can no longer increase the temperature but must go to vaporization. Therefore, the presence of a lid is recommended for assessing $\eta_{\text{heat}}$ since the effects of other testing parameter variations (except for boiling) are minimized to provide a better comparison among cookstoves.

As mentioned, SC has been identified as another, and previously preferred, metric for comparing cookstoves (MacCarty et al., 2010). The relationship between SC and $\eta_{\text{heat}}$ is shown
in Figs. 5-4 and 5-5 for the first and second study, respectively. Each of these graphs shows a linear relationship between $\eta_{\text{heat}}$ and $1/SC$. When $\Delta m_{\text{water}}$ in Eq. (2) is negligible compared to $m_{\text{water,i}}$, comparison of Eq. 5-2 with $\eta_{\text{heat}}$ in Eq. 5-1 gives:

$$
\eta_{\text{heat}} = \frac{c_{p_{\text{water}}} \Delta T}{LHV_{\text{fuel}}} \left( \frac{1}{SC} \right)
$$

Eq. 5-5

**Figure. 5-4.** Relationship between $\eta_{\text{heat}}$ and $1/SC$ for the experiments shown in Table 1 in the presence and absence of a lid. The linear line is consistent with Eq. (4) which has a predicted slope of 0.7.

Thus, when $\Delta T$ and the same type of fuel (associated with $LHV_{\text{fuel}}$) is constant for a study, then a linear relationship between $\eta_{\text{heat}}$ and $1/SC$ is expected. It is important to note that a small SC (or large $1/SC$) is beneficial for heating water since less fuel is burned to heat a given amount of water. Based on Eq. 5-4, it would be beneficial for studies to report $LHV_{\text{fuel}}$ and to
maintain and report a given ΔT so that studies reporting SC can be compared to studies reporting η\text{heat}.

As shown in Fig. 5-4, η\text{heat} or 1/SC is increased by adding a lid in comparison to not having a lid. Therefore, improving the consistency of η\text{heat} measurements as noted above is not the only benefit for adding a lid, but an additional benefit is higher η\text{heat} and 1/SC values. Fig. 5-5 also shows that minimizing the amount of boiling is beneficial to have higher η\text{heat} and 1/SC values. This can be accomplished by using a lid once boiling is achieved to minimize losses due to vaporization and decrease the amount of fuel that is used. Thus, for SC or η\text{heat} analysis there are benefits for using a lid, although the desire for a large η\text{heat} or small SC is dependent upon the cooking objective.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5-5.png}
\caption{Relationship between η\text{heat} and 1/SC for the experiments shown in Table 5-2 in the presence and absence of boiling. The linear line is consistent with Eq. 5-4 which has a predicted slope of 0.7.}
\end{figure}
With regards to variations in testing parameters for the first study which affect SC, Table 5-3 shows that SC in the absence of a lid is increased by 5.3 g/kg (parameter $\beta_3$ - the largest effect) from 12.8 g/kg to 18.1 g/kg when just the pot size is increased. This is likely due to a significant increase in the surface area of the water that is in contact with the air allowing for more evaporation and therefore a longer time required to reach the correct temperature, especially at the lower firepower. The large variation in SC could make cookstove comparison difficult if pot size is not consistent among studies since it is the pot size and not really the cookstove that affects the metric of interest. Similar to the analysis for $\eta_{\text{heat}}$, when a lid is present, SC $= 10.3 \pm 0.5$ g/kg no matter the variations in pot size, firepower, and mass of water. This reduced variation is due to the cancelling of similar positive and negative effects of the $\beta$ values. Therefore, the presence of a lid is also recommended for assessing SC which is consistent with the recommendation for $\eta_{\text{heat}}$ due to the relationship between $\eta_{\text{heat}}$ and SC shown in Eq. 5-4. For the second study, which is at the higher firepower for the base case, pot size had no effect whether a lid was present.

Finally, another important metric is how quickly the cookstove can be brought to a useful temperature. In this study, the temperature assessed was 90 °C. Time to 90 °C had the highest variation of all the metrics. For many of the testing parameters studied, the effects on the time to reach 90 °C are intuitive. It is not a surprise that having a lid would decrease the time to 90 °C, that a lower firepower would increase the time to 90 °C, or that a larger initial mass of water takes longer to reach temperature. It is not as intuitive as to why increased pot size increased time to boil, but it is likely due to increased rates of evaporation that cool the water down enough to have an impact on the heating rate. This is borne out in the data. For example, configurations 3
and 7 only differed in pot size and with the larger pot, configuration 7 lost 1.7 times the amount of water as configuration 3 on average. As expected, a doubling of the initial mass of water from the base case greatly increased the time to 90 °C (first study, time = β₀ = 29 min for 2.5 kg of water to time = β₀ + β₄ = 46 min). Unlike the cases for η_{heat} and SC, the presence of a lid did not reduce the variability in the time to 90 °C, with predicted times according to Eq. 5-3 ranging from 14 to 49 min. Thus, there is no clear indicator as to how to reduce variation in the time to 90 °C for cookstove although this metric is not used in the ISO 19867-1 testing standard.

5.5 Conclusions

Given the complexity and difficulties involved in characterizing and comparing biomass cookstoves (Taylor, 2009), this study provides insights into the use of cookstove performance metrics based on varying testing parameters including firepower, the presence a lid, pot size, initial mass of water, and the presence or absence of boiling. The total efficiency η was not greatly affected by variations in any of the testing parameters (i.e. no effect was greater than 6% of the base case). Thus, η is a consistent metric for cookstove comparison since variations in testing parameters had little impact. However, further analysis that includes SC and η_{heat} metrics can provide additional efficiency insights that may be beneficial for cookstove comparisons depending upon the cooking objective. According to Eq. 5-4, SC and η_{heat} will provide similar information as to the comparative effectiveness of the cookstove. When reporting SC or η_{heat} metrics, it would be beneficial to report both ΔT (difference between ending and starting water temperature) and LHV\textsubscript{fuel} so that one metric may be calculated from the other.
With regards to metric comparisons among cookstoves, it has been noted that many replicates are needed for accurate results (Lombardi, Riva, & Colombo, 2018) but it is also important to minimize variations in cookstove metrics due to variations in testing methods. This study showed that the use of a pot lid greatly reduced variation in both $\eta_{\text{heat}}$ and SC metrics even when there were significant variations in other testing parameters. For instance, although pot size significantly affected these two metrics in the absence of a pot lid, the presence of a pot lid essentially eliminated the effects of changing the pot size. Thus, the use of a pot lid would provide better consistency for cookstove comparisons when using these metrics. The time to reach 90 °C varied widely among changes in testing parameters. Therefore, this metric is difficult to use for cookstove comparisons without being compromised by testing protocols.

It should be noted that this study only addressed variations in testing parameters associated with lids, firepower, pot size, water amount, and ending temperature. These parameters, except possibly for firepower, are easy to control. Future studies in this vein that would be beneficial to assess would be variations in other testing parameters, such as wood composition/moisture content, burning patterns, and wood geometry/placement on cookstove metrics. Another area that could use additional development is finding additional laboratory based tests to help focus field based tests on only the most promising cookstoves.

This chapter is based off of a published article (Quist, C. M., Jones, M. R., & Lewis, R. S., 2020). I hereby confirm that the use of this article is compliant with all publishing agreements.
6 Physical testing vs. DSC for food kinetics – a cookstove researcher's perspective

6.1 Introduction

New biomass cookstoves are designed every year. Many cookstoves can be sorted into categories, such as rocket style stoves, 3-stone fires, and traditional designs. As the number of possible cookstove designs continues to increase and research into this area develops further, there is more need for faster testing methods. Currently the vast majority of cookstoves are tested using at least one of a few tests, for instance ISO 19867-1, the Water Boiling Test (WBT) and its derivatives, the Controlled Cooking Test (CCT), and the Kitchen Performance Test (KPT) (P. Bailis et al., 2014; R. Bailis, 2004; International Organization for Standardization, 2018).

When considering cookstoves for a given region, the popular cooking styles are considered during the cookstove selection process. For performance testing, the nature of the cookstove can determine which tests are useful. For example, the recently updated to ISO 19867-1 has become the leading laboratory test and was preceded in large part by the WBT. ISO 19867-1 evaluates the particulate and gaseous air pollutant emissions, energy efficiency (using the combination of thermal efficiency and cooking power), safety, and durability of the cookstove. The WBT also evaluated pollutant emissions and energy efficiency. Each of these tests uses the approach of a task-based evaluation using the heating up and boiling of water for its assessment.

A typical follow-up test would be that of the CCT (recently updated to ISO 19869), which is something of a hybrid of a lab and a field test where a person familiar with local cuisine and cooking methods comes into a lab and cooks the food. Because this test requires both the
local ingredients and someone familiar with the local cuisine and cooking methods, it is much more difficult to obtain the resources to run. Therefore, when selecting a design for a cookstove in an area where boiling is the primary method of cooking, the ISO 19867-1 (or the WBT) may be a good first step to determine the best stoves to move on to the field tests. However, this is not as viable of a solution for a frying or baking style cookstove because of the limitations of the current laboratory tests and so ISO 19867-1 might be skipped in favor of the more resource intensive CCT (or ISO 19869). To narrow down the cookstove models tested before entering this kind of labor-intensive workflow, modeling cookstoves has become more popular and will likely increase as more scientists are trained in modeling and the modeling software becomes more capable.

Thus, there is a need for continued and improved modeling of cookstoves. While heat flow can already be reasonably modeled with various software packages, it may also be useful to model the cooking process (i.e. transformation kinetics) to help account for regional variation in diet and cooking methods. Modeling the transformation kinetics would be used to gauge the appropriate speed of heating performance of the cookstove (i.e. can the cookstove heat up the food and the associated cooking medium fast enough), which would help narrow down appropriate designs for further testing or dissemination. For example, once a region has been chosen for designing or selecting a cookstove, key foods could be then identified. Once the foods are identified a researcher could use data to find the minimum heating rates and cooking temperatures based on cooking time expectations. The heating rates and temperatures could then be used to identify the required firepower and turn-down ratio of a prospective cookstove respectively. With sufficient data on common foods around the world, regions with similar cooking requirements could also be identified.
To appropriately assess minimum heating rates and cooking temperatures based on cooking time expectations, both transformation kinetics (associated with transforming the food from one state to another during cooking) and thermal conductivity of the foods in question should be investigated. This work will focus on two methods for measuring and modeling the transformation kinetics: 1) using the heat of reaction measured by a differential scanning calorimeter (DSC) and 2) from cooking and testing the physical characteristics of the food using a tensile tester. In general, this work introduces many of the concepts behind the measurements as well as investigates the effects of sample preparation and gives some examples of method development.

6.2 Materials and Methods

6.2.1 Masa

Masa is a variety of corn flour used in making several foods such as corn tortillas (flatbread). Masa is of interest for analysis because with masa it is possible to choose a ratio of dry mass to water, it is viable for frying applications, and it can be analyzed with DSC. Masa was mixed with de-ionized water in 1:1 wt% ratio. The masa was tested in 40 µL aluminum crucibles in a DSC (DSC 3+, Mettler-Toledo International, Inc., Columbus Ohio). Three heating rates were evaluated: 2, 5, and 10 °C/min. The results for these tests were analyzed using ASTM E698 (ASTM International, 2018).

6.2.2 Carrots

The carrots used in this analysis were whole carrots purchased at Smith’s Food and Drug (Provo, UT). Carrots were initially of interest as they can be boiled, fried, or baked in various
styles of cooking. For this experiment the carrots were cut into cylinders, approximately 1 cm thick and 1.9 cm in diameter. Carrots were added to room temperature water, which was then brought up to 80 °C and removed at 0, 5, 10, 30, and 60 minutes after the water reached 80 °C. For the physical testing of the carrot structure, a tensile tester was used (Instron 3345, Instron, Norwood, MA). The carrots were crushed in the tensile tester and the maximum force required was the metric used to determine the strength of the carrot. Carrots were tested in the DSC as chunks as well as crushed, using 40 μL and 100 μL aluminum crucibles as was appropriate for sample size.

6.2.3 Differential Scanning Calorimetry

DSC measures the difference in heat flow between a sample and the pan the sample is placed in versus a reference pan. Once the temperature has reached a steady rate, the heat flow difference between the sample side and the reference side will slowly and linearly increase with the increasing heat capacity of the sample. Deviations from this linearity indicate a thermal event, such as a reaction, melting, or glass transition. These deviations can be integrated with respect to time to find the energy associated with events such as melting or reactions. Pure materials, such as metals, tend to give very sharp, clear signals for thermal events, whereas mixtures tend to have events that are shallower and occur over longer periods of time. Masa and other breads or doughs are mixtures in a chemical sense, as are carrots, and so most thermal events that occur in that system will be relatively shallow and broad.

6.2.4 Kinetic equation for studies
Starting with modeling the food as a batch reactor and assuming the food volume remains constant (usually a reasonable assumption for food), the equation for concentration with time is as follows:

\[
\frac{dC}{dt} = -k * C^n
\]  

Eq. 6-1

where \(C\) is concentration, \(t\) is time, \(k\) is the reaction rate constant, and \(n\) is the reaction order. In the case of using physical characteristics to determine food kinetics, the physical strength of the food can be used in place of concentration. The assumption here is that the rigidity in the food is indicative of some concentration of chemical bonds, and can therefore be modeled using the same types of equations that would be used to describe chemical reactions. Defining \(x\) as the conversion yields the following equation:

\[
\frac{dx}{dt} = k * C_0^{n-1} * (1 - x)^n
\]  

Eq. 6-2

This equation is used as a starting point for assessing the experimental studies.

### 6.2.5 Kinetic Equation for DSC Results

ASTM E698 is based on Ozawa's approach to kinetics from DSC (ASTM International, 2018). In essence, Arrhenius behavior is assumed, kinetics are assumed to have a first order reaction, and the conversion at the peak value of the analysis is assumed to be constant and the same for all heating rates. This results in the following modification of equation 6-2 to give:

\[
\beta \frac{dx}{dT} = k_0 e^{\frac{-E_a}{RT}} (1 - x)
\]  

Eq. 6-3
where $\beta$ is the DSC heating rate of $dT/dt$ (units of K/min), $x$ is conversion, $E_a$ is the activation energy, and $R$ is the universal gas constant. Taking the natural log results in the following equation:

$$\ln(\beta) = \ln[k_0] + \ln[(1 - x) \left(\frac{dT}{dx}\right)_{peak}] - \frac{E_a}{R} \left(\frac{1}{T_{peak}}\right)$$

Eq. 6-4

Thus, when graphing the $\ln(\beta)$ vs $1/T_{peak}$, $E_a$ can be calculated from the slope of the line. Since the second ln term in Equation 4 is often much smaller than $\ln[k_0]$, the intercept is approximately equivalent to $\ln[k_0]$ with $k_0$ having units of min$^{-1}$. This approach is the same method described in the ASTM E698 standard used by the DSC software to obtain kinetic constants.

### 6.2.6 Kinetic Equations for Physical Testing

For physical testing, conversion ($x$) is defined as $(F_0 - F_t)/(F_0 - F_{ss})$, where $F_t$ is the maximum force required to crush the food at a given time, $F_{ss}$ is the maximum force required to crush food at steady state, and $F_0$ is the maximum initial force required to crush the food. Integrating Eq. 6-2 with $n=1$ gives

$$-\ln(1 - x) = kt$$

Eq. 6-5

Thus, a plot of $-\ln(1-x)$ versus $t$ would give a straight line with a slope of $k$ and a zero intercept. If $n=2$, then integration of Eq. 6-2 gives

$$\frac{1}{C_0} \left(\frac{x}{1-x}\right) = kt$$

Eq. 6-6

Here, $C_0 = 1$ since $C$ is a relative concentration where $C=(F_t-F_{ss})/(F_0-F_{ss})$ and at the beginning of the test $F_x=F_0$ and therefore $C_0=1$. Thus, a plot of $(x)/(1-x)$ versus $t$ would give a straight line with a slope of $k$ and a zero intercept. When finding transformation kinetics parameters from the
physical testing of carrot characteristics, k is calculated first at a specific temperature and then
the experiment can be repeated at other temperatures in order to then calculate Ea using the
Arrhenius equation.

6.3 Results

6.3.1 Masa

DSC results for three masa experiments at β = 2, 5, and 10 K/min are shown in Fig. 6-1
(40 µL crucibles). The samples at heating rates of 2, 5, and 10 K/min weighed 12.45 mg, 12.46
mg, and 18.14 mg, respectively. As the sample temperature increased during the three different
heating rates, the measured heat flow in W/g at each temperature resulted in a baseline with no
thermal events at temperatures below approximately 60 °C, followed by a fairly broad deviation
from the baseline signifying a thermal event and then a return to the baseline. The peak thermal
events occurred at 78.47 °C, 79.83 °C, and 82.83 °C for heating rates of 2, 5, and 10 K/min,
respectively. Since the reactions are kinetically hindered (i.e. slowed because it requires
activation energy, unlike some processes such as melting) and as a DSC heats up at different
rates, the peak temperature of the thermal event should also increase with increasing heating rate.
This phenomenon is observed in this data. Based on Equation 6-4 (or ASTM E698 standard used
by the DSC software), Fig. 6-1 shows that ln(k₀) = 119 and Ea = 361 kJ/mol. Although k₀ and Ea
appear to be very high, such that further testing with repeats should be done to confirm these
values, the Arrhenius equation leads to a reasonable value of k = 0.028 min⁻¹ at 80 °C.
Figure 6-1: DSC results of masa, graphed against reference temperature on the x-axis and a relative y-axis with units of W/g. The DSC heating rate ($\beta$) is shown for each sample. The maximum peak temperatures display the expected behavior of increasing with increasing heating rate.

6.3.2 Carrots

An example of typical results for an individual carrot crushing experiment following boiling of the carrot for a specified time is shown in Fig. 6-2. Typically, the force will start out at 0 as the surface of the instrument approaches the carrot. Once the instrument reaches the carrot, the force increases until eventually reaching a peak where the carrot begins to break apart. As soon as the carrot breaks, the force begins to decrease. The curve then decreases until the point at which the instrument begins to squeeze the juice out of the carrot. Following the examples in the literature, the maximum force required during the crushing process (shown at 30 minutes at 80 °C in Fig. 6-2) was used as the metric for carrot strength (Peng et al., 2014).

For this analysis, reaction orders of 1 and 2 were explored. Fig. 6-3 shows experimental data, based on Eq. 6-5 (1st order) and Eq. 6-6 (2nd order), for carrots boiled in water at 80 °C and removed at 0, 5, 10, 30, and 60 minutes for analysis. Fitting the data to Eqs. 6-5 and 6-6 gave
nearly similar k values of 0.02 min$^{-1}$ for a 1$^{st}$ order reaction and 0.04 min$^{-1}$ for a 2$^{nd}$ order reaction. For this analysis, $F_{ss}$ was 19 N. As can be seen in Fig. 6-3, both reaction orders fit very well though the 2$^{nd}$ order reaction had a slightly higher $r^2$ value (0.99 vs 0.97). Additional data at intervening time points and at longer times would enable a better selection of the appropriate model. Interestingly, the k values for cooking carrots at 80 °C are nearly the same as the k value for cooking masa at 80 °C. Thus, the transformation kinetics for carrots and masa, at least at 80 °C, are similar. Further studies for carrots at other temperatures would need to be conducted to compare transformation kinetics between carrots and masa at other temperatures. Although not part of this study, cooking carrots at additional temperatures and repeating the force analysis would enable calculation of an activation energy to provide transformation kinetics of carrots as a function of temperature.

Figure 6-2: Force of crushing carrot as a function of tensile tester extension. The maximum force was the metric used for analysis. Carrot was evaluated after cooking 30 minutes at 80 °C.
The DSC results for three carrot experiments are shown in Fig. 6-3. Two of these experiments were performed with similar sized carrots: the blue line is from a 39.28 mg sample and the black one is from a 33.07 mg sample, while the purple line is from a 70.80 mg sample using the same temperature program. As can be seen, the heat flow curves for these experiments are very different. Curves A and C are essentially flat, while curve B has a large peak (in this case, showing evaporation of the water in the sample). There are also multiple artifacts observed (i.e. places where the curve is not smooth). Since artifacts complicate analysis in general, the artifacts in Fig. 6-4 make the data unusable for determining transformation kinetics for carrots using DSC.

\[
y = 0.02x \quad R^2 = 0.97
\]
\[
y = 0.04x \quad R^2 = 0.99
\]

**Figure 6-3:** \(-\ln(1-x)\) for 1\(^{st}\) order reaction and \(x/(1-x)\) for 2\(^{nd}\) order reaction vs time, where \(x\) is conversion. Data is fit to Eq. 6-5 (1\(^{st}\) order reaction) and Eq. 6-6 (2\(^{nd}\) order reaction). 1\(^{st}\) and 2\(^{nd}\) order reactions had similar \(r^2\) values of 0.99 and 0.97, respectively.
Figure 6-4: Three examples of DSC experiments with carrots. Note that the y-axis is a relative axis in W/g as with an absolute axis the curves would be too far apart for investigation. These curves show some of the difficulties of analyzing carrot cooking with a DSC: artifacts (possibly from sample movement) as well as a large peak demonstrating evaporation from a poorly sealed pan.

6.4 Discussion

Both DSC and force analysis were useful for determining transformation kinetics, but under different circumstances. With the kinetic parameters determined from either method, it is possible to determine minimum required heating rates (by determining how long a food would take to cook given a heating rate), minimum required temperatures (by determining how long a food would take to cook at a given temperature, or if it will cook at all), and potentially find cultures that could benefit from the same kind of cookstove if the common foods in those cultures have similar heating requirements.

For example, transformation kinetics could be used to determine cooking times (i.e. the time to reach nearly 100% conversion) at different temperatures, which could then help specify metrics such as a minimum simmering temperature and/or a minimum heating rate to reach the
minimum simmering temperature. An example of this type of analysis is shown in Fig. 6-5 for masa, which also contains a short table of times to percent conversion. For this example, if 90% conversion in less than two minutes was defined as the cooking requirement then at 70 °C the masa will not cook enough and only 75% conversion occurs after 27 minutes. At 75 °C, it takes too long (7.5 minutes) to reach 90% conversion. At 80 °C, the masa meets the requirement after 1.3 minutes. This would mean differences between the performance of cookstoves above 80 °C would be less relevant to choosing the cookstove since the requirement has already been met.

![Figure 6-5: Time to percent completion.](image)

Curves are shown for five temperatures, 85 °C (solid blue line), 80 °C (brown small dashes), 75 °C (purple long dashes), and 70 °C (green dots).

As both methods for obtaining transformation kinetics parameters were successful for very different kinds of samples, it is useful to compare the attributes of each method. First, the varieties of instrumentation (DSC vs. Force analysis) used in this study are each widely available at research institutions. The nature of each instrument will determine which steps are important

<table>
<thead>
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<tr>
<td>[min]</td>
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<tr>
<td>10.0 %</td>
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<tr>
<td>20.0 %</td>
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in sample preparation as well as what kinds of samples are reasonable to run with each analysis. Further, DSC analysis lends itself especially well to approximating the method of heating for fried and/or baked foods as the sample is heated at a nearly constant rate from the bottom of the sample. This means that the DSC sample can be cooked in a similar way to field applications, while still measuring the heatflow during the entire process. Physical testing requires that samples be removed from the cooking process at various points, both complicating and slowing the data collection process.

With the tensile tester for the carrot studies, significant care had to be taken with sample preparation. Foods are not always homogeneous, which includes many phenomena such as the presence of a wood-like grain, inner regions that have different strengths from outer regions, or the food may be layered like an onion. These inhomogeneities can lead to variation in the strength of the material. Some of these variations can be from sample to sample, but others can depend upon the orientation of the sample in relation to the surfaces of the tensile tester. Additionally, the geometry of the sample is important for the tensile tester if normalization is required.

An example of a food that exhibits multiple aspects of these challenges is the carrots used in this analysis. Carrots have a grain, like wood, where the direction of the grain goes in parallel with the carrots longest direction. Additionally, the interior section of the carrot (phloem) has a different physical structure from the exterior section of the carrot (xylem). Due to these challenges, significant effort was required to determine how to take the carrot sample. Before even beginning the test, it was clear that the sample needed the grain of the carrot to be perpendicular to the surface of the tensile tester. This was accomplished by removing the furthest outer layer of the carrot, creating a cylinder from the inner part of the carrot which was then then
cut into 1 cm thick discs. Discs of approximately 1 cm in thickness were ideal as the carrot slice was thin enough to sit on the tensile tester without toppling over, but thick enough that the carrot slice would break apart before being crushed into juice.

The difference in the physical characteristics of the phloem and xylem also means that the carrot has different physical characteristics depending upon the ratio between those two parts, which changes down the length of the carrot. Figure 6-5 shows the maximum crushing force of raw carrot slices as a function of the outer diameter. Here, the larger outer diameter begins at the top of the carrot and then the diameter becomes smaller as the distance increases from the top of the carrot. As can be seen, the average crushing force required at the top end of the carrot may be greater than in the middle portion of the carrot. Thus, for these experiments only portions of a carrot with an outer diameter between 29 mm and 39 mm were used for consistency. This was more of a precaution in this case as very few carrots in a bunch would have portions above 39 mm in the outer diameter. Once data for raw carrots was proven to be consistent, the cooking experiments were run. The kinetic data was analyzed based on conversion as noted above, which has been shown to be the most consistent method for determining the kinetics of food structural losses from cooking (Rizvi & Tong, 1997).
Figure 6-6: Maximum force required to crush raw carrot as a function of the outer diameter of the carrot.

As can be seen from the factors that needed to be accounted for with the carrot samples (orientation of the sample, physical ratio of the sample to the whole of the carrot, sufficient size of sample), sample preparation is key for physical testing. Some of the requirements of physical testing also limit what kinds of samples can be used. For example, a flatbread will frequently start off as a paste which may be too soft for the tensile tester to detect. Further, as the flatbread cooks the shape may change and render comparison with uncooked material unsuitable, or it may not be transportable in a consistent form in a partially cooked state. For these kinds of foods, a different method of analysis is a better solution.

Foods such as breads (and especially flatbreads) are typically heated predominantly from the bottom and for some recipes can be flipped as part of the cooking process. DSC instruments also typically heat a sample from the bottom, which makes DSC analysis a candidate for analyzing the kinetics of flatbreads. Samples in a DSC are typically placed in a crucible to
prevent fouling of the sensor, and for this analysis the crucibles used were also hermetically sealed to prevent loss of moisture from the sample.

In addition, most of the water in the masa/water mixture is inert during the reaction, further diminishing the signal. These factors that decrease the signal from the cooking reactions create challenges for producing high quality and clear data on the DSC. Thus, when analyzing reactions like those of cooking masa, the DSC needs to be in excellent condition. Several blank runs should be performed before analysis to show repeatability, and the data will need to be free from artifacts.

This requirement for high repeatability is exacerbated by the fact that all food is a mixture in a chemical sense. As was mentioned above, most if not all of the water is inert throughout the cooking process. Thus, too much water would lead to too little signal for useful experimentation in a DSC. That was, in fact, one of the causes of the difficulties in obtaining consistent data with the carrot samples in the DSC. The ratio of the sample that was participating in the reaction (e.g. cellulose) to the sample that was not participating (e.g. water) was too low, which meant that any disturbance made the data unusable. Additionally, small differences in the thermal contact between the sample and the pan lead to further inconsistency. It is therefore easier to get data that can be used for kinetic parameter determination with something that has a higher percentage of dry material, such as masa.

Some specific challenges to the masa include mixing thoroughly to increase homogeneity, the stickiness of the sample which may keep the sample from making good contact with the bottom of the DSC crucible (which would inhibit heat flow), and making a good seal on the sample pan to prevent mass loss. Additionally, because the sample is heated from the bottom and typically the heatflow measurement is also taken from the bottom of the sample, good
thermal contact between the sample and the pan is a necessity for good DSC data. Masa, after mixing with water, is quite sticky and can easily get stuck on the wall (preventing contact with the bottom of the crucible) and can also end up with a bubble at the bottom that will act as an insulating layer between the masa/water sample and the crucible. Either of these scenarios will result in data that cannot be realistically compared to other runs and also may not even show the thermal event in question. Use of a plunger of some kind to gently press the sample to the bottom of the crucible can help with each of these scenarios and adding a small layer of cooking oil to the pan might also improve thermal conductivity and accuracy.

If oil is used as an attempt to improve the DSC signal, care must be taken to make sure that the oil does not touch the part of the pan that comes in contact with the lid because that could prevent the cold weld from forming a good seal between the pan and lid. The stickiness of the masa/water mixture and the presence of water in the sample mean that either the sample or the water in the sample can also be deposited on the surfaces the aluminum crucible needed for the cold weld. If these deposits occur, then the seal may not be strong enough to stop mass loss and the signal from the reaction can be completely swamped by the signal from the mass loss. The sample may also end up deformed in this case, and the baseline will shift upwards because the loss in mass would also result in a loss in heat capacity. Data from an experiment experiencing mass loss would also be unusable for kinetic determination from DSC data.

6.5 Conclusions

Modeling of cookstove systems has seen increased development, and it may be useful to begin including the transformation kinetics of the food that is cooked to the models. Primarily this could be used to describe the requirements for the minimum heating rate required for the cookstove, as well as a minimum temperature requirement for simmering. This will necessarily
require customization to the cooking methods and foods common to the area the stove is either
designed or considered for. Another benefit from learning about the foods common to the area
the cookstove is designed for is that other areas with similar cooking requirements can be
identified and if a cookstove is successful in one of those areas it may be a good starting point
for the others. Once the possible foods to be used as metrics are chosen, then the type of food can
be used to choose which method of determining kinetics is more applicable.

Determining transformation kinetics through physical testing was found to be effective
for carrots in this study to obtain a characteristic rate constant at 80 °C. It was difficult to
ascertain whether the transformation kinetics followed a 1st or 2nd order kinetic model such that
further testing is needed. However, the rate constant for either order was nearly the same.
Additional studies at other temperatures would enable the determination of an activation energy.
Many similar foods could also be tested in this manner (squash, radish, apple, celery, etc.).
However, foods that require more preparation such as breads may not be appropriate for this type
of analysis. Good candidates for physical testing (with a tensile tester) hold their shape when
cooked, have enough structural integrity to be charted easily as their physical structure degrades,
and have sufficient consistency of the maximum crushing force from sample to sample.

If a food is not a good candidate for physical testing, then it may be possible that it will
be a good candidate for testing with a DSC. The keys for finding a food that is good for using a
DSC to obtain transformation kinetics include a strong enough reaction to result in a peak in the
signal (which can be aided by changing the ratio between water and dry ingredients) and the
ability to get good thermal contact with the bottom of the DSC crucible. Flatbreads like the masa
tested in this work are an excellent example of this, and it should work well for similar foods.
Determining transformation kinetics through DSC was found to be effective for masa in this
study to obtain transformation rate parameters. The associated rate constant at 80 °C was similar to the carrots. This may be due to some chemical similarities between foodstuffs in general. Further studies need to be performed to determine how transformation kinetics may vary among different foods at different temperatures. Hopefully between physical testing and DSC testing it is possible for a cookstove researcher to find enough foods to test to gain insight into which stoves may be best for their target market.
7 Conclusions and Future Work

The aim of this work is to assist future cookstove researchers, designers, and disseminators with deeper knowledge of the strengths and weaknesses of laboratory testing, as well as help develop new tools to improve the cookstove design process. This included investigating possible sources of error in the thermal efficiency ($\eta$) calculation, developing a model for tracking the transient $\eta$, comparing the effects of experimental design choices on various metrics, and investigating possible ways to obtain food transformation kinetics in cookstove research. The following is a brief summary of the methods used to accomplish these goals and main conclusions learned from the process.

7.1 Uncertainty analysis and design guidelines of biomass Cookstove Thermal Efficiency Studies (Chapter 3)

The aspect of uncertainty that was investigated was the uncertainty in the values used in the thermal efficiency equation. This was done using a propagation of uncertainty approach, and included uncertainty in measurements from instrumentation as well as uncertainty in literature values. Several experiments were run, and the uncertainty in the $\eta$ values calculated from those experiments was compared to the propagated uncertainty. The propagation of uncertainty and experimental results led to these observations:

- Propagated uncertainty increases as $\eta$ increases, which could lead to difficulty when comparing high efficiency cookstoves.
• Experimental uncertainty in η was greater than could be accounted for from propagation of uncertainty analysis.

• Lower Heating Values (LHVs) of biomass fuels should be reported for all studies because these are by far the single highest cause of uncertainty from measured or literature values.

• Experimental changes that could be used to decrease the uncertainty in η have significant limits. For example, increasing ΔT is bound by the freezing and boiling temperatures of water.

7.2 Transient thermal efficiency estimation (Chapter 4)

The first attempt at expanding the capabilities of laboratory testing was finding a way to calculate transient η. This was done to gain insight into the performance of the cookstove as it was used. Transient η was modeled with several key assumptions, including linear mass loss of wood, linear increase of charcoal mass, and a mass transfer coefficient that is independent of time and temperature. Multiple experiments were then performed with endpoints at shorter times than the testing methodology would normally use in order to compare against the modeled results. The model and comparison with experimental values lead to some conclusions:

• Assuming linear mass loss of wood, linear increase of charcoal mass, and a mass transfer coefficient that is independent of time and temperature, it is possible to estimate the thermal efficiency of a cookstove at any time during the testing process.

• Steady state thermal efficiency is reached tens of degrees below boiling for even high thermal mass cookstoves (like the one used in the study) and so with accurate
temperature measurement it may be possible to decrease the required maximum
temperature in testing to save experimental time when assessing thermal efficiency.

- The efficiency model with time used in this study can be used to determine if the test was run for long enough by showing if the test had reached steady state or not.

7.3 Effects of Variations in Testing Parameters on Water Boiling Test Performance

Metrics (Chapter 5)

Continuing with investigations into causes of variance, this time the focus was on learning about some factors that can account for differences between results originating in different laboratories. While there are standardized laboratory methods for cookstove analysis, there is some leeway in some of the decisions used when designing a cookstove study. This study investigated the effects of some of these decisions (specifically firepower, the presence a lid, pot size, initial mass of water, and the presence or absence of boiling) on several metrics ($\eta$, $\eta_{\text{heat}}$, SC, and time to 90 °C). This was done with two sets of factorial experiments. The more notable observations are below.

- Overall thermal efficiency, $\eta$, was the metric least affected by changing testing parameters
- Time to Boil was extremely variable and not as useful for cookstove comparisons
- Thermal efficiency due to heating, $\eta_{\text{heat}}$, and specific consumption, SC, are related and can be used to distinguish between cookstoves with strict testing methodology controls.
- Using a pot lid decreased the variance in $\eta_{\text{heat}}$ and SC more than any other factor
7.4 Physical Testing vs. DSC for Food Kinetics – a Cookstove Researcher's Perspective

(Chapter 6)

With the number of ICS that have been designed and disseminated, there have been relatively few successful implementations of ICS in the field (i.e. disseminations where the ICS became the primary method of cooking). Given this seeming lack of success, it may be beneficial to look at the issue from a slightly different perspective. Instead of finding an area and designing a cookstove, it may be possible to compare the transformation kinetics of the major foods cooked in regions with successful ICS implementations to those of other regions around the world. As a very simplified example, imagine that there are several geographic regions of interest – A, B, C, D, E, F, G, and H. In this example, regions A and B have had successful ICS implementation. Next, the most common transformation kinetics of the most common local cuisines in each region are tested. If, for example, region B has similar cuisine to regions C and F then it may be that the ICS used in region B would be a good candidate for implementation or a basis for a slightly modified version that could be then used in regions C and F. Clearly, significant research would be required to characterize any region, and so as a starting point this work was designed to show some of the strengths and weaknesses in using two different methods for assessing transformation kinetics – physical testing and differential scanning calorimetry (DSC). This was accomplished by using both physical testing and DSC on carrots and DSC on masa to calculate transformation kinetic parameters.

- Physical testing was successful to obtain transformation kinetics with a food that changed from being relatively hard to relatively soft. For this study, carrots were used for physical testing.
- Differential Scanning Calorimetry (DSC) testing was successful to obtain transformation kinetics with a food that had a higher concentration of solid matter. For this study, masa was used for DSC testing.

- Rate constants for transformation kinetics were similar for both carrots and masa even though the kinetics were determined using different testing methods.

### 7.5 Future Work

Research into ICS will continue for the foreseeable future. Ideally, the ideas in this work will aid in the process of the creation and dissemination of future ICS. Increased accuracy of results, faster testing times, and more data from the same measurements may be possible when applying the above findings of this work to the WBT or ISO 19867-1 when designing a new cookstove or testing one for comparison with other options. Additionally, it would be helpful to see what level of difference is shown when using different types of fuel (i.e. different species of wood, paper/cardboard, etc.). This would show if it is helpful to add fuel type requirements to the testing protocol, or if one type is sufficient. Another area that could use some exploration is increasing the possible daily throughput of the tests. In that vein, it may be useful to test a variety of cookstoves with ISO 19867-1 and choose multiple lower temperature ending points to see at what point the lower temperature ending points begin to affect the results (i.e. show different results for the metrics reported) and which stoves are affected most. If lower temperatures do not change the results in a significant manner, then each test will take less time and cookstove studies might be able to be finished faster. Also in the interest of speeding up testing times, it may be helpful to research methods for using more defined and consistent fuels (such as gas or liquid fuels). Currently there are many challenges inherent in using gas or liquid fuels when
testing biomass cookstoves, mainly a lack of radiative heat transfer and different flow characteristics. If it is possible to closely mimic the behavior of solid fuels with gas or liquid fuels that would help with consistency by decreasing the variation in the fuel (both by decreasing variance in LHV as well as having a consistent physical shape) and also would make testing faster and fuel preparation could be minimized.

A possible next step in the transformation kinetics branch of this research would be to select a few kinds of food, fully characterize them, and see how different each of them are. Ideally this would include some foods cooked in similar ways (like tortillas and chapatis or other flatbreads) as well as different ones (like vegetables or baked breads). It may be possible to determine cooking times at different temperatures for several varieties of food in two or more regions, then compare the various curves. Realistically, the foods would need to be categorized by cooking style, such as boiling, frying or baking. Then metrics could be determined for cookstove selection. For example, it may be useful to look at the five most common foods cooked by boiling and by frying in an area with a successful ICS dissemination (Area 1) and a target area (Area 2). If 80% of the foods in Area 2 are determined to have cooking times within 2 minutes of at least one of the foods in Area 1, then the ICS used in Area 1 could also be suitable for Area 2. Alternatively, it may be possible to look at the most common foods in two regions and if there are many foods with similar transformation times at a given temperature but the cooking methods are different, then the target region may be a candidate for developing recipes that would make the foods there suitable for an ICS designed for another region.
REFERENCES


