DISSERTATION

Toward the Understanding and Optimization of Chimneys for Buoyantly Driven Biomass Stoves

Submitted by

Jason Prapas

Department of Mechanical Engineering

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Doctoral Committee:

Advisor: Bryan Willson
Co-Advisor: Morgan DeFoort

Anthony Marchese
Jennifer Peel

Abstract

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The vast majority of indoor combustion devices in the developed world make use of stacks (flues, vents, chimneys, smokestacks) to channel flue gases out of the operator space [1].In the developing world, where indoor air pollution kills several million people every year, the use of chimneys with biomass cooking and heating stoves has been met with limited success and a high level of controversy. Due to a lack of theoretical understanding, design criteria, poorly executed installation practices, and/or insufficient maintenance routines, many chimney stoves have exhibited inadequate indoor emissions reductions in addition to low thermal efficiencies. This work aims (a) shed light on the physical phenomenon of the stack effect as it pertains to dynamic, non-adiabatic, buoyancy-driven stoves (b) apply new understanding toward the optimization of two types of biomass chimney stoves: plancha or griddle type stoves popular in Central America and two-pot stoves common in South America.

A numerical heat and fluid flow model was developed that takes into account the highly-coupled variables and dynamic nature of such systems. With a comprehensive physical model, parameter studies were conducted to determine how several field-relevant variables influence the performance of stack-outfitted systems. These parameters include, but are not limited to: power/wood consumption rate, chimney geometry, stove geometry, material properties, heat transfer, and ambient conditions. An instrumented experimental chimney was built to monitor relationships between air flow, differential pressure, gas temperatures, emissions, and thermal efficiency.

The draft provided by chimneys was found to have a strong influence over the bulk air-to-fuel ratio of buoyantly-driven cookstoves, greatly affecting the stove's overall performance by affecting gas temperatures, emissions, and efficiency. Armed with new information from the modeling and experimental work, two new stoves were designed and optimized to have significant reductions in fuel use and emissions.

Acknowledgements

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CHAPTER 1

Introduction and Motivation

1.1. A Global Problem

Indoor air pollution resulting from the combustion of solid biomass fuels is linked to chronic obstructed pulmonary disease (COPD), asthma, cataracts, lung cancer, low birth weight, acute respiratory infections and a host of other medical conditions [2, 3, 4, 5, 6, 7, 8]. While many of these health effects are linked to particulate matter (PM), carbon monoxide, a product of incomplete combustion, also poses serious health risks to families that burn biomass indoors. These emissions are a concern for more than 3 billion people globally who use biomass as their primary source of energy each and every day.

Chimneys have been utilized to vent smoke out of living quarters since at least the first century in Han Dynasty China [9]. In the modern world, nearly all indoor combustion devices in developed regions utilize stacks to evacuate emissions from occupied spaces [10].While chimneys may appear to be an obvious solution to mitigate indoor air pollution in the developing world, they are a subject of much debate. Chimneys have a strong influence on the overall performance of the stove, including the ability to degrade performance.

By understanding the operating principles of a chimney, the potential benefits that one can offer, as well as the common failure modes encountered in practice, more informed decisions can be reached about the utilization of chimneys in improved stove programs.

1.2. A Seemingly Simple Solution

Within developed regions, nearly every solid fuel combustion system that operates within an indoor environment includes a ventilation system to transport combustion products outside of the user envelope [10]. In less developed regions this feature is less prevalent. Most end-users prioritize stove cost and fuel savings over indoor air quality, and chimneys often add cost to a stove without saving fuel. Additionally, many poorly executed chimney stoves have led experts to wonder whether chimney stoves introduce as many problems as they solve [3, 10, 11]. Still, the enhanced ventilation afforded by chimneys has been linked to improved indoor air quality in several stove interventions [2, 12, 13].

The chimney of a natural-convection driven stove has the ability to change several crucial operating parameters of a stove, including the air-to-fuel ratio, the average gas temperature, the thermal efficiency, the rate of charcoal production, etc.; a chimney should be regarded as an integral and influential component, capable of being advantageous or deleterious to a stove system depending on design, implementation, and maintenance.

1.3. Information Gathering In the Field

A formative set of experiences in the field helped to motivate this work. One commonality of all stoves is that they are used by people; it has been extremely important to observe how people in various regions interact with traditional and improved cooking technology. As a stove designer, it is necessary to understand usage patterns and regional cooking practices to ensure that a stove will be popular and better for users than existing technology [1].

The bulk of the relevant lessons learned in the field took place in the Melgar Province of Peru and in Valle de Angeles, Honduras. These regions have major differences in cooking practices, fuel type, atmospheric conditions, and incentives for using improved stoves.

Both regions, however, have been actively targeted by various groups for chimney stove intervention projects. A short summary of information obtained in each region follows.

1.3.1. Melgar Province, Peru. From February 2010 to June 2012, three trips to Peru occured with approximately forty days in the field. The majority of the field work occured within indigenous communities surrounding Ayaviri, located in the Melgar Province. This region is shown in Figure 1.

Figure 1. Map of region in Peru where field work was conducted as part of this research.

1.3.1.1. *Background*

At elevations of 14,000 feet or greater, the communities surrounding the high Andes city of Ayaviri are presented with various challenges when it comes to preparing meals. Day to day life remains largely unchanged from centuries past. Citizens live in extreme poverty, with the majority of people working as subsistence farmers with virtually no disposable income. Above tree line, fuel wood is extremely expensive and/or unavailable. For centuries, the dung of livestock (primarily cow, alpaca, and sheep) has served as fuel for primitive adobe stoves, such as the stove shown in Figure 2. In all cases observed, this fuel is freely collected from the livestock of the family and was in ready supply. The climate was sunny and arid during the author's work (May-June), but community members spoke of the difficulties of drying dung throughout the wet season (November to March).

Traditional cooking in the high Andes is a recipe for disastrous human health. High altitudes result in lower density air, requiring more volumetric flow to bring adequate oxidizer into the combustion zone. Cooler ambient conditions have resulted in a culture of closed doors with minimal ventilation. Lack of woody-biomass forces users to use livestock dung, which generally has much higher emissions factors (mass pollutants emitted per unit mass fuel consumed) for carbon monoxide and total suspended particles than wood when burned in the same stove [14]. The low energy density and high moisture content that is typical of dung leads to slow, inefficient, and smoky cooking, exacerbating the indoor air pollution problem. In order to gain insights as to the ways in which these community members might respond to a chimney stove intervention, a series of tests, observations, and surveys were completed. Specifically, the field work in Peru that contributed to this research consisted of:

- Testing traditional dung-burning stoves in homes using the standard water boil test
- Surveying end-users about building and maintaining stoves, collecting fuel, and cooking
- Observing traditional cooking within a range of homes
- Installing several dozen improved stoves
- Training community members on the construction, operation, and maintenance of new stoves
- Discussing logistics issues with professional stove installers

FIGURE 2. Traditional dung-burning stove from the Melgar province in the High Andes of Peru. Stoves are hand-built from adobe and are typically operated in small, poorly ventilated huts.

- Follow up visits to discuss stove change

1.3.1.2. *Traditional Cooking*

The unimproved stoves that were encountered in Peru could be summed up as extremely smoky but relatively powerful and time-efficient. The average time to boil (ttb) five liters of water was 34 minutes 41 seconds $+/-6$ minutes for properly functioning stoves, of which there were eight. One stove went out three times during the testing and thus took 76 minutes to boil five liters of water; the operator of this stove indicated that this was a common occurrence when she was cooking. The average fuel use of the unimproved stoves was $2.14+/-0.48$ kg to take five liters of water to boil. This corresponds to approximately 6.3 % thermal efficiency when the value of 11 kJ/kg is used for the low heating value of cow dung [15]. More detailed data from field testing can be found in Appendix Section 3.1.

While there were variations in designs, most traditional stoves involved a side-by-side two pot arrangement, as shown in Figure 2. Generally speaking, one large pot was used for cooking stews, with a smaller pot or kettle used to boil water for tea. The average primary pot diameter was 26.5 cm +/- 3 cm.

Approximately half of the stoves seen had some form of chimney, but most did not function properly and were thus ineffective at transporting smoke out of the cooking structure. Common failure modes of chimneys included: restrictive geometries, insufficient chimney height, poor sealing between pots and stoves (leading to exfiltration of combustion products and reduction of chimney effect), and long horizontal chimney sections.

Many of the families did not regularly clean ash from the combustion chamber and it would accumulate, blocking air flow. Starting of stoves was difficult; most cooks used a small amount of alcohol (poured on a fuel pellet) to ignite the stove. One burning strategy that was observed in a few houses was the arrangement of the fuel in a cylindrical shell, allowing for air flow through the core of the fuel. More than half of the cooks also used a blowpipe to help start the fire.

Most families had built a separate small adobe structure specifically for preparation of food. The average size of this room was 3.85 +/- 2.6 m^2. None of the rooms observed had windows that could be opened; they were intended to provide light not ventilation. Coughing and eye irritation was pervasive with women and children; the author even managed to develop an acute upper respiratory infection within several days of indoor testing.

1.3.1.3. *Improved Stove Intervention*

In 2011, fifteen InkaWasi stoves were installed in three separate villages surrounding Ayaviri, Peru. A more detailed description of the construction and performance of this stove is described in Sections 4.7.2.1 and 5.6.2 respectively. The InkaWasi stove has been distributed to tens of thousands of homes around Peru and Bolivia by various groups [16]. In 2012, the 2011 stove recipients were revisited to see how the stoves were being used a year after installation. Based on surveys, only three of the fifteen recipients were consistently using their stove a year after installation. Another three users occasionally used the InkaWasi, but relied on their traditional unimproved stove for most tasks. The remaining nine recipients did not use their stove at all or used it for non-cooking related tasks, such as food storage shown in Figure 3. Survey responses indicated that people did not like how long the new stove took to boil water, that the firepower was difficult to regulate, and that it used the same or more fuel than its predecessors to complete cooking tasks. Furthermore, the stove had a serious usability issue: the permanent pot holes that were cut into the top of the InkaWasi were one size, preventing users from using different pots when occasions required.

If people put pots that were too small in the pot holes, large volumes of smoke would billow out around the pots. Pots that were too large did not fit down into the gas path, significantly diminishing heat transfer.

FIGURE 3. This InkaWasi stove, installed in 2011, had been converted to a makeshift food storage device less than a year after installation.

Following the disappointing outcome of the 2011 installations (20% stove adoption) a new strategy was developed to bring a nearby community, called Chosecani, improved stoves. In collaboration with partners from University of Colorado's Center for Energy and Environmental Security, as well as the Peruvian nonprofit organization, Caritas International, an education campaign was implemented. This included community meetings, graphical handouts, surveys, one-on-one conversations with prospective users, and investment by interested parties in raw and prepared materials. Those who were still interested in obtaining a new stove, after hearing about its benefits (health, durability) and shortcomings (speed, power regulation) would need to prepare 20 adobe bricks, and purchase several small pieces of hardware to reserve their stove. This procedure was intended to establish who was truly interested and willing to invest in a healthier stove. Twenty four new InkaWasi stoves were then installed in Chosecani, with many recipients being involved in the construction of their new stove and/or the construction of of neighbors' stoves.

Follow up visits were conducted in late Spring 2013 by a colleague from the Center for Energy and Environmental Security at The University of Colorado at Boulder. Based on surveys, twelve of the twenty four users were consistently using their stove approximately one year after installation. Several others used their new stove to support larger cooking activities that required higher capabilities than their traditional stoves could provide alone. Those who chose not to use their new stove again cited slow cooking speed as a main reason for discontinued use. Several other common opinions about the InkaWasi are listed in Table 1.

Table 1. Common Pros and Cons of the InkaWasi Stove Based on User Feedback

Pros	Cons
-Lower fuel use than traditional stove	-Very slow startup
-Allows for burning of dung or wood	-Quickly fills with ash, difficult to clean
-Higher durability than traditional stoves	-Pot holes only accomodate one pot size
-Effectively removes smoke from room	-Chimney requires constant cleaning to maintain clear flow path
-Aesthetically pleasing	-Higher cost than traditional stove (typically free)

1.3.1.4. *Additional Important Information*

The overwhelming majority of the people who were seen cooking are the family matriarchs. In many cases, mothers had small children within close vicinity to them while cooking. Through verbal surveys, we determined that the average woman was spending approximately 2.5 hours per day cooking. Most were not happy with their traditional stoves because it caused irritation to their eyes and lungs. Since dung fuel was free and relatively simple to collect, fuel use of the highly inefficient stoves was not a major concern. When asked what features would make a new stove better than traditional stoves, answers included:

- Less smoke
- Faster boiling of water
- Ability to use different pots without sacrificing fuel use, time to boil, emissions
- Ability to cook multiple things at once
- Easier to clean
- More durable

These requests formed a framework for the development of a new two-pot stove (which evolved into the L6040, described in subsequent sections).

1.3.2. Valle de Ángeles, Honduras. From December 2011 to June 2012, three trips to Honduras occurred with approximately fifteen days in the field. The majority of this field work occurred within 100 kilometers of the capital city, Tegucigalpa. This region is shown in Figure 4. As considerably less time was spent in the field in Honduras than in Peru, fewer data were obtained in the field. Conisderably more griddle stove data were collected in the laboratory.

FIGURE 4. Map of region in Honduras where field work was conducted as part of this research.

1.3.2.1. *Background*

Valle de Ángeles, in the heart of Honduras, represents a good cross section of communities that use planchas, or griddles, for cooking. Griddles allow for direct cooking of tortillas while cooking other food types in pots that sit on the griddle surface. Planchas are a popular stove type in several other Latin American countries, including Guatemala, Nicaragua, and Mexico [17].

Honduras has received much attention for improved stove initiatives given the escalating deforestation rates largely due to large and growing demands for wood cooking fuel [18]. In addition government has taken an active official position to bring higher efficiency, cleaner burning stoves to Honduran households [19]. While logging is strictly regulated, illegal fuel collection and sales is extremely common given the universal demand for wood [20]. The estimated deforestation rate is approximately 70,000 hectares per year [19]. This combination of deeply ingrained traditional practice with government regulation has some parallels to the charcoal fuel crisis in Haiti [21].

The author's work in Honduras involved testing the performance of traditional plancha stoves, collecting user feedback on the pluses and minuses of various stove features, and eventually testing a serious of prototype revisions, developed at the EECL, within user homes.

1.3.2.2. *Traditional Cooking*

There was a large variety of traditional stoves that were seen in the communities visited in Honduras. Most involved perching a large flat piece of sheet metal over several stones or blocks. Many people use the tops or bottoms of oil drums as a cooking surface, as shown in Figure 5. This material is not designed for thermal cycling, which leads to warping and failure (cracks, holes) over time. These traditional stoves rarely have a chimney for ventilation. Given Honduras' tropical climate, many users cook in relatively open and/or well-ventilated structures, but heavy rains also motivate some users to cook indoors.

Generally speaking, the Honduran diet is centered around corn [22], rice, beans, and chicken. Tortillas are made from a specially prepared corn flour, called masa, which requires heating a mixture of lime and ground corn. These foods are relatively resource intensive, requiring substantial heat and time to complete. Many users in the field were seen keeping their stoves running for multiple hours at a time to simmer beans, corn, or simply to keep the stove warm for later cooking tasks.

FIGURE 5. Traditional plancha stove in Valle de Ángeles, Honduras. Construction typically consists of 3 blocks, covered with cement, with a steel oil drum top.

1.3.2.3. *Preferred Temperatures for the Cooking Surface*

While in the field, infrared temperature measurements provided insights into the temperature range that users preferred when cooking tortillas and food in pots. These measurements helped to form specifications for cooking surface temperatures of the HM5000 plancha stove that was developed as part of this work and is described in greater detail in Section 4.7.1.2.

In field work carried out by the author and colleagues, the ideal tortilla-cooking temperature was found to be between 275-350 degrees Celsius. For cooking on pots, no maximum temperature was encountered, but temperatures less than 150 degrees Celsius had limited utility. In some cases, people used sub-150 degrees Celsius surfaces to keep food warm prior to serving meals.

1.3.2.4. *The Justa Stove*

The Justa stove is an improved stove designed by a multi-organization team (including Trees, Water & People, The Aprovecho Research Center, and Rotary International) in 1998. It utilizes a 'rocket' style combustion chamber geometry made of refractory tile, which is then insulated with wood ash [23]. The cooking surface is made from sheet metal with square steel tube reinforcements on the underside. The stove body is largely made from bricks and mortar.

Several thousand Justa stoves have been installed in Latin America, with Honduras being a country of main focus. Studies have indicated that replacing traditional unvented stoves with the Justa can significantly reduce personal exposure to particulate matter and carbon monoxide [23, 24].

In field testing and user interviews, common opinions emerged about the benefits and drawbacks of the Justa. These comments are summarized in Table 2.

1.3.2.5. *Additional Important Information*

Many Hondurans utilize fatwood kindling, regionally referred to as ocote, for starting and maintaining cooking fires. This wood, high in pitch, burns with a very high particulate emissions factor [25]. Ocote is popular with users because it combusts easily and with high intensity. The large particles that develop when ocote burns in a diffusion flame tends to

Table 2. Common Pros and Cons of the Justa Stove Based on User Feedback

Pros	Cons
Lower wood use than traditional stove	Slower startup
Effectively removes smoke from room	Stove requires constant cleaning to maintain clear flow path
Large cooking surface	Poor heat distribution, with hot spot in center, cooler spots elsewhere
Cooking surface retains heat better than traditional stove	Cooking surface warps with heat
Higher durability	Higher cost
Aesthetically pleasing	Requires several man hours to construct

clog systems that they are burning in, as shown in Appendix I Figure 64. These deposits can also scale the inside walls of chimneys with creosote.

One hundred percent of the cooks encountered in Honduras were women. Many users start their stoves in the early morning with high intensity to make all of the days tortillas (in some cases more than 50) at once. Users were often frustrated with warps within the cooking surface. Pots were generally found to be highly dented or damaged and typically used without lids. Many pots made poor contact with the cooking surface, owing to nonflat planchas as well as pots.

1.3.3. Common Issues With Chimneys in the Developing World.

While Peru and Honduras are vastly different regions with unique cultures, diets, fuel supplies, and traditional stove types, several common themes emerged with respect to chimneys. The literature also underscores these issues [14, 26, 27, 28, 29, 30, 31]. The following subsections outline several of these common problems with chimneys.

1.3.3.1. *Incentive*

One of the primary obstacles to the implementation of effective chimney stoves is communicating the potential benefits to end-users. Many end-users are unaware of the lethal effects of indoor air pollution, or that there is an alternative way to cook. This is where education campaigns for potential users become as important as access to improved technology [26]. As described in Section 1.3.1.3, the adoption rate of stoves in rural Peru was considerably higher when an education campaign was administered in the recipient community.

Secondly, programs do not exist yet that show monetary benefit to improved stoves from a health perspective. Carbon programs have been established that incentivize the use of more fuel-efficient stoves by stove programs; how can governments and NGOs have sustainable health-focused stove programs without similar mechanisms in place?

1.3.3.2. *Customer Needs and Preferences*

Too often, improved stoves enter design phases and production without ample assessment of what features people actually want to be included in their stove. This is believed to be a major contributor to failed stove programs over the years [27]. As challenging as it is to accomplish, the development of efficient, clean, and affordable stoves is not enough. These devices must also be desirable to use for impact to be achieved. They need to disrupt and displace exisiting stoves, not supplement them. While innovations can occur that are not developed by users (such as powered fans, dampers, pot rings, etc.) the overall stove must fit the needs of end-users first and foremost [28].

1.3.3.3. *Lack of Proper Instruction on Importance and Operation of Improved Stove*

As was experienced in the author's field visits, educating users on the health and environmental issues associated with traditional stove use as well as how to properly use and maintain an improved stove is an extremely important element of sustained impact.

Without user interaction and training, people may not engage with new technology, deciding instead to utilize traditional methods that are well known and understood. As

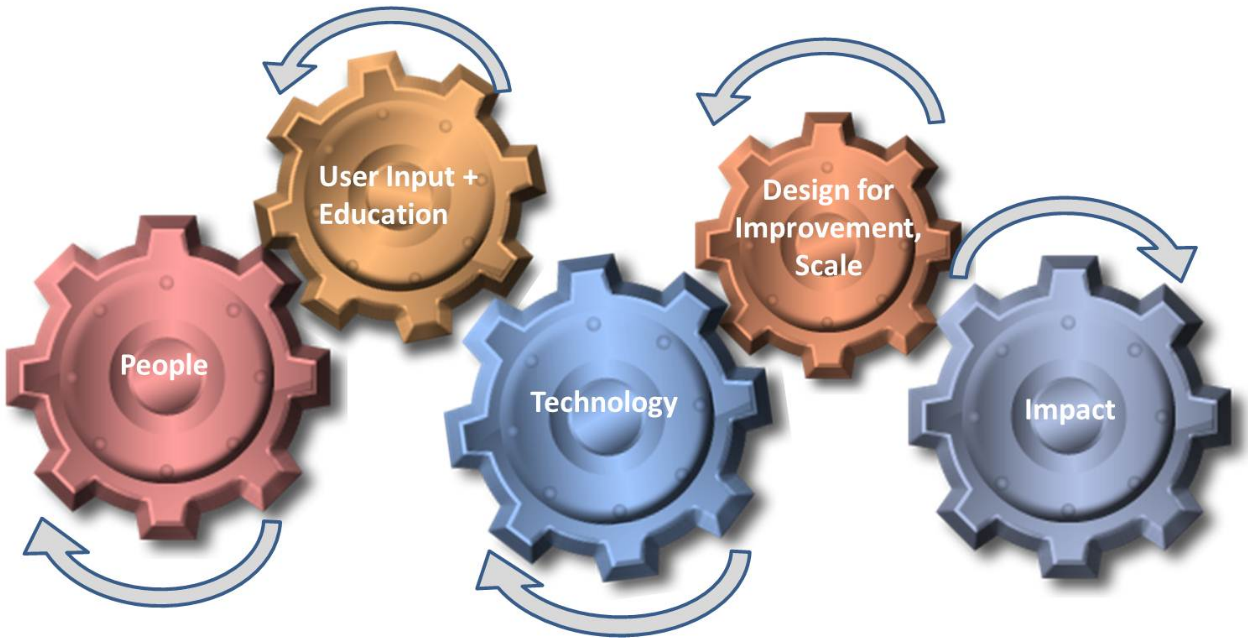


FIGURE 6. Several elements are required to produce impact from the human-centered cooking technology sector. Input, education, and scaleable imroved designs are needed.

shown in Figure 6, user input and education connect people to new technology, facilitating impact.

1.3.3.4. *Insufficient Understanding to Produce Significantly Improved Chimney Stoves*

While improved stoves for the developing world have received attention for several decades, the fundamental science around stoves is still in its infancy. The reality that many stove developers come to is that stoves are complicated physical systems wrapped in deceivingly simple packages. Complicating factors include, but are not limited to:

- Solid fuel burning: simultaneous pyrolysis and combustion lead to intractable chemical reactions. Fuel variability(composition, geometry, moisture content, etc.) only increases complexity
- Transient effects: A stove may take 30 minutes to boil water, but twice as long to reach steady state

- Non fully developed flow: Many stove geometries result in a series of internal flow sections that never reach a fully developed state
- Heat loss: an unavoidable reality of any thermal system. A buoyantly-driven stove relies on temperature differences, so heat loss cannot be ignored in many cases
- Users: All stoves require tending by one or more users and all people use stoves differently. This is a significant variable that greatly affects the performance of a cook stove

Chimneys are an additional source of complexity as they introduce new heat loss considerations, flow dynamics, and feedback loops. Adding a complicating element to an already complex system can be dissuading, particularly when scientific tools are not readily available to aid the designer.

1.3.3.5. *Poor Installation*

Even if a chimney stove has been properly designed, implementation of the stove in a user's house presents its own share of challenges. As Dr. Veena Joshi states: "It is unfortunately true that stoves in the field are often not built, operated, or maintained in the ways intended by their designers" [14]. Improper installation can occur for two main reasons: (a) the designer of the stove did not provide clear or sufficient installation instructions (b) the installer did not follow the installation instructions. While there are infinite combinations of ways in which a stove could be installed improperly, certain themes arise with high frequency. These include, but are not limited to:

- Long outdoor sections: exposed to the elements (rain, wind, etc.) and generally lower surrounding temperatures than indoors, outdoor chimney sections can cool the flue gas and reduce the lifetime of the chimney

- Horizontal sections: non-vertical chimney sections introduce viscous and thermal losses without offering any height for buoyancy. This reduces the effective draft of the stove
- Smoke reintroduction: emissions need to vent sufficiently far from occupied areas or they may be reintroduced into the home, as shown in Figure 7.
- The chimney outlet is at a lower height than the house apex: homes experience their own chimney effect in which warm air rises to the apex of the home. If the height of the chimney is lower than the house apex, the stove chimney will have to compete with the chimney effect of the house.
- Inability to clean: many chimneys are installed without consideration of how they will be routniely cleaned. Soot and creosote can build up on the chimney walls, restricting flow and altering the internal pipe roughness. Chimney fires can also result from this buildup
- Poor sealing: poor sealing in a chimney system can lead to smoke leaks outward, or infiltration of cool ambient air, reducing the stove's effective draft.
- High thermal mass sections: materials such as adobe and cement rob the flue gas of heat, reducing draft.

Several of these problematic practices are featured in Figure 7.

1.3.3.6. *Maintenance*

Another major hurdle in the path of successful chimney stove implementation is poor maintenance of the chimneys themselves. Unless a chimney is cleaned regularly and repaired when damaged, its performance is likely to decline over time. In addition to reduced performance, poorly maintained chimneys can pose serious fire risk, as the creosote that scales

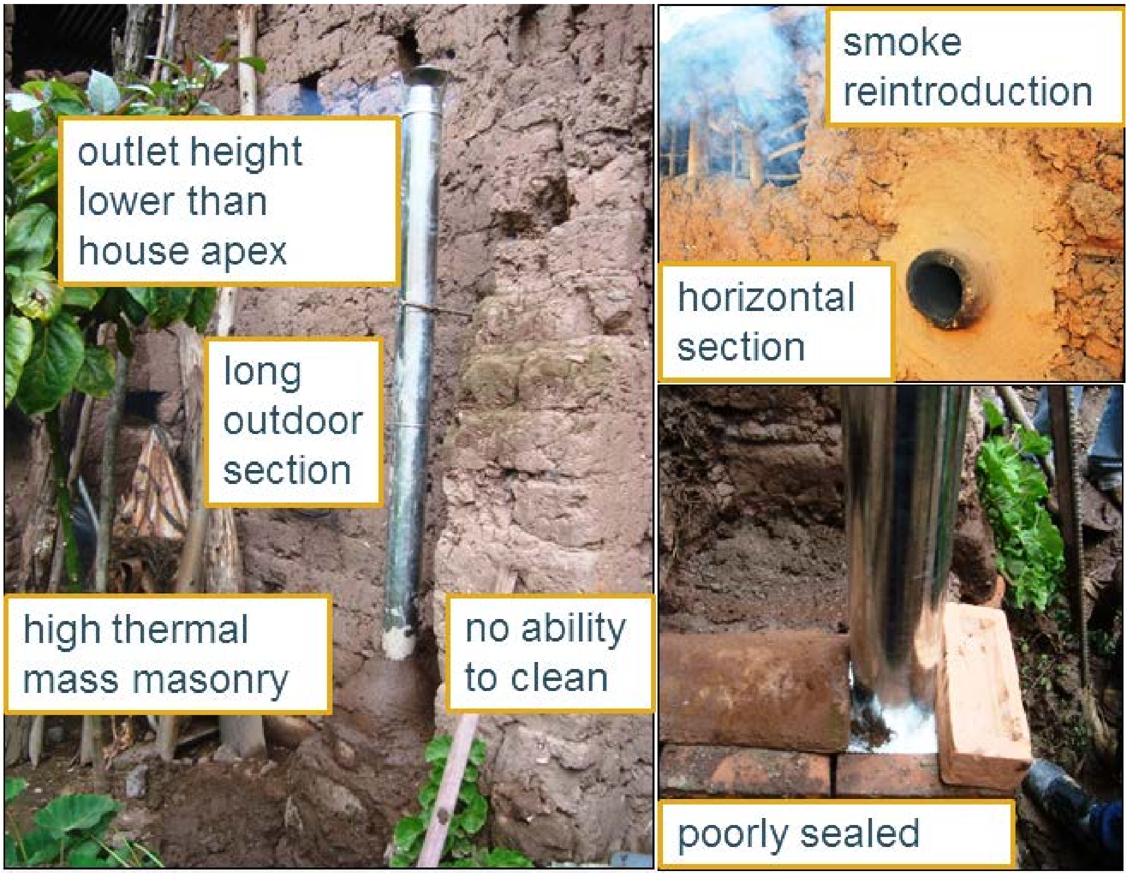


FIGURE 7. Common installation problems seen with chimneys in the developing world. Photos courtesy of Dr. Bryan Willson.

the chimney walls is combustible material [32]. In one of the 2012 follow up visits to check on 2011 installations in Peru, one user claimed that his straw roof (such as that shown in Figure 8) was ignited by an overly hot chimney.

1.3.3.7. *Durability*

In many cases, the chimney structure is one of the first parts to fail on a chimney stove [29, 30, 31]. Chimneys need to be constructed of robust materials that can survuve the caustic high temperature environment presented by biomass combustion. When a chimney malfunctions or fails, it can lead to dangerous outcomes, such as backdraft, chimney fires, or leaks. Replacing the chimney can be an expensive undertaking to families that are deep

FIGURE 8. Traditional Peruvian adobe straw roof with protruding chimney.

in poverty. Many designers have looked to design stoves without chimneys to avoid the cost and complications associated with them.

1.4. Chimneys in the Developed World

In 1744, Benjamin Franklin wrote a pamphlet describing a new invention he called the 'Pennsylvania Fireplace.' Franklin set out to invent a stove that would utilize less fuel and release less smoke into households. While Franklin's iterations showed promise, it was found to produce backflow of smoke into homes. It took several revisions by Franklin's contemporaries before the stove functioned properly [33]. While this anecdote is over two and a half centuries old, it remains highly relevant to those designing stoves for the developing world.

Within the developed world, where stove technology has reached greater maturity, there are guidelines, codes, and regulations that are meant to stymie many of the issues encountered earlier in history [34, 35, 36]. The regulations were established to protect users and the environment from dangerous, polluting devices. In addition to these available resources, the EPA established a process in 1988 requiring that wood stoves comply with certain performance standards if they are to be used in the United States [37, 38]. Additionally, individual states have established their own mandates to keep polluting stoves from operation [39]. These regulations have forced stove manufacturers to develop new, affordable technologies to meet the strict standards. Presently, a non-catalytic wood stove must produce less than 7.5 grams of particulate matter per hour from the outlet of the chimney. This is an achievable goal for stoves in the developing world, but many traditional stoves currently emit more than this amount within the home.

1.5. Potential of Chimneys

A large portion of this work is to understand how chimneys influence the behavior of stoves beyond mere ventilation of combustion products. The following sections briefly describe areas in which a chimney might play a significant role.

1.5.1. Combustion Efficiency.

There is experimental evidence that emissions from a natural convection biomass stove can be affected through manipulation of air flow (Baldwin, 1987; MacCarty, 2008; Champier, 2011). Forced convection stoves have shown promise, but face obstacles in the areas of cost, reliability, and fan/blower power supply. A properly designed chimney system may be able to achieve similar air flow rates as forced convection systems with no moving parts or required power inputs, as discussed in Section 5.2.2.

It is important to note, however, that a highly polluting cookstove does not become clean and improved simply by forcing more air through the combustion chamber. Each stove and fuel combination requires careful design to ensure that air and fuel are mixing optimally without deleteriously cooling the combustion chamber or negatively impacting the functionality of the stove.

1.5.2. Thermal Efficiency. Thermal efficiency is a key performance parameter of a cookstove. A more thermally efficient stove uses less fuel to accomplish the same task, reducing the burden of fuel costs and/or time to collect fuel.

Generally speaking, thermal efficiency gains within a cookstove are realized through heat transfer enhancement between hot flowing gas and the cooking apparatus. This can be done through a variety of methods, several of which involve increasing the convective heat transfer coefficient, h, through higher Renolds number flow [40].

As a chimney induces draft within a stove system, it can significantly increase the velocity and thus Reynolds number of the flowing gas in comparison to a non-vented stove. It is worth considering, however, that the induced draft pulls in ambient air, which serves to cool the system gas. An optimization analysis would be required to find the ideal gas flow-temperature combination to have an increase in heat transfer for a given stove.

1.5.3. Ventilation of Combustion Products. The primary function of a chimney is to bring products of combustion (complete and incomplete) outside of human-occupied space. A chimney stove only accomplishes this by successfully pulling emissions through the stove and out of the chimney without leaks or backflow. Emissions that aren't evacuated outdoors, described in the literature as fugitive emissions, can bring indoor air pollution levels to dangerous magnitudes [41]. It is important, therefore, to think of emissions from a chimney stove coming from these two separate zones, as shown in Figure 9.

There is an international working group, with which the EECL participates, that is in the process of creating ISO standards around the performance of cook stoves. These standards will cover efficiency/fuel use, total emissions, indoor emissions, and safety. There are currently plans to quantify the indoor emissions separately from emissions out the chimney as part of these standards. This will provide valuable resolution to chimney performance in terms of human health.

1.5.4. Appropriate Dispersal of Chimney Emissions. It is not enough for a chimney to pull emissions out of one home and into the air. One expert, Dr. Kirk Smith, has indicated that extensive outdoor air pollution from incomplete combustion can limit the impact of chimney stoves by increasing ambient pollutant concentrations, negatively impacting the air quality of entire communities [10]. There has been evidence of this community-wide air contamination affecting the indoor air quality of individual homes in the Western world as well [42].

As shown in Figure 10, the perceived effectiveness of chimneys may be different depending on whom is asked.

1.6. Problem Statements

In order to design, build, and install the best possible chimney stoves for different regions in the world, tools need to be developed which account for field-relevant conditions,

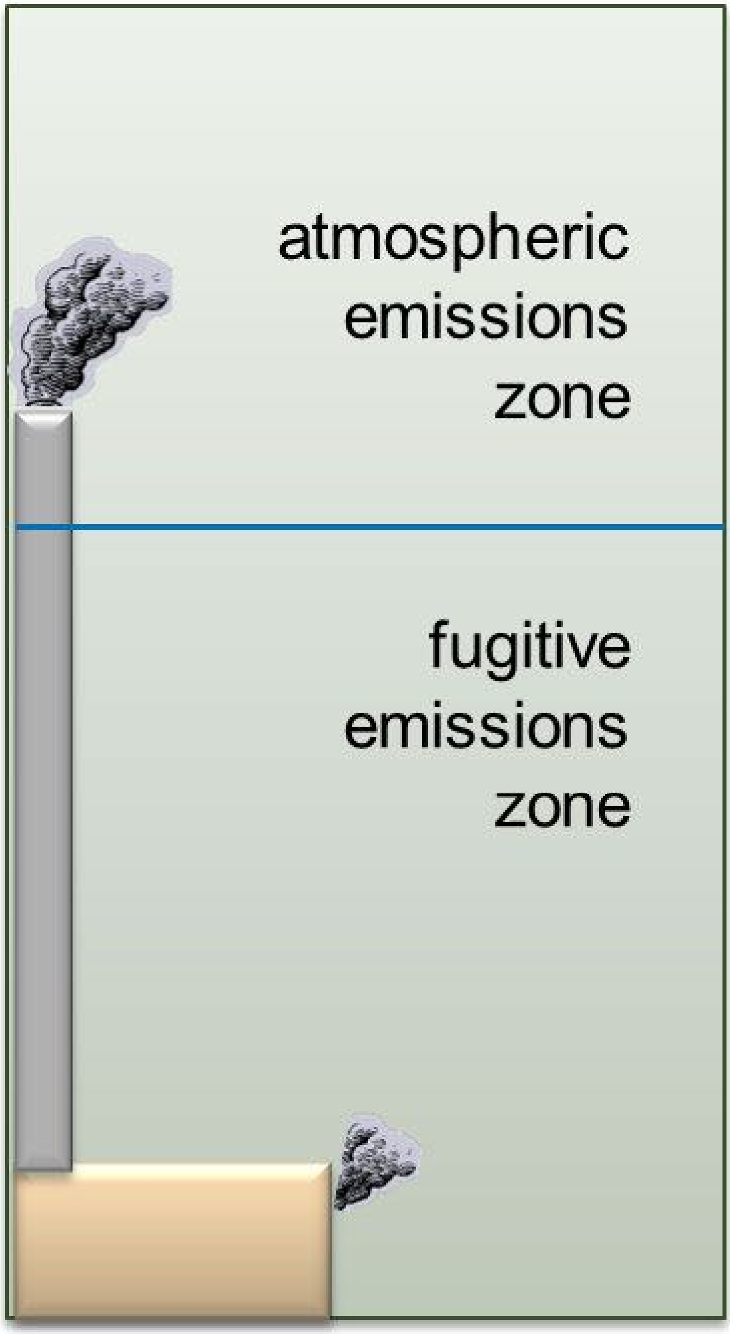


FIGURE 9. Emissions from a chimney stove need to be considered in terms of room emissions and stack emissions.

while being flexible enough to suit many stove types. Real-world considerations include fuel variability, heat loss, cooking power, wind, elevation, etc.

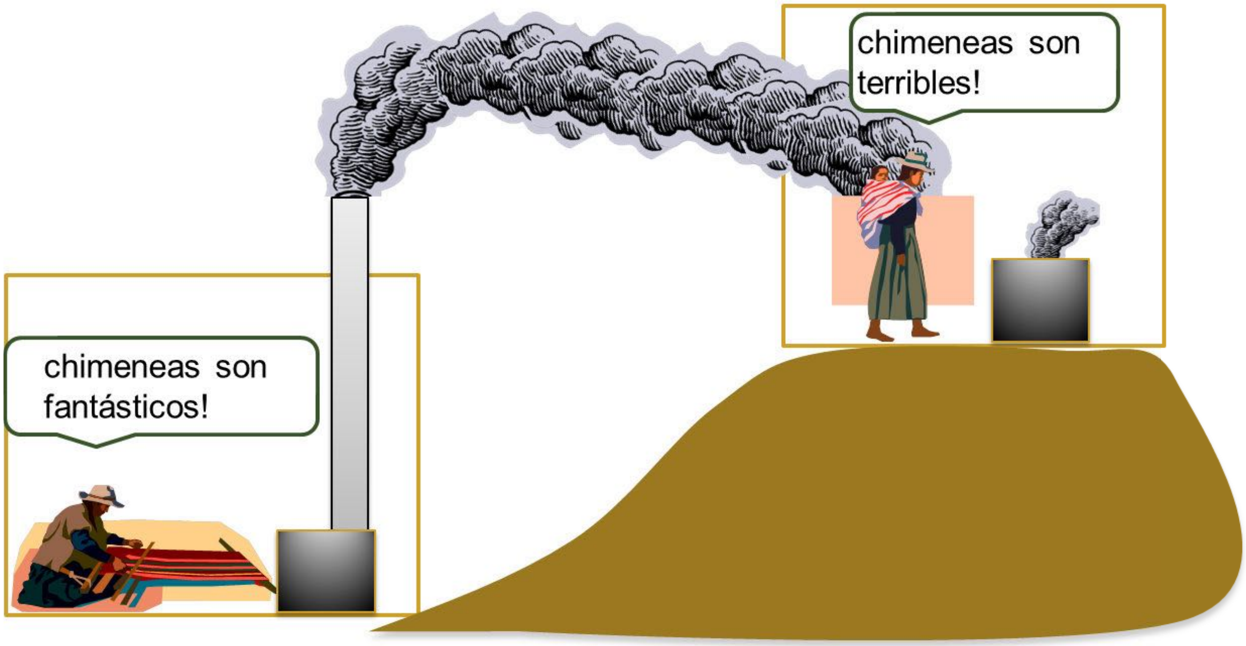


FIGURE 10. Opinions on chimney stoves are highly varied amongst technology experts and users.

TABLE 3. Problem Statement 1

Problem	Potential Solution
There aren't sufficiently realistic or flexible models that describe the behavior of chimney stoves	Development of modular, dynamic, buoyantly-driven model that incorporates real-world variables.

A physical model is only as good as its ability to describe the behavior of the system it is modeling. The three billion people that require improved stoves are not interested in conceptual devices that make hypothetical improvements. The stove development community needs tools that lead to truly improved stoves that can be implemented in communities that need them.

TABLE 4. Problem Statement 2

Problem	Potential Solution
How do we know the model works? Can it be used for optimization of design or operation of stoves?	The model will be validated through laboratory data. It will then be applied toward the optimization of two types of stoves.

One of the primary challenges in the implementation of improved chimney stoves is a lack of testing protocols, methods, and metrics that quantify how a chimney is performing overall.

Table 5. Problem Statement 3

Problem	Potential Solution
There are no established, standard metrics or methods for describing the effectiveness of a chimney from both efficiency and health perspectives.	Develop methods and metric(s) that incorporate(s) heat and emissions losses (fugitive emissions) to more completely describe chimney stove performance.

1.7. The Key Missing Pieces

There are a host of problems that degrade the effectiveness of chimney stoves. The deficit of understanding present in chimney stove design is by no means insurmountable. Shedding light on the interactions between the chimney, excess air, emissions formation, wood consumption rate, heat transfer rates, and ventilation rates, could result in a great deal of improvement in a short period of time. Stove designers, program administrators, government groups and end users all directly or indirectly need answers to questions regarding chimney stoves:

(1) How is fuel consumption rate influenced by a chimney?

(2) How is the formation of emissions influenced by a chimney?

(3) How is the thermal efficiency of a stove influenced by a chimney?

(4) Can more understanding of the physical and chemical mechanisms that drive chimney stove performance lead to new stove designs that make significant performance improvements?

(5) When the pros and cons are weighed, do chimney stoves present a viable solution?

The overall objective of this work is to provide useful insights and tools aimed at these questions.

CHAPTER 2

Background

2.1. Literature Review

This work is not the first scientific investigation of chimneys. There is very little evidence in the literature, however, of scientific rigor being applied specifically to chimneys for improved cookstoves. A thorough survey of peer-reviewed articles and texts yielded valuable information that has provided a foundation for the current work. In the following sections the most helpful literature will be summarized. It has been parsed into fundamental natural convection research, chimney-specific research, and improved chimney stove research.

2.1.1. Fundamental Science.

Natural convection is a common source of scientific inquiry, given that it is present in a wide variety of systems from deep sea vents to space shuttle heat exchangers. There is a wealth of literature on the fundamental science behind the phenomenon. Of particular interest to the current work are the contributions related to buoyant flow in open tubes, as that is most analogous to chimneys.

Gebhart et al. wrote the authoritative text on natural convection, *Buoyancy-Induced Flows and Transport*, and included sections relevant to the current work [43]. This resource provides a thorough set of correlations for heat transfer from and within enclosed geometries, such as pipes and parallel plates. It also provides guidance on how to treat the gas properties that change with temperature (such as density, heat capacity, etc.). While there is no explicit treatment of chimneys or stacks, there are references to such works within the text.

The classic text, *Fundamentals of Heat and Mass Transfer*, by Incropera and Dewitt was an oft utilized reference throughout this work [44]. In addition to offering correlations for heat transfer, the text includes discussion of dimensionless parameters that help classify the nature of convection flows (examples include the Rayleigh and Grashof numbers). Another useful text by several of the same authors, entitled *Introduction to Thermal Systems Engineering*, was also consulted regularly [45].

For more complex treatments of internal flows, Mills' Heat Transfer was also utilized. Mills' text also includes a thorough treatment of the use of lumped thermal capacitance to determine thermal responses of solid objects [46].

While several other fundamental science references were used to support this work, they are distributed throughout the dissertation and need not be highlighted here. A common conclusion within the literature is that an exact analytical solution to natural convection problem of this nature is intractable: approximations and simplifications abound. This results in a large gradient of model complexity across the literature. Many employ the Boussinesq Approximation in solving for the mass, momentum, and energy equations [47, 48]. This approximation includes:

- Viscous dissipation is neglected in the energy equation.
- Fluid density is assumed constant in all cases except for when buoyant forces result.
- Gas is considered incompressible

2.1.2. Scientific Chimney Literature. Natural convection chimneys had their research heyday in the early and mid-20th century. Up to the second half of the twentieth century, a substantial percentage of the population in the developed world utilized solid fuels for heating purposes. Many homes in Northern Europe still utilize wood stoves [49]. The scientific community became interested in understanding the physics of how chimneys operated to enhance the safety and efficiency of the systems that so many people were using. Several of these studies performed are relevant to improved stoves for the developing world today. A summary of the most useful papers is featured in Table 6.

TABLE 6. Scientific Chimney Literature From the Mid-20th Century

Author	Title and Year	Synopsis
Achenbach, P.	Physics of Chimneys, 1949 [50]	Clear summary of simplified physics of chimneys
Achenbach, P.	Performance of 14 masonry chimneys under steady state conditions, 1948 [51]	Draft resulting from chimneys of various materials at several mass flow rates.
Brown, W.G.	Fundamentals of Chimney Performance, 1956 [52]	Friction loss charts, discusses wind effects.
Brown, W.G. and Wachmann, C.	Draft Performance of Chimneys, 1960 [53]	Introduces new concept of non-isothermal losses in chimneys, a pressure loss created by temperature gradient between centerline and cooler walls.
Dropp, H.	Chimney Flues, Vent Piping, and Drains, 1928.	Discusses operation challenges with chimneys including condensation of flue gas constituents due to temperature drop in chimney
Fitzsimmons, C.	New Developments in Chimneys and Flues, 1944.	Efficient appliances causing lower chimney temps, affecting draft.
Schmitt, L.B.	Performance of Residential Chimneys, 1948 [54]	Model for available draft proposed. Wind effects quantified in laboratory simulation.

There have also been useful references published more recently in the area of industrial chimneys. While these industrial stacks are considerably larger than those used on domestic stoves, many useful connections exist between the two scales. In his book *Combustion and Pollution Control in Heating Systems*, Hanby features an entire chapter on the heat transfer and fluid flow considerations of chimneys used for industrial applications [55]. Many of his insights are applicable to chimney stove systems, such as the calculation of an overall heat transfer coefficient, fluid pressure loss terms, and gas temperatures.

Cortes and Campo provide a thorough treatment of the calculation of exiting temperatures of combustion gases from industrial chimneys using Nusselt number correlations that Campo had developed in previous work [56, 57]. While the geometries and Reynolds numbers associated with these chimneys are also of a significantly different scale from domestic chimney stoves, the approaches taken to calculate heat transfer coefficients from Nusselt number correlations proved helpful.

2.1.3. Improved Chimney Stove Literature. This is by far the sparsest area of the literature; the lack of available resources for designers of chimney stoves is a major motivation for the current work. Baldwin's seminal 1987 report, *Biomass Stoves: Engineering Design, Development, and Dissemination*, describes some of the issues associated with modeling buoyantly driven flows. He expresses concern regarding the use of any constant gas property assumptions and refers the reader to several resources for numerical solutions of convection systems. As Baldwin's objective was to provide a broad body of information on all biomass cookstoves, he doesn't offer a flexible numerical model for chimney stoves. He does underline the potential opportunities afforded by chimneys by saying: "To reduce smoke levels and improve cleanliness in the kitchen, chimneys are an option that should always be considered and encouraged" [40].

As far as numerical optimization of buoyant stoves, perhaps the best known example is that of Urban, Bryden, and Ashlock in their article: *Engineering Optimization of an Improved Plancha Stove* [17]. In this study, the authors couple computational fluid dynamics (CFD) with a genetic algorithm that makes random geometry changes that are then run through the CFD model. The authors report significant thermal efficiency gains by the numerically designed stove over the baseline. They also point out some limitations of their approach. The model was restricted to make only minor geometry changes to one part of the stove to allow for reasonable computation times. Specifically, the authors allowed flow baffles to be placed in different locations and configurations within the gas flow path. The geometry of the chimney, combustion chamber, and cooking surface remained fixed. For a different type of stove, a different model would need to be generated from scratch. Also, the optimization was geared toward maximizing thermal efficiency, but there are opportunities to optimize a stove more holistically by incorporating emissions minimization, and user-driven preferences. Lastly, while the study reveals the potential for use of computational tools in the development of a new biomass stove, it doesn't make the design tool available to the reader.

Lastly, there have been some strong efforts by this author's predecessors at the Engines and Energy Conversion Laboratory (EECL) to model the behavior of improved stoves. Agenbroad established steady state correlations with natural convection rocket elbow stoves that described relationships between gas temperature, mass flow rate, air-to-fuel ratio, and efficiency [58]. His development of dimensionless performance parameters is particularly effective, as it lends itself to a range of stove sizes and operating firepowers. For simplification he assumed constant gas properties, fully developed flow, and adiabatic buoyant sections. Incorporating less idealized elements in the numerical model was area for expansion taken on by this work. Zube also proposed numerical techniques toward understanding buoyancy driven cookstoves, concentrating on heat transfer efficiency optimization [59]. He also used constant gas property and steady state assumptions. His recognition that higher gas velocities led to higher thermal efficiency stands out as a motivation for this work, as a chimney facilitates higher mass flow rates through increased draft.

While there has been a good amount of work done at the EECL in numerically modeling stoves, none of the work has concentrated on larger stoves that are outfitted with chimneys; this adds complexity in the form of increased heat loads and losses, higher magnitudes of draft, and more heat and viscous loss terms.

2.2. Dimensionless Groups

Dimensionless groups are used frequently in thermal-fluid problems to characterize the nature of the scenario being investigated. Many such dimensionless parameters were used throughout this work to aid in understanding and modeling of chimney stoves. Several groups are defined and put in context in the following sections. More detail of their specific values in chimney stoves can be found in Chapters 3 and 5:

2.2.1. Reynolds Number.

The Reynolds number, which is the ratio of inertial forces to viscous forces, is described below:

$$Re = \frac{VL}{\nu} \tag{1}$$

where V is the fluid velocity, L the characteristic length, and ν the kinematic viscosity of the fluid. The Reynolds number is used to describe the flow regime that exists at locations within a fluid system. In the case of chimney stoves, understanding the local Reynolds number helps describe heat transfer, pressure losses, and mixing phenomena that occur in such places as the combustion chamber, gas path, or chimney.

2.2.2. Nusselt Number.

The Nusselt number describes the ratio of convective transport to conductive transport within a fluid. Alternatively, it can be thought of as a ratio of conduction thermal resistance to convection thermal resistance. It is defined as:

$$Nu = \frac{hL}{k_{gas}} \tag{2}$$

where h is the convection heat transfer coefficient, L the characteristic length of the fluid channel, and k_{gas} the thermal conductivity of the fluid. The Nusselt number has a strong dependence on the Reynolds number, and can be approximated with empirical correlations found in the literature. This is discussed further in Chapter 3.

2.2.3. Biot Number. Similar to the Nusselt number, the Biot number describes the ratio of convection transport to conduction transport. In this case, however, the conduction is through a solid that shares an interface with the fluid.

$$Bi = \frac{hL}{k_{solid}} \tag{3}$$

where h is the convection heat transfer coefficient, L the characteristic length of the solid, and k_{solid} the thermal conductivity of the solid.

In heat transfer, this quantity helps determine whether a lumped thermal capacitance analysis can be carried out with reasonable accuracy. Conventionally, when $Bi \ll 0.1$ lumped thermal capacitance can be used; this can be interpreted as saying that heat transfered to the solid by the gas is dissipated instantly and the solid becomes a uniform temperature. In the context of stoves, where heat transfer from a gas to a solid is the most important heat transfer mechanism, the Biot number emerges as a crucial parameter.

2.2.4. Prandtl Number. The Prandtl number is the ratio of momentum diffusivity to thermal diffusivity, defined below:

$$Pr = \frac{c_p \mu}{k} \tag{4}$$

where c_p is the specific heat of the gas, μ the dynamic viscosity of the gas, and k the thermal conductivity of the gas.

The Prandtl number is an important parameter as it is used extensively to calculate other quantities such as free and forced convective heat tranfer coefficients.

2.2.5. Grashoff Number. The Grashoff number describes the ratio of the buoyant forces to viscous forces in cases of free convection. It is defined by:

$$Gr = \frac{g\beta(T_{bulk} - Tamb)L^3}{\nu^2} \tag{5}$$

where β is the volumetric expansion coefficient (treated as 1/T with ideal gases), L a system length-scale, and ν the kinematic viscosity of the fluid.

2.2.6. Rayleigh Number. The product of the Prandtl and Grashoff numbers often occurs in correlations for convection as the Rayleigh number:

$$Ra = \frac{g\beta(T_{bulk} - Tamb)L^3}{\nu\alpha} \tag{6}$$

where α is the thermal diffusivity of the fluid.

2.3. Buoyantly Driven Flow

The ideal theoretical draft provided by the flow of heated gas in a vertical pipe that is surrounded by cooler air can be described by:

$$\Delta P_{stack,ideal} = (\rho_{amb} - \rho_{flue})\, g \cdot Z \tag{7}$$

where ρ_{amb} is the density of ambient air, ρ_{flue} the density of flue gas at the average gas temperature in the control volume, g the gravitational constant, and Z the height of the chimney.

Thus, the taller the chimney the greater the driving pressure. Draft will also increase with increasing flue gas temperature, as the density of a gas is highly dependent on temperature.

All physical systems experience energy losses when run in the real world. The major pressure loss associated with chimney flow is the viscous loss associated with friction to the chimney walls. The non-ideal theoretical draft provided by the flow of heated gas in a vertical pipe that is surrounded by cooler air can be described by:

$$\Delta P_{stack,nonideal} = (\rho_{amb} - \rho_{flue})\, g \cdot Z - \frac{K \cdot \rho_{flue} \cdot V^2}{2} \tag{8}$$

where K is the overall resistance coefficient of the control volume and V the average velocity of flue gas in the control volume. As can be seen in Equation 8, the loss term that is subtracted from the ideal draft scales with the square of the velocity. This means that at higher flows, the loss term can become significant.

The overall mass flow rate can be expressed in terms of the chimney height, losses, and area, as well as the gas density difference through:

$$\dot{m}_{total} = A_{chimney} \left(\frac{2 \cdot g \cdot Z}{K} \right)^{0.5} \left(\rho_{flue} \left(\rho_{amb} - \rho_{flue} \right) \right)^{0.5} \tag{9}$$

where $A_{chimney}$ is the cross sectional area of the chimney.

Equation 9 is referred to as the gravity-flow capacity equation [60].

In both equations 8 and 9, there is an overall loss coefficient, K. The following section describes the derivation of this term.

2.3.1. Overall Fluid Flow Resistance.

The overall loss term, K, is composed of several minor and major loss terms:

$$K = k_{minor} + k_{major} \tag{10}$$

where

$$k_{minor} = k_{inlet} + k_{outlet} + n_{bends} \cdot k_{bends} + ... \tag{11}$$

and

$$k_{major} = \frac{F \cdot L}{d_i} \tag{12}$$

where F is the friction factor, determined from the Moody chart [61] or from empirical correlations that utilize surface roughness and Reynolds number [62]. L is the length over which flow occurs, and d_i the hydraulic diameter in which flow occurs.

In the case of a stove, inlets, outlets, pipes, bends, channels, expansions and contractions all have separate loss terms associated with them and can be approximated using table values from the literature [60].

2.3.2. Analogous Scenario to Chimney Driven Flow. As a flow driven by a potential difference (temperature), chimney stoves can be thought of as analogous to an electronics circuit. Within a circuit electron flow, or current, is determined by a driving voltage difference and system resistances.

$$i = \frac{V_2 - V_1}{R_{eq}} \tag{13}$$

Within a natural convection chimney stove, volumetric gas flow is proportional to a driving density difference and flow resistances.

$$Q \propto \frac{\rho_{amb} - \rho_{hot}}{K_{eq}} \tag{14}$$

2.3.3. Elevation Effects. As shown in Equation 8, draft, or ΔP is dependent on the density difference between the hot chimney gas and the ambient air. In accordance with the ideal gas law, these densities are, in turn, dependent on temperature and pressure:

$$\Delta P_{stack,ideal} = (\rho_{amb} - \rho_{flue})\, g \cdot Z \approx \frac{P_{amb}}{R}\left(\frac{MW_{amb}}{T_{amb}} - \frac{MW_{flue}}{T_{flue}}\right) \cdot g \cdot Z \tag{15}$$

where P_{amb} is the ambient barometric pressure, R the universal gas constant, MW_{flue} the molecular weight of the flue gas, and MW_{amb} the molecular weight of the ambient air.

In many cases, such as high excess air exhaust scenarios, the molecular weight of the flue gas and the air can be considered equal, allowing for the simplification:

$$\Delta P_{stack,ideal} \approx \frac{P_{amb} MW_{air}}{R}\left(\frac{1}{T_{flue}} - \frac{1}{T_{amb}}\right) \cdot g \cdot Z \tag{16}$$

Barometric pressure, P_{amb} is a strong function of altitude [63], approximated by the following expression:

$$P_{amb} = P_{ref} e^{-\frac{Z}{Z_{ref}}} \tag{17}$$

where P_{amb} is the approximate atmospheric pressure at a particular elevation, P_{ref} the sea-level reference pressure of 101,325 Pa, Z the altitude at the region of interest, Z_{ref} the reference altitude (7000 meters in this case). As is discussed in Chapters 3 and 5, this sensitivity of the barometric pressure to altitude has important implications to the behavior of chimneys.

2.4. Heat Transfer Within a Buoyantly Driven System

2.4.1. The Chimney Conundrum.

Designers of chimney stoves know too well that two of the objectives they seek to meet are at odds with one another. A well ventilating stove ensures that all products of combustion (complete and incomplete) are syphoned through the stove and out of the chimney. This requires a robust draft, which in turn requires a large temperature difference between the flue gas and ambient air. An efficient stove, however, strips as much heat out of combustion gases as possible, transferring energy to the cooking operation. A stove designer, therefor, must carefully balance the benefits and downsides of a chimney system during the stove design process. This challenge of maintaining adequate draft with 'modern' appliances was discussed by Fitzsimmons in the 1944 publication: *New Developments in Chimneys and Flues*[64]. The current work is partially aimed at equipping stove designers with some of the tools required to better face the competing physics of a chimney stove.

2.4.2. Modes of Heat Transfer. Each of the three modes of heat transfer plays an important role in the function and performance of chimney stoves. The following sections detail some of the considerations regarding each mode.

2.4.2.1. *Heat Transfer by Convection*

In addition to the natural convection heat transfer mechanism that facilitates the stack effect, convection plays several fundamentally important roles in stove systems:

- Hot combustion gas passes its heat to cooking surfaces/apparatus through convection
- Chimney gas temperatures drop partially through convection to chimney walls
- Cooking surfaces, the stove body, and the chimney are cooled by natural and forced convection
- Foods with liquid fractions distribute energy partially through convection

In cases where buoyant and inertial flows occur simultaneously, it is useful to calculate the Archimedes number [65]:

$$Ar = \frac{Gr}{Re^2} \quad (18)$$

While a chimney stove produces draft through natural convection, the gas flowing throughout the stove can be treated as forced convection provided that the Ar number is well below 1. As flows through stove cooking sections are generally horizontal, buoyant forces can typically be ignored, so the Ar analysis is only considered an important paramter for vertical chimney flow in this work.

Quantifying cooling of the chimney by convection requires determination of natural and/or forced convection terms. This is largely dependent on how much chimney length exists in the presence of wind. Natural convection is always present as relatively hot solid surfaces are surrounded by cooler air.

2.4.2.2. *Conduction Heat Transfer*

Conduction plays a particularly important role in plancha style stoves due to the necessary heating of the griddle and the cooking apparatus or food that sits on top of the griddle. As hot gas flows underneath the griddle, heat is passed to the plancha through convection. Then heat must pass through the griddle material via conduction. Heat is also tranferred laterally through the griddle by conduction. Depending on the cooking task, heat is either transferred directly to food, such as a tortilla, or to a pot. After heat conducts through the pot, it passes into the water or food through convection. In reality, there is an interface resistance that separates the griddle from the cooking apparatus or food. These resistance can be small in the case of direct cooking and/or with very flat pots/griddles or it can be quite large in the case of non-flat pots/griddles. As described in Section 1.3.2, pots in the field were generally found to be dented and non-flat.

2.4.2.3. *Radiation Heat Transfer*

Radiation plays a particularly important role in the combustion chamber, where stove temperatures are hottest. The flame radiates to the griddle, but also outside of the mouth of the stove, in the case of front or side load wood stoves. As the stove body, including the chimney, becomes warmer, radiation plays an increasingly important role; radiation heat transfer scales with the temperature magnitude to the fourth power, as shown in Equation 19.

$$Q_{rad} = \epsilon A \sigma \left(T_{hot}^4 - T_{cold}^4\right) \tag{19}$$

Where ϵ is the emissivity, A the area of the radiating body, σ the Stefann Boltzmann constant (5.67 X $10^{-8} W m^{-2} K^{-4}$), T_{hot} the radiating temperature, and T_{cold} the receiving temperature. As can be seen, in cases where the emissivity, area, or temperature difference is very low, radiation heat transfer may be of insignificant magnitude.

In cases where radiation is to be accounted for, it can be linearized into a thermal resistance, not unlike a convection or conduction resistance. It requires simple factoring of equation 19, as shown below:

$$Q_{rad} = \epsilon A \sigma \left(T_{hot}^4 - T_{cold}^4\right) = \epsilon A \sigma \left(T_{hot}^2 + T_{cold}^2\right)\left(T_{hot} + T_{cold}\right)\left(T_{hot} - T_{cold}\right) \tag{20}$$

which means that radiation can be cast in a form conducive to Newton's law of cooling:

$$Q_{rad} = h_{rad} A \left(T_{hot} - T_{cold} \right) \tag{21}$$

where

$$h_{rad} = \epsilon\sigma \left(T_{hot}^2 + T_{cold}^2 \right) \left(T_{hot} + T_{cold} \right) \tag{22}$$

Finally the resistance to radiation heat transfer can be cast as:

$$R_{rad} = \frac{1}{h_{rad}} = \frac{1}{\epsilon\sigma \left(T_{hot}^2 + T_{cold}^2 \right) \left(T_{hot} + T_{cold} \right)} \tag{23}$$

2.4.3. Thermal Circuit and the Overall Heat Transfer Coefficient. Combining the various thermal resistances into an equivalent overall resistance allows for the determination of an overall heat transfer coefficient:

$$U_{overall} = \frac{1}{\frac{1}{h_i} + \frac{D}{k} + \frac{1}{h_o} + \frac{1}{h_{rad}}} \tag{24}$$

where $U_{overall}$ is the overall heat transfer coefficient, D the thickness of the material through which heat is being conducted, and k the thermal conductivity of the solid material.

This technique can be used over a large range of control volumes within a stove system. Some exampled include:

- Heat transfer from flue gas to water in a pot, as depicted in 11

- Cooling of the flue gas from the centerline of the chimney to the outside ambient air
- Heat transfer from the combustion chamber to the front of the stove body (important when designing for safety)

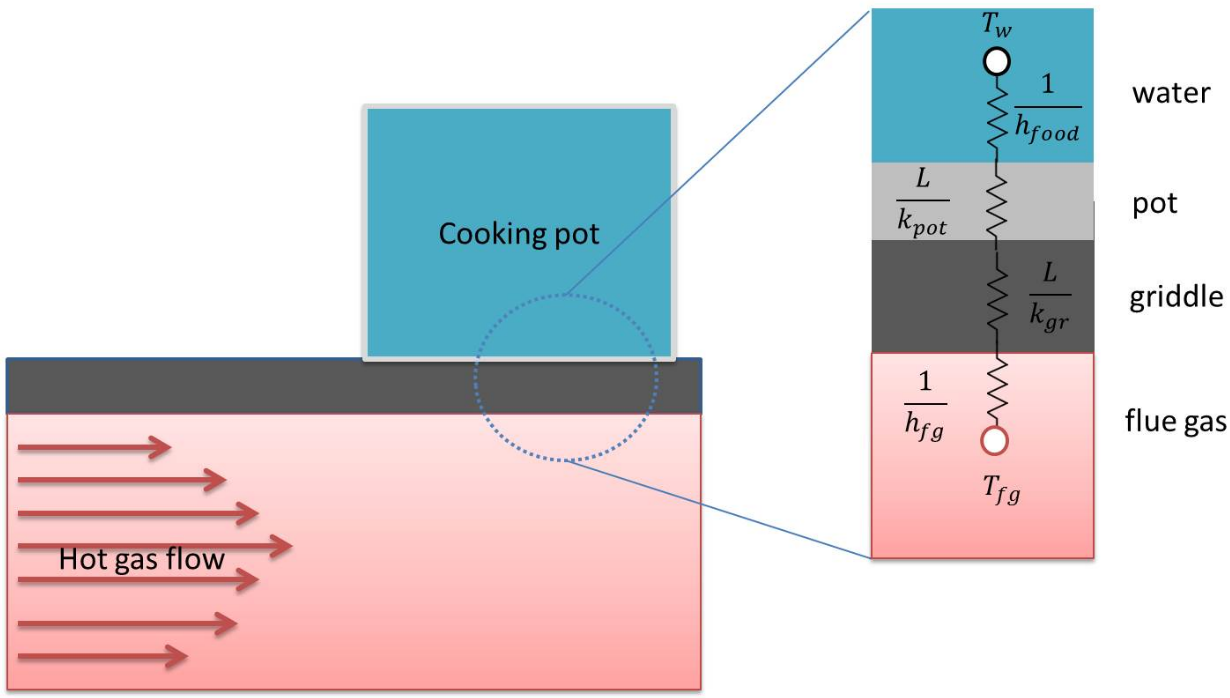


FIGURE 11. Thermal circuit representing the heating of water in a pot that sits on a griddle stove.

2.5. Mathematical Determination of Gas Temperature

Utilizing the overall heat transfer coefficient derived in the previous section, the determination of for gas temperature can be carried out relatively easily through determination of the exact solution of the differential equation associated with conservation of energy.

In order to calculate the flue gas temperature at a location within the stove, it is necessary to perform an energy balance over a control volume, as described in [55]:

(25) $$dQ = -U(T_{bulk} - T_0)dA$$

(26) $$dQ = HdT$$

substituting Equation 26 into 25 yields the first order differential equation:

(27) $$-U(T_{bulk} - T_0)dA = HdT$$

where H is the supplied heat, defined by:

(28) $$H = \dot{m}_{total} \cdot c_p \cdot (T_{fg} - T_{amb})$$

where c_p is the heat capacity of the flue gas, T_{fg} the temperature of the flue gas, T_{amb} the ambient temperature, and:

(29) $$\dot{m}_{total} = \dot{m}_{fuel} + \dot{m}_{air}$$

where $\dot{m}_{fuel}$ is the wood consumption rate/mass flow rate of the fuel and $\dot{m}_{air}$ the mass flow rate of the incoming air.

Through separation of variables:

(30) $$\frac{U}{H}\int_0^A dA = \int_{T_{in}}^{T_{out}} \frac{dT}{T - T_0}$$

yielding

(31) $$\frac{-UA}{H} = ln\frac{(T_{out} - T_0)}{(T_{in} - T_0)}$$

and ultimately:

(32) $$T_{out} = T_0 + (T_{in} - T_0)e^{-\frac{(UA)}{H}}$$

where T_{out} is the temperature exiting a control volume, T_0 the ambient temperature, T_{in} the temperature entering the control volume, U the overall heat transfer coefficient of the control volume, A the area in which heat transfer is occurring, and H the supplied heat to the control volume.

This solution is used frequently throughout this work to calculate gas temperatures. Examples include:

- calculating the temperature of gas entering chimney through knowledge of gas temperature entering the stove from the combustion chamber, estimates for convection/conduction/radiation terms within the stove section, and geometry of the stove.

- calculating the temperature of gas exiting the chimney through knowledge of the gas temperature leaving the stove, estimates for convection/conduction/radiation terms of the chimney, and height and diameter of the chimney.

2.6. Chemical Kinetics of Wood Combustion

The combustion of wood is sometimes described by a generalized, one-step overall reaction processes similar to that in Equation 33:

$$woodgas + a(O_2 + 3.76N_2) \rightarrow n_1CO_2 + n_2H_2O + n_3N_2 + n_4O_2 + n_5CO + n_6H_2 \tag{33}$$

where the wood-gas is described by some overall elemental composition, $\mathrm{CH}_y\ \mathrm{O}_z\ \mathrm{N}_f$. The overall carbon content of wood can vary based on wood type and harvest environment, i.e. hardwood, softwood, local climate where the wood is harvested, nutrient availability, etc. This carbon content ultimately affects how much air is required for complete combustion. Most wood is composed of approximately fifty percent carbon [66]. Estimates for the stoichiometric amount of air to burn 1 kg of biomass ranges from 4-7 kg [67, 68]. A more accurate estimation of wood combustion can be obtained by considering the actual chemical structure of wood and the subsequent evolution of pyrolysis gas.

Wood is primarily comprised of chains of cellulose ($C_6H_{10}O_5$), hemi-cellulose, and lignin strung together in a complex molecular structure [69]. The combustion of wood occurs in several steps. First the wood must be heated to the point where trapped water vapor is expelled and the molecular chains between wood molecules, such as cellulose and lignin, break down and the molecules are subsequently vaporized [69]. Next, due to the complex nature of the evolved wood molecules and the trapped oxygen within them, pyrolysis begins. The pyrolysis gases quickly transition into a semi-stable, thin, flame region where the gas mixes with the surrounding air. Due to (a) the radiation losses to the wood at the base of the flame (b) radiation losses to the surroundings, and (c) convection losses to the air, effective wood-gas flame temperatures can vary between 1100K and 1700K [70, 71] which is considerably lower than the adiabatic flame temperature of 1920 K [72]. Wood-gas flame temperatures have been measured in stoves at the EECL cookstove laboratory to be between approximately 1300-1500K [73] for natural convection cookstoves. After the flame front, excess air is mixed with the combustion products and allows for some additional oxidation of CO and other products, however the gas quickly cools to the point where further oxidation is effectively terminated. These above steps are depicted in Figure 12.

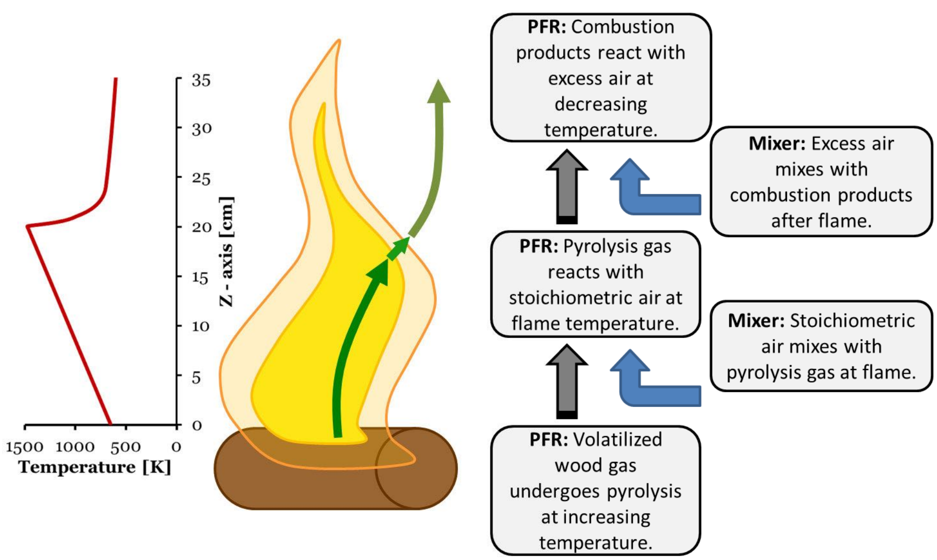


FIGURE 12. Model for wood flame. Figure courtesy of M. Baumgardner.

Recent interest in the applications of pyrolysis stoves as well as improvements in experimental techniques and analysis have increased the depth of knowledge of the components of wood gas [70, 71, 74]. Several studies have analyzed pyrolysis gases for several different solid fuels using thermogravimetric (TG) mass spectrometry and fourier transform infrared (FTIR) analysis of the evolved and reacted gases [75, 76, 77]. Ranzi et al. summarized this research and developed a chemical reaction mechanism with 327 species and 10934 reactions detailing not only the oxidation of evolved wood gases but also the interactions between these species in the pyrolysis zone prior to the flame [74]. Ranzi's work was consulted in the chemical kinetic modeling that is described in Section 3.3.6.1.

2.7. New Contributions to the Field

The challenges described in Chapter 1, as well as the prior work and literature review described in this Chapter, point toward a deficit of understanding around chimneys for use on biomass stoves in the developing world. This research is intended to fill in some of those gaps. The specific goals listed below have helped guide the work and should aid the reader in understanding the motivations and implications of the work that is to be described throughout the dissertation.

- Development of an experimental setup and procedures that allow for the collection of important information regarding the highly coupled behavior of biomass-fired natural convection chimney stoves.
- Development of a simplified numerical model that allows for quick estimation and optimization of chimney systems while capturing important real-world considerations, such as material properties, heat loss, fluid pressure loss, and varying power.
- Development of metrics that describe whether a chimney is performing well in its primary duty of ventilating combustion products out of user-occupied spaces.
- Development of a set of intuitive tools, such as graphical lookup charts, that aid stove designers in their development of clean, efficient, chimney stoves.

- Development of a new chimney stove that utlilizes the knowledge obtained throughout this work to achieve superior performance in comparison to existing stoves.

CHAPTER 3

Development of Computational Modeling Tool

3.1. Purpose of a Computational Model

A central piece of this work is the development of a simplified numerical model that can be used to describe, predict, and optimize the performance of buoyantly-driven biomass chimney stoves. A properly functioning model could be a powerful asset to a stove designer, allowing for valuable insights with a minimum expenditure of resources. In other thermofluid-centered energy systems (such as engines, furnaces, turbines, etc.) computational modeling/simulation has become an increasingly important element of technological advancement [78, 79, 80, 81]. Being able to alter stove, fuel, and user parameters in a virtual environment and run simulations could lead to significantly more economical and productive stove design processes.

3.2. Modular Structure of the Stove Model

To allow for a variety of geometries and operating parameters, the overall system model is discretized into modules, as shown in Figure 17. These modules can be thought of as interchangeable subsystems that work in series to describe an overall stove system.

The first module relates to the thermochemical combustion of fuel. While understanding the complex mechanisms of combustion is not a focus of the current work, being able to describe how bulk combustion parameters (such as excess air, combustion zone temperatures, and modified combustion efficiency) change with certain chimney-related variables was investigated. How carbon monoxide production rate is influenced by air flow, for instance, is an important relationship to understand with any stove. The combustion module is also vital in capturing the power output and emissions production of a stove. Wood is consumed and converted to heat and flue gas in the combustion chamber.

The outputs of the combustion module serve as inputs to the stove heat transfer model. These variables include, but are not limited to: total mass flow rate, wood mass flow rate, heat flux, gas temperature, and gas density.

The second module, referred hereto as the stove module, uses the variables passed from the combustion module as inputs to describe the heat and mass transfer from the combustion gases to the cooking apparatus, stove body, and ultimately into the chimney. The stove module is where the main function of any stove system is physically described; one cannot understand a cookstove without understanding how it delivers cooking energy. In the stove module, energy is stripped from the hot exhaust gases and transferred into cooking operations. The gas, with reduced enthalpy, is then passed into the chimney module.

The chimney module uses the outputs of the stove heat transfer module to initiate buoyancy-driven convection with heat and viscous losses. The resulting draft can be used to describe the makeup air that will be pulled into the front of the stove. This represents an important feedback mechanism with buoyantly driven stoves. How changes in draft-induced air flow affect the overall performance of the stove is heavily investigated in this work.

The chimney module could also be used to drive an atmospheric emissions model (plume dispersion based on velocity, density, and height from chimney model output). This extension was not a focus of this work but remains an opportunity for future expansion.

The development of each of these modules has required careful consideration of the highly coupled variables at play. As buoyantly driven flows ultimately rely on the temperature difference between the system and the ambient environment, most variables in the physical model can be traced back to one or more evolving system temperatures. A representation of the highly coupled nature of many of the relevant temperature-dependent variables required for a numerical model of a stove system is shown in Figure 13.

The flue gas temperature is itself a function of fuel type, firepower, location in the stove, and cooking load. This last point is worth mentioning since, in preliminary testing, the plancha stove behavior was shown to be influenced by what is being cooked on the griddle surface. When large pots of cold water have been placed on the surface, for instance, the gas temperature in the chimney has been reduced, which in turn, reduces draft. An accurate cookstove model would incorporate this effect, as a cookstove ultimately needs to be clean-burning and efficient while it is *cooking*, not heating the air of a room.

3.3. Major Considerations

3.3.1. Heat Loss.

The manner in which a chimney stove system loses heat, either to cooking loads, into the stove body, or through the chimney, heavily influences the flowing gas temperature. This, in turn, influences gas density, mass flow rates, viscous losses, thermal efficiency, etc. of a given stove. Understanding how stove characteristics influence heat loss as well as how different heat loss scenarios affect overall stove performance is required to produce a realistic model of a stove.

3.3.2. Ambient Conditions.

The environmental conditions surrounding a chimney system can significantly affect its overall performance. The following items were believed to be the most important ambient conditions to be included in the model.

3.3.2.1. *Elevation*

Elevation is an important variable to consider when attempting to describe the realistic behavior of cookstoves. In the model's current version, the user of the model enters an elevation, and the barometric pressure is calculated in accordance with the equations shown in Section 2.3.3. This value is stored and used as needed while the model iteratively solves the system of physical equations. Eventually, GIS data could be stored in the model such that the elevation (and barometric pressure) is determined based on global location.

3.3.2.2. *Wind*

Wind is a difficult parameter to capture given its variability in speed and direction over time. Nevertheless, wind effects should not be ignored; the behavior of a chimney stove can be affected in two significant ways:

(1) The flow of wind can significantly change the natural draft through its impact on the fluid dynamics of the chimney outlet. Wind can boost or reduce the draw of air through a stove, depending on direction and speed of wind as well as the location of the chimney exit relative to any built or natural structures.

(2) Wind can greatly increase the heat loss that occurs from areas of the chimney that are exposed to the environment. This, in turn, effects the buoyant force and overall behavior of the stove.

In order to capture these effects, wind can be modeled through incorporation of convective cooling elements as well as pressure loss terms. If a chimney has two meters indoors and one meter outdoors, it can be discretized into two heat transfer zones with two separate convective heat transfer coefficients.

3.3.2.3. *Local temperature*

An obvious variable that should not be overlooked is the ambient temperature where a stove is being run. All heat transfer is based on temperature differentials, where the ambient temperature is often being subtracted from a higher temperature to provide a driving temperature difference (ΔT).

3.3.3. User Variability. Stoves are run by people and each person has a distinct manner in which they run a stove. In many cases, these differences manifest as differences in fuel use, efficiency, and emissions [82]. While it is beyond the scope of this work to capture the subtle behavioral differences of individuals, allowing the model to be run with different firepower and cooking load inputs helps bring elements of realism to the simulated environment.

3.3.4. Temperature Dependent Properties and Variables. As described in Chapter 2, much of the work involving the numerical modeling of industrial stacks and cookstoves treats the systems as adiabatic. Accounting for heat losses allows for more accurate temperature predictions along with the host of properties that are ultimately temperature dependent, as discussed previously.

3.3.4.1. *Investigation of Dimensionless Group Sensitivity*

As described in Chapter 2, dimensionless groups have been heavily utilized in this work to characterize flow and heat transfer within chimney stoves. Much of the iterative numerical modeling is built upon correlations that use these dimensionless groups. As shown in Figure 13, many of the dimensionless groups and properties that are used to calculate them are dependent on gas temperature.

The Reynolds number, used to determine heat transfer coefficients and whether flow is laminar or turbulent, involves knowledge of the gas velocity, characteristic length, and

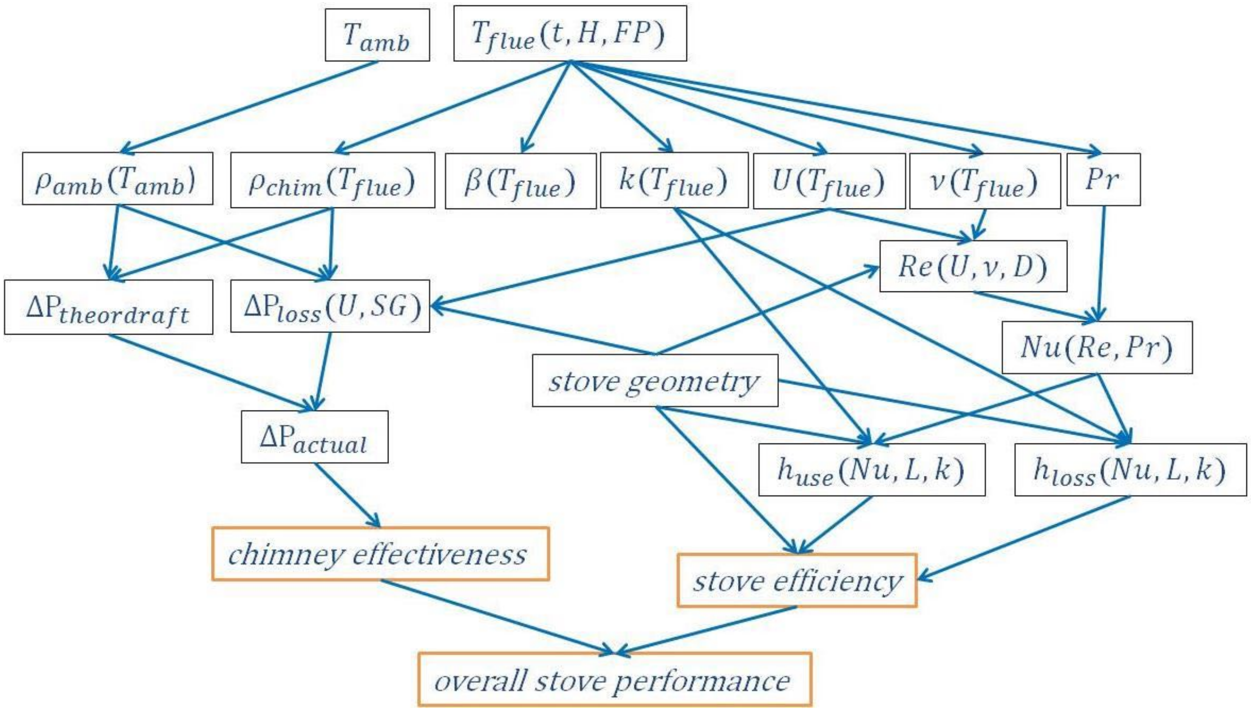


FIGURE 13. Many of the variables used to numerically describe the behavior of a stove are explicitly or implicitly dependent on gas temperature.

kinematic viscosity, as shown in Equation 1. The kinematic viscosity of flue gas can be described with the following approximation from Hanby [55]:

$$\nu(T) \approx (0.1335 + 0.000925 \cdot T)\, 10^{-4} \;\; m^2 s^{-1} \tag{34}$$

where T is the gas temperature in degrees Celsius.

In many cases in the literature, the kinematic viscosity is assumed constant. To illustrate the importance of keeping ν temperature-dependent, the Reynolds number for a 2 ms^{-1} gas flow in a 10 cm pipe was calculated over a temperature range of 50-750 degrees Celsius, changing only the kinematic viscosity in accordance with Equation 34. This is shown in Figure 14.

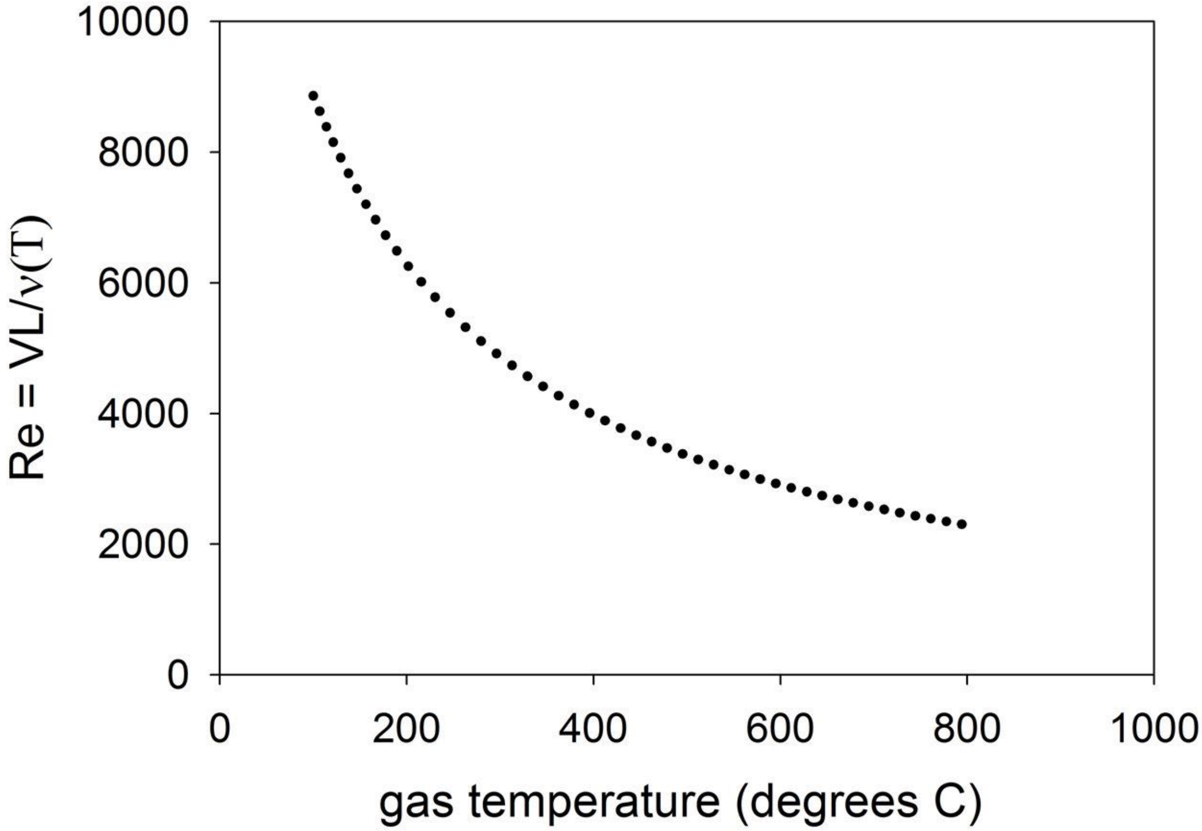


Figure 14. The sensitivity of the Reynolds number to the temperature dependent kinematic viscosity. In this particular case study, velocity was set to 2 m/s in a 10cm ID pipe.

As shown in Figure 14, the Reynolds number changes significantly as the temperature-dependent kinematic viscosity is varied over nominal stove temperatures. Holding kinematic viscosity constant in thermo-fluid modeling could result in significant inaccuracies.

The Prandtl number, defined in Equation 4 is another important gas property that tends to be treated as a constant in the literature [55]. It is used to calculate the Nusselt number and subsequest heat transfer coefficients. Unlike the Reynolds number, the Prandtl number has no geometric dependency; it is a property of a fluid alone. Like the Reynolds number the Prandtl number is composed of temperature dependent properties, namely specific heat, dynamic viscosity, and thermal conductivity of the fluid being studied.

From thermodynamic table values [83], the specific heat of the gas can be approximated by:

$$c_p(T) \approx -5.349X10^{-10}T^3 + 6.88X10^{-7}T^2 + 2.75X10^{-5}T + 1.002 \;\; kJkg^{-1}K^{-1} \tag{35}$$

where T is the gas temperature in degrees Celsius. This equation assumes the flue gas has the same specific heat capacity as air, which is considered a safe assumption given the high excess air present in the emissions from chimney stoves [55].

The dynamic viscosity of the gas can be approximated from table values [84] as:

$$\mu(T) \approx 3.064X10^{-8}T + 1.956X10^{-5} \;\; Pa \cdot s \tag{36}$$

As shown by the equation, this is a linear relationship.

The thermal conductivity of the gas is approximated by Hanby as:

$$k(T) \approx (0.1335 + 0.000925 \cdot T)\, 10^{-4} \;\; Wm^{-1}K^{-1} \tag{37}$$

where T is the gas temperature in degrees Celsius [55].

While the magnitude of the Prandtl number doesn't change drastically over the relevant temperature range, it changes enough to affect results of calculated parameters such as the Nusselt number describing flow within the chimney. Assuming turbulent flow within a cylinder [44]:

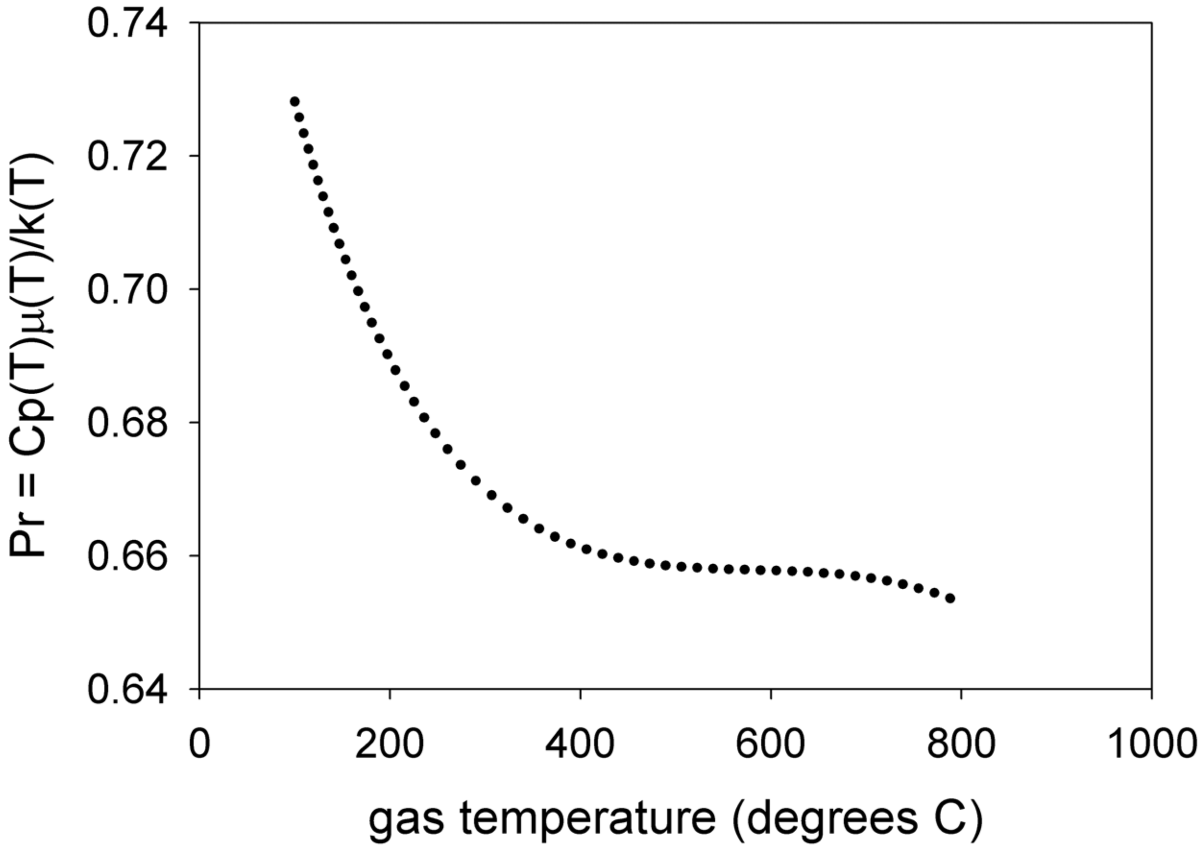


FIGURE 15. The sensitivity of Prandtl number to the temperature-dependent specific heat, dynamic viscosity, and thermal conductivity

$$Nu(T) \approx 0.023(Re(T))^{0.8}(Pr(T))^{0.4} \tag{38}$$

where T is the gas temperature in degrees Celsius. As described in Chapter 2 the Nusselt number is an essential parameter for calculation of convection heat transfer coefficients. The temperature dependencies of the Nusselt number and thermal conductivity translate to a temperature dependent convection coefficient:

$$h(T) \approx \frac{Nu(T)k(T)}{L} \tag{39}$$

When these temperature effects are bundled together in parameters such as the convection heat transfer coefficient shown in Equation 39, the difference in outcomes can be significant through compounding of error. As shown in Figure 16, choosing to ignore the variability of fluid properties with temperature could lead to a non-negligible difference in the calculated convection heat transfer coefficient. This, in turn, would lead to inaccurate estimations for convection heat transfer.

The convection coefficient is, in turn, used to calculate heat transfer to cooking apparatus as well as heat loss from the stove and chimney.

3.3.5. Feedback Mechanism Between Draft and Stove Behavior. While draft is a relatively simple quantity to measure experimentally, it is a harder quantity to model once interdependencies are considered. How does the draft impact air flow from one stove to the next? What are the implications to overdrafting/underdrafting a stove? Does added draft affect the heat output of wood in the combustion chamber? This work includes investigations into the feedback mechanism between the draft/pulling power of the chimney and the overall behavior of the stove. Once insights from experimental work (discussed in Chapter 5) were gained, the model was refined to more accurately describe this feedback mechanism.

3.3.6. Emissions. It is well known that the air-to-fuel ratio in hydrocarbon combustion systems influences the formation of emissions, such as carbon monoxide, soot, and nitrous oxide [85, 86, 87]. As increased draft within a stove system leads to increased mass flow

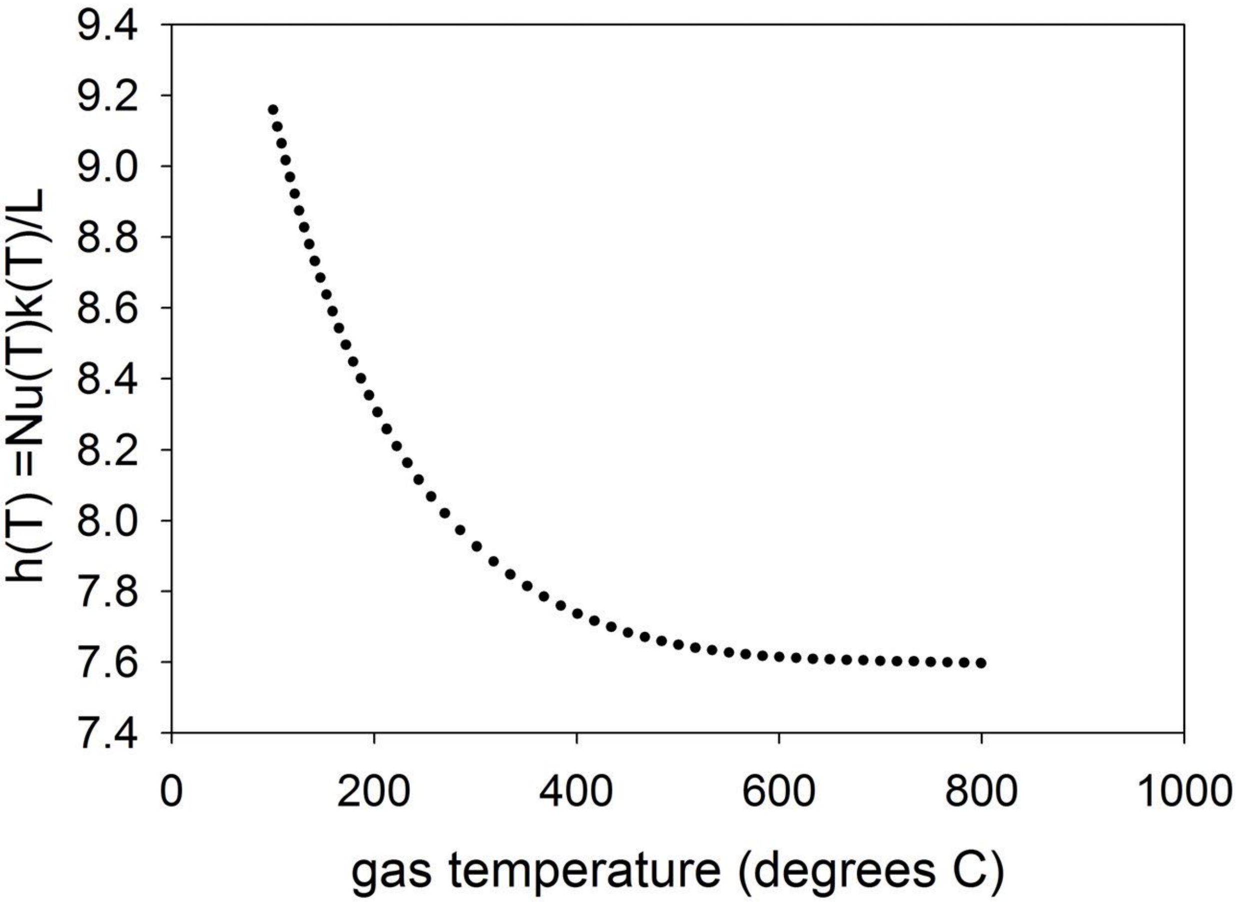


FIGURE 16. The sensitivity of the convection heat transfer coefficient to the temperature-dependent Nusselt number and thermal conductivity. This case is for the convection transport to the walls of a 10cm ID chimney in which 2 m/s gas is flowing.

rate of air, there are important parametric studies that can be carried out to investigate how changes to a stove system may effect the production rate of air pollutants. Chemical mechanisms that describe the production of carbon monoxide from hydrocarbon combustion exist, but soot production from solid fuels remains an intractable problem.

3.3.6.1. *CHEMKIN-PRO Modeling*

As described in Section 2.6, the chemical kinetics of wood combustion can be simplified. In the present study, the Ranzi et al. mechanism was used to model the gas phase chemical kinetics in the chimney stoves tested herein. Only the major vaporized wood species from the softwood Ranzi et al. model were taken to represent the evolved wood gas; the fuel mass fractions can be found in Table 7. Using the species distribution in Table 7, the stoichiometric amount of air was found to be 6.1kg for 1kg of fuel, which is consistent with previous studies [67, 68]. Charcoal was excluded from the chemical modeling for simplification. This was believed to be reasonable given that charcoal accumulation is relatively minor in both stoves that were tested.

TABLE 7. Evolved wood gas composition

Species	Mass Fraction
$C_{11}H_{12}O_4$	0.238
$C_5H_8O_4$	0.029
$C_6H_{10}O_5$	0.338
C_3H_5OH	0.044
$C_2H_4O_2$	0.010
C_2H_5OH	0.008
C_2H_4	0.007
CH_3OH	0.065
CH_2O	0.030
CH_4	0.003
CO_2	0.098
CO	0.058
H_2O	0.062
H_2	0.009
Total	1.000

As part of this work, this chemical approximation for the reaction has been run through a simulated chiney stove system in the CHEMKIN-PRO©software suite. Specifically, the chimney stove combustion processes studied herein were modeled as a series of plug flow reactors and CHEMKIN was utilized to explore the interaction between various parameters such as air-to-fuel ratio, reaction zone temperatures, wood combustion rate, and combustion efficiency. A direct numerical study for a turbulent flame was not practical for the current analysis as studies of such type can take weeks to run and petascale computing power to describe an extremely simple flame [88]. Additionally, these types of simulations can only be done (in full detail) with very small chemical mechanisms (< 20 species) [89]. Therefore a semi-turbulent model was approximated following the steps outlined below:

(1) The fuel species from Table 7 are reacted through a short pyrolysis section approximated by a plug flow reactor (PFR) beginning at 650K and ending at the flame (several models were run, ranging from 1300-1700K)
(2) A stoichiometric amount of air is mixed with the pyrolysis products
(3) The stoichiometric mixture of fuel and air is reacted through a very short (1-2mm) reaction zone, which is held at the flame temperature (1300-1700K)
(4) Excess air (also at the flame temperature) is then mixed (non-reactively) with the combustion products
(5) The fuel-lean mixture is allowed to react whilst being subjected to a decreasing temperature profile for the remainder of the stove gas path (note the temperature profile is taken from experimental measurements).

The entire connected model was solved via CHEMKIN-PRO ©. The non-reactive mixing sections were simulated using the embedded mixer model, while the reacting sections were all simulated using PFRs with the experimental stove dimensions, velocity measurements, and temperature profiles applied where necessary. It was found experimentally that the firepower during a given test fluctuates slightly and thus affects the overall bulk flame temperature. Therefore, the model results for most of the plots are shown as a band ranging in a peak flame temperature from 1400 to 1600K.

3.3.7. Useful Heat Transfer. Heat exchange is highly dependent on temperatures and velocities of flowing gases. Estimating heat transfer to cooking loads as other variables are changed could allow for the optimization of thermal efficiency for chimney stoves. For example, if a stove is run with a damper fully open, it may pull in too much excess air, cooling gas temperatures and reducing heat transfer to cooking operations.

3.4. Desired Structure of Model

In order to be a scalable, with reasonable run times, a modular, lumped parameter model was believed to be the optimal choice. A depiction of this structure is shown in Figure 17.

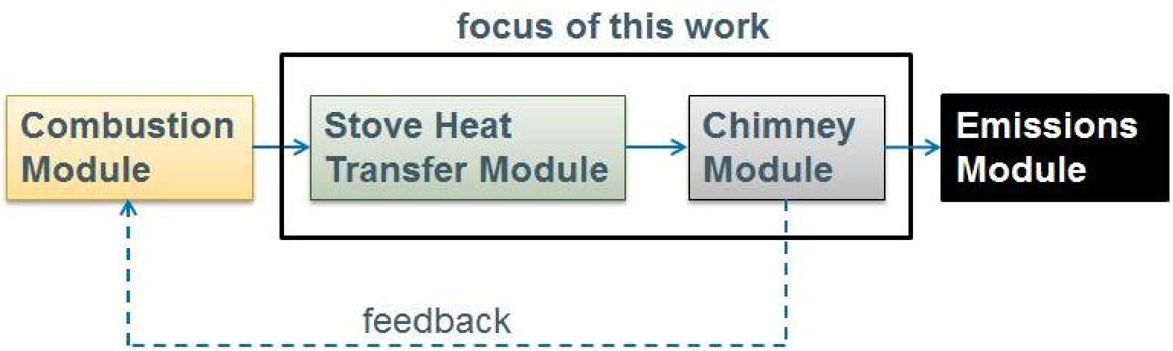


Figure 17. The model can be considered a lumped parameter model in which variables and calculated values are passed from one module to the next.

The stove system is essentially discretized into three separate subsystems, each interacting heavily with the others through the passing of information. This lends itself to the swapping of stove and chimney types with minimal modification of the overall model.

3.5. Platform Selection

There are many viable software choices for numerically solving simplified thermofluid systems. The selection for the software platform used to develop the numerical model came down to several criteria:

- The platform needs to be capable of producing modular, lumped parameter style structures

- The platform needs to be capable of producing executable files that could eventually be distributed to the international stove community without costly software licensing
- The platform needs to be highly stable with reasonable run-times.
- The software needs to be accessible to the author.

When using these criteria as a guide, Matlab©emerged as the strongest candidate for the model platform.

3.6. Sequence of Calculation

The numerical model that was developed as part of this work is of simple construction, meant to arrive at accurate estimates of important stove parameters within short run times. The sequence of calculation is summarized below. Portions of the code generated for this work can be found in Appendix B.

(1) Universal constants are initiated and stored for use in later portions of the code
(2) Chimney-specific information is initiated and stored. This includes items such as height, wall thickness, thermal conductivity, and diameter.
(3) Stove specific information is initiated and stored. This includes the geometric features of the gas path, the thickness and thermal conductivity of the cooking apparatus, etc.
(4) Combustion chamber information in initiated. Here, the geometry and heat transfer characteristics of the combustion chamber are entered into the model database for later use.
(5) Fuel specific information is initiated. This includes lower heating value, moisture content, and approximate geometry.

(6) Ambient conditions are initiated including ambient temperature, elevation, and wind speed.

(7) A series of values are calculated from the input parameters and constants. These include, but are not limited to hydraulic diameter of the combustion chamber, ambient barometric pressure, kinematic viscosity of ambient air, area of the combustion chamber occupied by fuel, etc.

(8) An initial guess section is executed for the various parameters that will be iteratively calculated in the subsequent while loop

(9) Convergence criteria for the iterative solver is specified. For as long as this condition fails to be met, the while loop will continue running iterations

(10) Iterative equation solver. In this section a while loop runs until the convergence criteria is met. The majority of the model's calculations occur in the while loop since most equations involve dependencies with other variables. Further details of the while loop's internal calculations follow below:

    (a) Average velocity and Reynolds number values for the combustion chamber, stove, and chimney sections are calculated from total mass flow rate and gas density values. In the first iteration of the while loop, these values are highly inaccurate as they are calculated from initial guesses.

    (b) Friction factor and fluid flow loss terms are calculated from Reynolds numbers, geometries, etc.

    (c) Average Nusselt number values are calculated from Reynolds/Prandtl number relations.

(d) Average convective heat transfer coefficients are calculated from Nusselt numbers.

(e) Average overall heat transfer coefficients are calculated from convection, conduction, and radiation coefficients.

(f) Average bulk temperature of gas leaving the combustion chamber is determined from firepower, excess air, and ambient temperature information.

(g) Heat transfer through the stove (cooking) section is calculated using the differential equation solution described in Section 2.3.2. This results in an updated bulk gas temperature value that serves as an input value for the chimney section.

(h) Heat loss through the chimney is calculated using a differential equation solution of the same form as above but now using a chimney-specific average overall heat transfer coefficient, U. This results in a chimney exit temperature, as well as the average chimney temperature.

(i) Draft, pressure drop, and total mass flow rate are calculated from temperatures and preceding information.

(j) The newly calculated mass flow rate is cycled back into the top of the while loop for the next iteration.

(k) Eventually, the convergence criteria is met. While a number of choices exist for the convergence criteria (velocity, excess air, exit temperature, etc.) the criteria used for the current version of the model requires the difference between the average chimney temperature of the current guess and the previous guess to be less than 0.00001 degrees K.

(11) Post processing. This is the segment of the code that generates tables, plots, etc. with the calculated data.

Items 2-6 in the above scheme can be input from a graphical user-interface front panel or hard coded.

CHAPTER 4

Experiment Setup and Methods

4.1. Objectives of Experimental Work

The overall objective of this work is to shed light on the physical phenomena that occur within natural convection chimney stoves such that chimney stoves can be better understood and designed for real users. In his seminal VITA report *Biomass Stoves: Engineering Design, Development , and Dissemination*, Samuel Baldwin states: "The actual combustion and heat transfer processes occurring in a stove are too complicated, too highly interdependent, and too variable to model and predict easily. Testing is a must."[40]. Sharing in that philosophy, the author deemed it essential to test actual stoves in a laboratory environment, where variables could be carefully monitored and controlled.The collection of experimental data has be used to validate numerical models, discover novel interconnections, and become acquainted with some of the realities of stove operation and maintenance.

4.2. Advanced Research Chimney

The heart of the experimental setup that was designed for this work is the Advanced Research Chimney, hereto referred as the ARC. The ARC, pictured in Figure 18 is a highly instrumented, modular, chimney system that is constructed of one, two, three, or four (depending on the test) 60 cm long sections of 10mm ID pipe. The pipe segments are constructed of thin-walled 316 grade stainless steel. Each segment interlocks to allow for stacking with a relatively tight seal. All sections have been outfitted with probe insertion points to allow for multiple configurations and locations for the various instruments. While the chimney is of higher overall quality and price than those found in the developing world, it was chosen to limit variables in laboratory testing and facilitate augmentation with probe entry points. Chimney pipes in the field are typically constructed of galvanized steel and have an oval shape. Galvanized steel presents challenges and safety risks in welding operations [90]. The oval shape of the typical snap fit galvinized chimneys would also present unnecessary complications to modeling and analytical work.

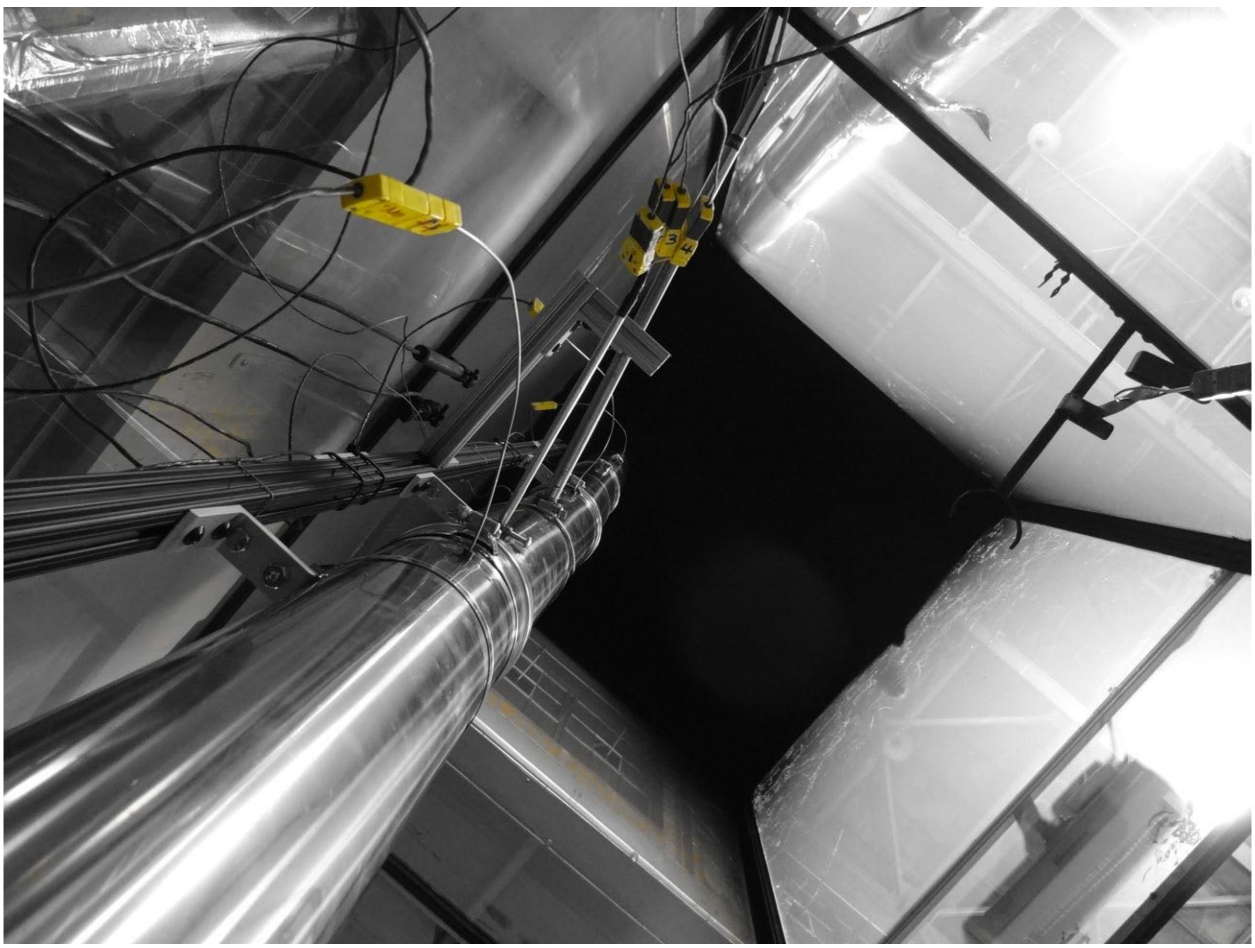


FIGURE 18. The Advanced Research Chimney (ARC) used for data collection in this work.

Major equipment utilized throughout the experimental work is summarized in Table 8. Individual components are described in greater detail in sections below.

Table 8. Major Equipment Utilized in This Work

Description	Manufacturer and Model	Function/Comments
Thermal camera	Flir E40	Video and still camera modes allow for transient and steady state surface temperature analysis
High temperature hot-wire anemometer	Kanomax 0205 with anemomaster controller unit	Simultaneous point-source velocity and temperature measurements for gas stream
Digital differential pressure transducer	Omega PX653	Measurement of actual draft of chimney system
Laminar flow hood	NA: custom built	Safe and controlled capture of flue gases
Gravimetric particulate emissions sampler	NA: custom built	Collection of PM_{10} and $PM_{2.5}$ for mass
Thermocouple array	Omega K-type thermocouples	Various gas, stove, and chimney temperatures
Flue gas analyzer	Testo 350XL	Real-time CO, CO_2, and O_2 concentration measurements
NDIR CO_2	Siemens Ultramat 6	Real-time CO_2 concentration
NDIR CO	Siemens Ultramat 6	Real-time CO concentration
positive displacement pump	Sutorbilt Legend, Model CACLBPA	Laminar hood blower, fixed volumetric flow ($\approx 0.1\text{m}^3\text{s}^{-1}$)

4.2.1. Chimney Instrumentation. The following subsections outline the instruments that were physically located in the Advanced Research Chimney during testing.

4.2.1.1. *Differential Pressure Probe*

The differential pressure resulting from the temperature difference between the combustion gases and the ambient air is called draft. This differential pressure is a critical parameter to be measured as part of this experimental work because it quantifies the force that pulls fresh makeup air into the front of the stove. As the pressure induced by natural convection is relatively small compared to many examples in engineering, a specialized low differential pressure sensor (Omega PX653) was required for testing. Given the small magnitude of pressure, it was important to quantify pressures from external sources (such as the hood blower) in baseline testing before collecting experimental data. The differential pressure probe was located approximately 8.5cm from the base of the chimney. This location is non-ideal from an entrance length perspective, as the gas bends into the chimney, but enough chimney height needed to be above the sensor to achieve accurate readings for the short section chimney testing. This tradeoff was considered to be acceptable.

4.2.1.2. *Axially Distributed Thermocouple Array*

An array of K-type thermocouples was used to measure the gas and chimney wall temperatures over a wide range of operating conditions. All gas-wetted probes were nominally 1/16" diameter to minimize influences to natural flow. Chimney outside wall temperatures as well as cooking surface temperatures were measured by welding thermocouple wire directly to metallic surfaces. This technique has been used in previous work at the EECL with high success.

In the chimney, axial gas temperature probes were made to sit in the center of the chimney. As subsequent data revealed, this is not the optimal location for measuring the average radial temperature, but it did provide repeatable data that could be translated into average temperatures once the radial temperature profile was established.

4.2.1.3. *Multiprobe for Measurement of Radial Temperature Profiles*

As described in Chapters 2 and 3, an accurate determination of the average temperature of the flue gas flowing through the chimney is crucial in understanding the overall stove system. Heat loss occurs axially, as the chimney loses heat primarily through convection and conduction. There is also a radial temperature drop due to cooling at the chimney walls. It was determined that this temperature profile should be captured in order to relate the axially distributed thermocouple measurements (in which the probes were centered in the chimney) to an overall average temperature.

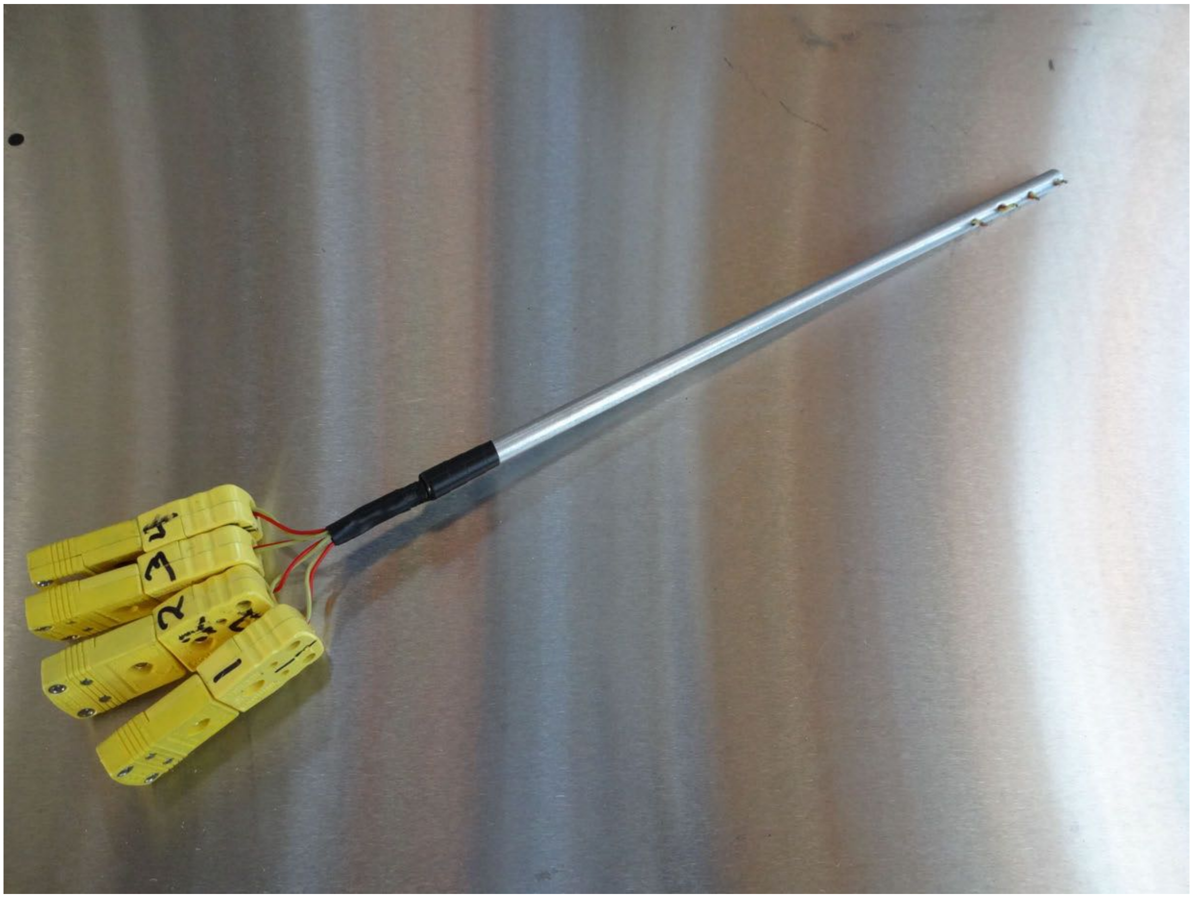


FIGURE 19. Customized multiprobe used to quantify radial temperature profile in the chimney

Ideally, several multiprobes would be used simultaneously at different axial locations to determine how the radial temperature profile evolved as gas cooled in its path up the chimney. Due to a limited number of data channels available, however, the multiprobe was run at one axial location, 64 cm above the base of the chimney.

4.2.1.4. *High Temperature Hot-Wire Anemometer*

A specialized high-temperature hot-wire anemometer and accompanying logging unit (Kanomax Anemomaster) was acquired to measure bulk velocity of the flue gas. It has an integrated thermocouple and an operating temperature range of 0-350 degrees Celsius. Direct measurement of the combustion gas velocity in the chimney is highly desirable as it is a highly coupled characteristic of the stoves physical behavior. The velocity of the flowing combustion gas is important for its relationship to the following:

- convective heat and mass transport: the convective coefficients are highly dependent on velocity.
- viscous pressure losses: the pressure produced by fluids flowing through ducts is proportional to velocity cubed or higher.
- drag force losses: obstructions to flow encounter drag forces that scale with velocity squared.

The velocity measurement also provided an independent means of comparison for calculated mass flows (described in Section 4.4.

4.2.1.5. *Verification of Velocity through Particle Image Velocimetry*

Particle image velocimetry (PIV) is a technique for capturing information on the velocity (bulk, radial profile) by illuminating tracer particles with laser sheet and following their motion with a high speed camera. A simplified PIV setup was developed in order to:

- validate the measurement of the hot-wire anemometer
- provide evidence for turbulent versus laminar flow regime
- help shed light on radial velocity profile as well as wall boundary conditions

The rudimentary PIV setup consists of a class IV 100mW laser (Wicked Lasers Krypton ©series) with a line expanding lens, a transparent section of pipe with a nominal 4 inner diameter, a camera, a personal computer and the HM5000 plancha stove. Rather than seeding the stove system with particles, naturally occurring wood smoke was used as the tracing agent. The anemometer was running approximately one meter downstream of the transparent PIV section for validation purposes.

Figure 20. Rudimentary Particle Image Velocimetry (PIV) setup used to validate the high temperature hot-wire anemometer

4.2.1.6. *Real-Time Gas Sampling*

The Testo(R) model 350 flue gas analyzer was used for stack measurements of carbon dioxide, carbon monoxide, and oxygen concentrations. With this particular instrument, the carbon dioxide is measured with a non-dispersive infrared (NDIR) sensor, while the carbon monoxide and oxygen concentrations are measured with less accurate electrochemical sensors.

4.3. Laminar Flow Hood

In order to capture all of the gases emitted from a stove being tested, all data was collected within an enclosed laminar flow hood. The hood has air drawn through HEPA filters to prevent background particles from adding noise to emissions data. Flow is induced by a positive displacement pump. Rotations per minute are controlled, monitored, and recorded from the SCADA.

4.3.1. Hood Instrumentation. The laminar flow hood is equipped with temperature, humidity, and differential pressure sensors to monitor bulk gas flow. Using the ideal gas law, total mass flow through the hood can be estimated through knowledge of the volumetric flow rate and density of the gas being pumped.

4.3.2. Influence of the Hood On Natural Behavior of a Stove. Since the draft induced by biomass stoves are generally relatively weak (fractions of an inch of water column), it is important to understand how the blower that drives flow through the laminar flow hood influences the behavior of stoves being tested. To determine this, velocity and differential pressure were baselined with the hood blower on prior to lighting each stove. In all cases, the influence of the hood was found to be insignificant. When turned on, no velocity or pressure drop readings register with the analytical equipment.

4.4. Mass Flow Measurement

Throughout this work, it has been essential to quantify the total and gas specific (CO, CO2) mass flow rates from a given stove being tested. The following procedure describes how these mass flow values are calculated from the raw data obtained.

(1) Baseline ambient CO and CO2 are measured for several minutes before the stove is ignited.

(2) Hood gas temperature and pressure is measured. Multiplying the volumetric flow (fixed by the positive displacement pump) by the average hood gas density leads to a calculated total hood gas mass flow

(3) Volumetric concentrations of CO and CO2 are measured redundantly with Testo and NDIR sensors

(4) Ambient CO and CO_2 concentrations are subtracted from the concentration measurements

(5) Carbon flow is calculated based on CO and CO2 mass flows, weighted by their respective molecular weights

(6) Wood flow is calculated, calculated based on the assumption that wood is composed of fifty percent carbon. [66].

(7) Total mass flow is calculated based on calculated wood flow, percent oxygen in the stack (leading to excess air), and the assumption of stoichiometric air to fuel ratio of 6.15 kg air:1 kg wood.

4.5. Supervisory Control and Data Acquisition

For data acquisition, control of the hood pump, and in-test monitoring, a user interface and logging program were custom-built using National Instruments LabVIEW ©software. Data was conveyed to this program using NI compactRIO ©hardware. As shown in Figure 21, quantities such as gas and chimney wall temperatures, draft, CO and CO_2 emissions are shown in real-time.

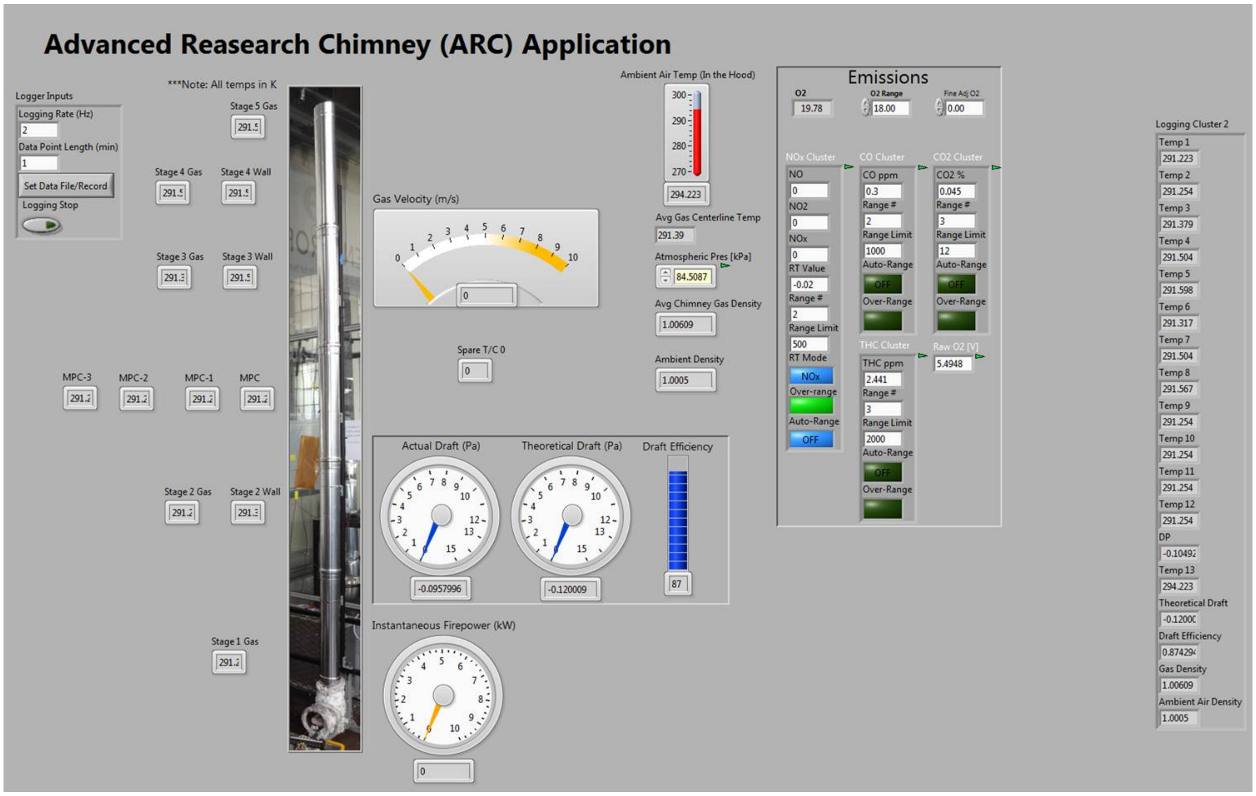


FIGURE 21. The front panel of the SCADA software created specifically for this work.

Data from the ARC and laminar flow hood were collected every second and saved to a data file. Data for the in-chimney gas concentrations were monitored and saved using Testo's SCADA software, included with the hardware.

4.6. Source of Heat

As the chimney effect is the result of gas temperature differences, studying chimney behavior required the use of heat sources. Several of the heat sources utilized in this work are described in the following subsections.

4.6.1. Electric Coil. In the early stages of this research, there was a desire to decouple the physical phenomenon of the stack effect from biomass-specific combustion. To this end, an electronic simulate fire was designed to produce controllable heat inputs into a chimney system that reached magnitudes that were representative of biomass stoves. Nickel chromium wire coils were assembled to sit ontop of a refractory tile inside of an elbow chamber, as shown in Figure 22.

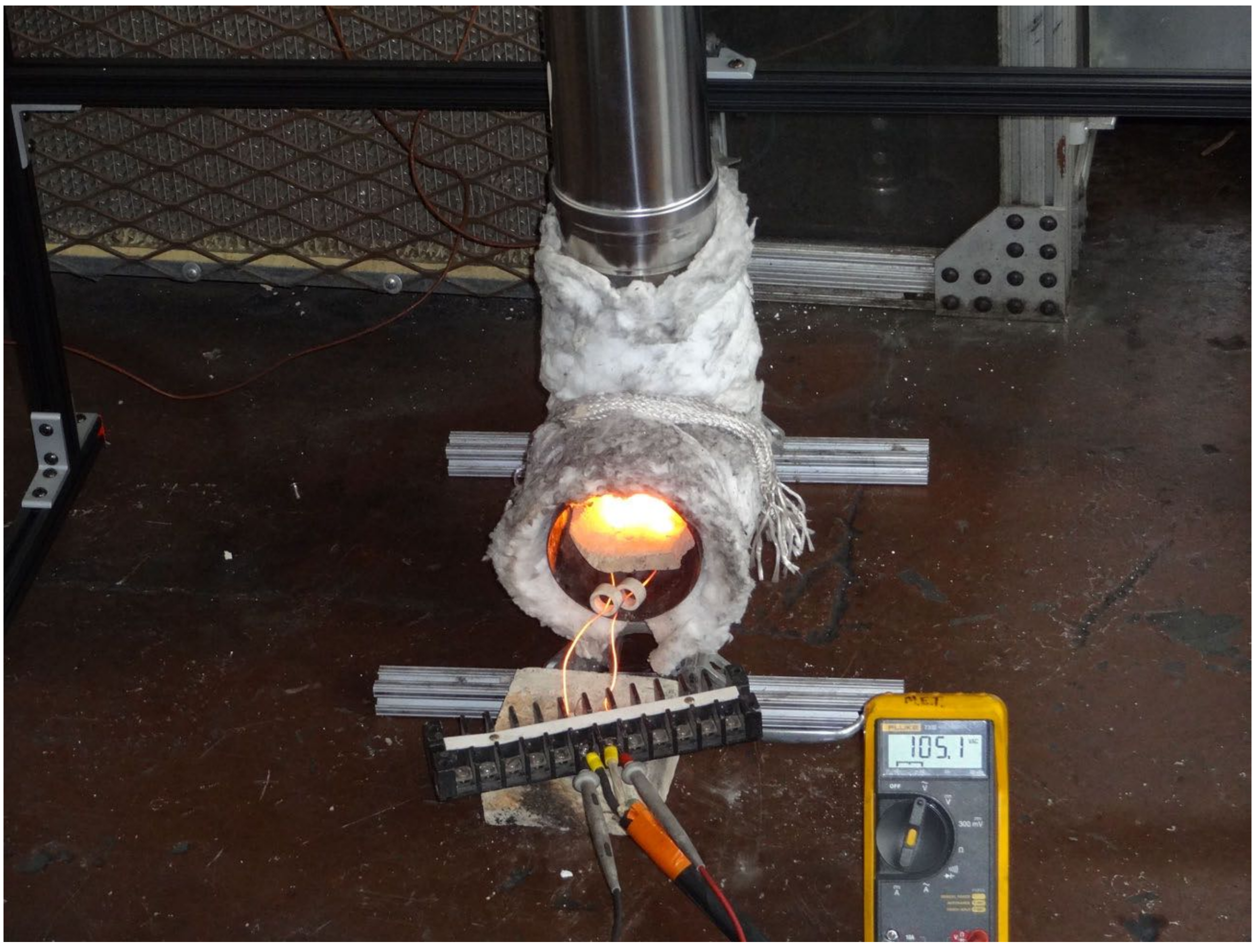


FIGURE 22. The heat input of a fire was replicated by use of a nickel-chromium wire coil connected to a variable AC power supply.

The power of the simulated fire follows the simple electronics law:

$$Q_{simfire} = iV \tag{40}$$

where $Q_{simfire}$ is the heat produced by the electricity flow (assumed to be 100 percent efficient), i is the current supplied to the coil, and V the voltage provided to the coil.

A variable AC power supply was used to regulate the voltage, allowing for precise control of power output from the system. As the resistance per unit length of wire was known, the total length of wire determined the resistance of the simulated fire as shown in equation 41.

$$i = \frac{V}{r} = \frac{V}{\left(\frac{r}{length} length\right)} \tag{41}$$

where r is the electrical resistance.

The wire was then coiled to allow for higher volumetric energy density (power emitted per unit volume) in the elbow chamber. The elbow was connected to the ARC to allow for measurements of gas temperature and velocity.

Eventually the simulated fire technique became obsolete as answers were sought that related more specifically to biomass combustion such as wood consumption rate, air to fuel ratio, and emissions production.

4.6.2. Propane Burner. Concerns that the gas dynamics of a flame were being ignored with the electronic simulated fire, described above, prompted brief work with a camp stove style propane burner. Again, there was a desire to control firepower, to perform an array of measurements over a wide sweep of firepowers. Power of the flame was controlled via a fuel knob. Power was measured from the propane burner through a mass loss over time technique. As the lower heating value of propane is well known, power is simply governed by:

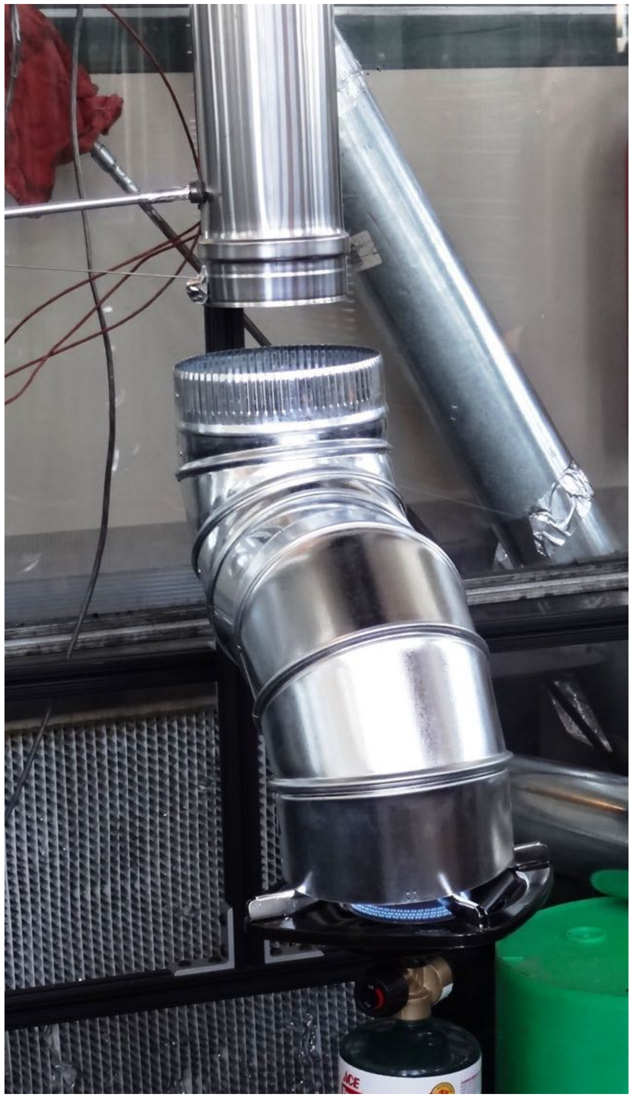


FIGURE 23. Propane burner to simulate biomass cookstove with elbow to act as radiation barrier to avoid erroneous temperature readings.

$$Q_{burner} = \dot{m}_{propane} LHV_{propane} \quad (42)$$

where Q_{burner} is the heat supplied by the burner, $\dot{m}_{propane}$ the mass flow rate of propane, and $LHV_{propane}$ the lower heating value of the propane fuel.

As with the electronic simulated fire, the propane burner eventually gave way to wood burning tests, described in the following sections. Both the electric coil and the propane burner served to produce heat flux magnitudes that were comparable to a wood fire, but neither was capable of imitating important mechanisms of wood fires.

4.6.3. Shim Arrays. Prior work at the laboratory indicated that firepower within a stove is highly dependent on the surface area of wood present in the combustion chamber. Led by these findings, arrays of wood fuel were assembled to provide standardization of wood burn rate/firepower throughout testing through manipulation of fuel surface area. Each fuel array was assembled from untreated pine paint stirrer shims. Shims were spaced from each other by stapling 10cm long sections of shims in between full length shims, as shown in Figure 24. Three different arrays, composed of four, six, and nine full length shims, were utilized to produce low, medium, and high firepower burns.

The paint stirrer shims were sufficiently long, approximately 45 cm, to allow for 15 minutes of burning with minimal intervention from the stove test administrator. This was designed to reduce variability among tests.

4.6.4. Standardized Wood Blocks. The vast majority of cookstove testing conducted at the EECL's Advanced Cookstove Laboratory has been carried out with one of two types of standardized wood fuel rods. These rods are approximately 5cm wide X 2.5cm tall X 25cm long, cut from store-bought untreated spruce-pine-fir 2X4s. Smaller stoves use similar rods which are 2.5cm wide rather than 5cm.

Figure 24. Fuel bundles made from precisely spaced wooden shims allowed for regulation of stove firepower.

4.7. Stove Types

4.7.1. Griddle Stoves. As mentioned in Section 1.3.2, griddle cookstoves have reached a high level of popularity in several Latin-American countries due to the ability to cook foods such as tortillas directly on the heated surface. The following sections describe the two griddle stoves tested and modeled in this present work.

4.7.1.1. *Justa*

One of the most popular improved cookstoves in Honduras is the Justa. The Justa is assembled in-country of locally available materials such as brick, mortar, ash, and sheet metal. There are several versions of the stove and designs are readily available online. Several reputable stove organizations (including Approvecho, TWP, and Prolena) have been involved in the continued improvement of the Justa over many years.

As part of this work, a fully functional Justa was replicated at the EECL from blueprints supplied to the lab by the Honduran government. The author had been trained in construction of the Justa in Honduras by certified stove installers. Materials were kept as true to developing world versions as possible. Refractory brick for the combustion chamber was shipped from Honduras to ensure that material properties would be consistent.

The griddle surface of the Justa encapsulates the gas path to minimize indoor air pollution. Combustion products are vented out of a 10cm ID chimney. Once completed, the Justa is quite massive, weighing several hundred pounds. While the Justa is a stationary "built-in" stove, it was assembled on a wheeled cart at the EECL to allow for quick transport in and out of the testing hood.

4.7.1.2. *HM5000*

A major portion of this work was the development of a modern improved plancha stove that took advantage of field-gathered user feedback and engineering methodologies to achieve superior performance in the areas of thermal efficiency, combustion efficiency, and ease of use. The author designed, fabricated, and tested several dozen versions of this stove throughout a year-long development cycle.

4.7.2. Two-Pot Stoves.

While the author's experience with two-pot stoves concentrated on regions in the high Andes of Peru, similar stoves are popular in many regions all over the world. These designs allow users to multi-task while cooking and potentially salvage some

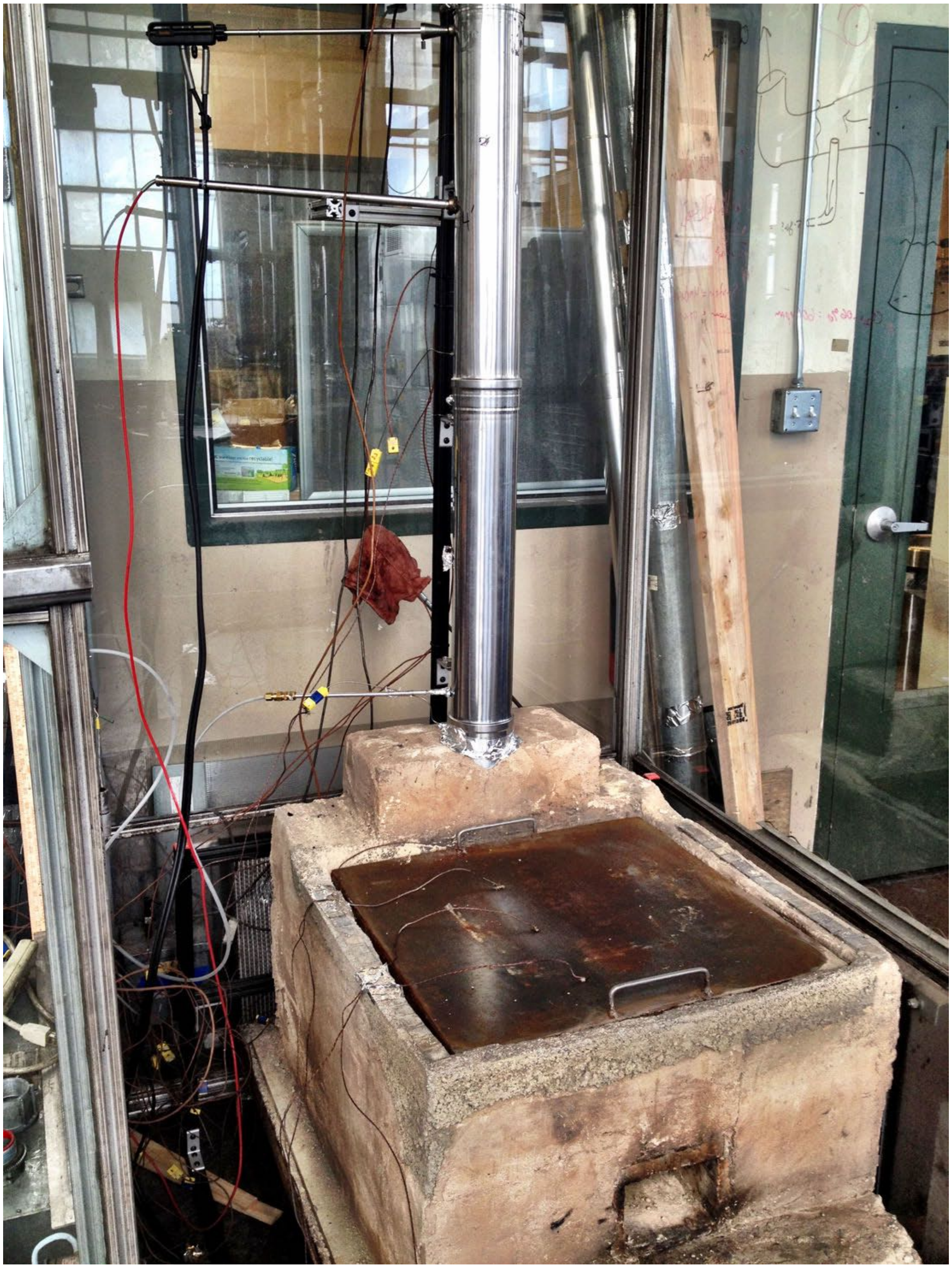


FIGURE 25. The Justa stove, designed over many years by various groups to provide improved performance.

heat from escaping chimney gases through use of an auxiliary cooking station. The two-pot stoves involved in this work are described in the following sections.

FIGURE 26. The HM5000 plancha stove, developed as part of this work was tested extensively.

4.7.2.1. *InkaWasi*

The InkaWasi was first developed in Peru in 2001 by staff of the German development organization, Gesellschaft für Internationale Zusammenarbeit (GiZ) [16]. In the past decade, the stove has undergone several design changes. The version discussed in this work has been named the UK Version by GiZ. The stove, pictured in Figure 27, is

Table 9. Descriptions of Griddle Stoves Used In This Work

Component	Justa Stove	HM5000
Combustion chamber	Refractory tile, rectangular elbow geometry, opening 14cmX10cm, depth 28cm, height 28 cm	Specialized metal alloy, flared rectangular elbow (see Figure 49, opening 12cm X 16cm, depth 30cm, height 28cm
Gas Flow Path	insulated with wood ash, ≈ 3 cm depth	insulated with composite blanket material, ≈ 1.5 cm average depth, but varies from front to back.
Cooking Surface	mild steel, ≈ 56 cm X 56 cm	cast iron, ≈ 64 cm X 46 cm
Chimney	galvanized steel, 10cm OD, ≈ 2.4 meters tall standard	galvanized steel, 10cm OD, ≈ 2.4 meters tall standard

4.7.2.2. *L6040 Prototype*

The L6040 prototype was designed over a period of several months to achieve high thermal efficiency, low time-to-boil, flexibility for fuel (accepts wood or dung), more balanced power sharing between front and back pot, and effective ventilation of combustion products out of a chimney.

4.8. Equivalent Exhaust Fan Testing

In recent years, there has been much attention toward forced convection stoves providing significant performance advantages over natural draft stoves [91, 92, 93]. To compare electrically driven fans to thermally driven chimneys, a fan/chimney equivalence setup was developed. As shown in Figure 29, a fan was mounted to the top of a two meter tall, 10 cm ID chimney. A power usage meter was utilized in between the fan and the power supply to capture power consumption data at different flow rates.

The fan add-on was then removed and a heat source (propane burner) was introduced into the bottom of the chimney until the same mass flow rates were achieved without the fan.

FIGURE 27. The InkaWasi stove, primarily designed by GTZ/GiZ for South American markets.

Care was taken to separate the propane burner from the chimney inlet to prevent any flow restriction. The targeted velocities were adjusted to account for the temperature difference

FIGURE 28. The L60460, a two-pot experimental prototype stove developed as part of this work.

between the cold air pulled in by the fan and the hot combustion products released by the propane burner.

Figure 29. Powered fan installed on top of chimney for natural convection equivalence testing.

4.9. Variable Draft Testing

An important portion of this work involved observing how a chimney stove system responds to different magnitudes of draft. In order to capture these data, the ARC system was run in three configurations: 61cm, 116cm, and 227cm tall chimneys. The Justa and HM5000 stoves were run with each of the three configurations (short chimney, medium chimney, taller chimney) at three different firepowers (low, medium, and high), set by use of the shim arrays described in Section 4.6.3.

4.10. Simulated Cooking Cycle Testing

In addition to looking to understand how different portions of a cookstove perform as draft, firepower, and geometry is varied, there is a need to understand how a stove performs overall in cooking tasks. As stoves are run by individuals with unique cooking and refueling styles, it can be hard to pin down the performance of a stove without testing it over a standard cooking cycle. As experts have pointed out, the performance of stoves can be likened to that of automobiles: while vehicles are driven differently by different individuals, performance can be normalized through standard driving cycles [10].

The standard laboratory test for cookstove performance is the Water Boiling Test (WBT) formalized by the Partnership for Clean Indoor Air. In this test, a known quantity of water is brought from ambient temperatures to boiling by the stove being tested. At the EECL, a modified version of the WBT is employed to reduce error, based on prior work [94] The wood use, charcoal accumulation, and water loss are measured to provide an energy balance. When emissions sampling equipment is available, the amount of CO and PM that is produced during this simulated cooking cycle can also be measured. Through this approach, stoves can be compared based on emissions produced and wood consumed during the completion of a standardized task.

As the name implies, the Water Boiling Test was designed to quantify the performance of stoves that are used for tasks analogous to boiling water. A griddle stove, however, presents challenges in using the WBT to quantify performance. Griddles are used for direct surface cooking as well as cooking in pots.

As part of this research, a new variation of the standard WBT was proposed and developed specifically for evaluating the performance of griddle stoves. The Global Alliance of

Clean Cookstoves (GACC) is currently funding the development of this method. A technical advisory group, composed of international stakeholders, has been formed to help create a griddle protocol that will allow for accurate and efficient evaluation of griddle stoves. While this is a work in progress, the following section outlines the current state of the protocol (subject to change).

4.10.1. Development of Protocol for the Testing of Biomass Griddle Stoves. With any testing protocol, there is an objective to eliminate variables which influence results but are difficult to control, predict, or quantify. In cookstove testing, variables of this type make it difficult or impossible to determine the true performance of a cookstove. Through the designing and testing of griddle/plancha stoves, contact resistance between griddle surface and cooking pots was identified as one such important variable that has considerable influence on the performance of a griddle stove when using conventional testing methods such as the water boiling test.

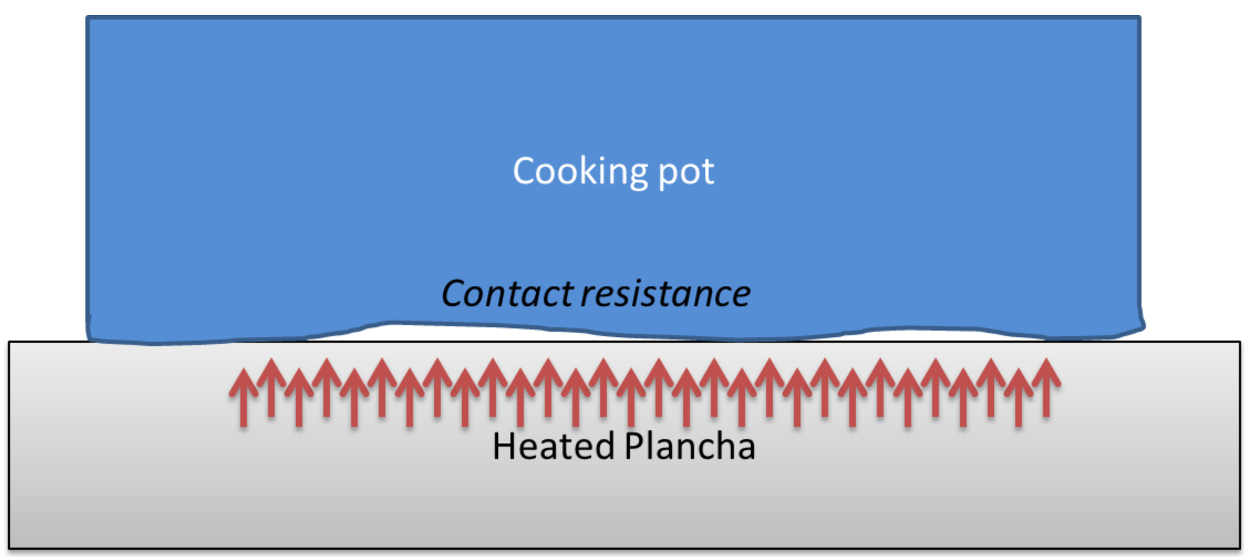


Figure 30. Contact resistance between the griddle top and the cookpiece was identified as a large variable and motivated the development of flexible-bottom pots that conform to the griddle surface.

When a cooking pot sits on a griddle surface, it may introduces inaccuracies to stove performance evaluation in several ways:

- The heat transfer from stove to water is greatly effected by the flatness of the pot and griddle, as shown in Figure 30. This can make results difficult to replicate and/or compare.
- Griddle stoves have relatively large cooking surfaces, much of which is used at a given time for a diverse number of tasks (as shown in Figure 31). One pot on the griddle surface provides insufficient information regarding the entire cooking surface.
- Cooking a tortilla directly on a griddle surface is physically distinct from boiling water in a pot. Evaluating a griddle stove based on pot-style cooking does not capture enough information.

FIGURE 31. Griddles are used for a diverse set of cooking tasks. This image was captured during a field visit in Honduras.

For this reason, a flexible-bottom pot was designed to facilitate a WBT-style test that reduces error associated with using rigid pots on a griddle. The pots are composed of translucent mylar and assembled in accordance with the instructions listed in Appendix C.

FIGURE 32. Flexible-bottom pots were constructed and used for testing as part of the griddle testing protocol.

It is important to note that much of the cooking carried out on griddle stoves does occur in pots. Using a flexible bottom pot exclusively may reduce test-to-test variability, but lacks real-world considerations. To address this, the protocol is being developed to capture performance through direct griddle cooking (simulated with the flexible bottom pots) and pot-style cooking (utilizing standardized steel pots).

CHAPTER 5

Results and Discussion

There is no substitute for physical data when investigating a system as variable and physically complex as a cookstove. The apparati described in Chapter 4 were designed to capture data for the following purposes:

- Validate the numerical model described in Chapter 3
- Obtain new insights that enhance understanding
- Evaluate the performance of stoves in real environments run by actual people to capture real world compexities
- Explore the operating region of stoves and make iterative changes toward optimization

The majority of data discussed in the next several sections revolves around the testing of the two griddle stoves described in Section 4.7.1. This was due to the fact that a new griddle stove and griddle stove testing protocol was being developed in parallel to this work, allowing for the collected data to serve multiple functions. The optimization of the two pot stove also involved a considerable amount of laboratory testing and is described separately in Section 5.6.2.

5.1. Temperature Profiles

The temperature of the gas flowing in the chimney is a crucial parameter in the performance of a chimney stove, as previously described in Chapters 2,3, and 4. Temperatures were measured radially and axially to most accurately capture the overall average temperature of the flue gas in the chimney.

5.1.1. Axial Temperature Profiles. As the majority of chimneys encountered in the field are of simple, single-walled, uninsulated steel construction, heat loss along the height of the chimney (axially) is believed to be an important factor to include in any serious analysis of chimney stoves. As shown in Figure 33, the temperature drops approximately 90 K from inlet to outlet over a 2.2 meter chimney at high firepower (7.5kW). At lower powers, the temperature drops 45- 60 K.

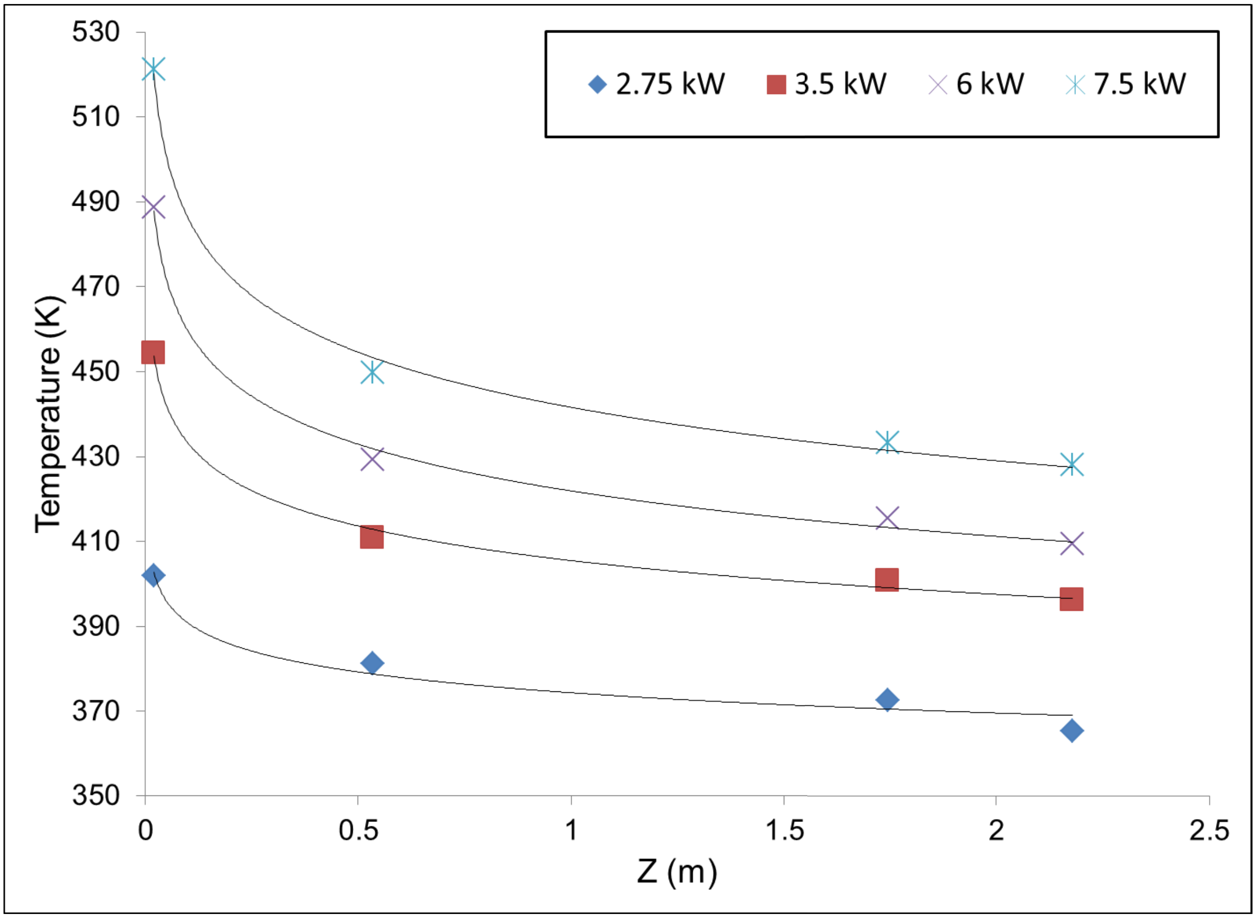


Figure 33. Axial temperature profile of gas in the chimney for four different firepowers. Data are from single tests once steady state behavior had been reached at each firepower. Chimney is 10 cm OD, single wall, non-insulated.

The theoretical draft, as defined in Equation 7, would be overestimated by 9.2 % and 8.3% for the high and lower power cases respectively by using the chimney gas inlet temperature rather than the average chimney gas temperature. Some design scenarios may tolerate this error, while others would benefit from determining the true average temperature. It is important to note that this measured temperature drop occurred in a controlled laboratory environment.

In the lab, the dominant modes of heat loss are natural convection cooling from the outer wall of the chimney, as well as radiation to surrounding objects. Forced convection due to the laminar flow hood was ignored as multiple tests confirmed that the hood introduces negligible velocity terms to the air surrounding the chimney (see Section 4.3.2).

In the field, temperature drop in the chimney could be highly variable from day to day, season to season, and location to location. Forced convection in the field can greatly increase heat loss if chimney sections are exposed to wind, for instance. Running a stove on a cold winter morning within a high thermal mass adobe structure would lead to higher radiation heat loss from the chimney as well.

5.1.2. Radial Temperature Profiles. As described in Section 4.2.1.3 radial temperature profiles in the chimney were measured over high and lower firepowers. As seen in Figure 34, there was a measurable temperature drop from the centerline to the wall of the chimney.

This radial temperature drop is important for two main reasons:

(1) The chimney temperature is highest in the center of the chimney, so gas temperature would be overestimated by using centerline temperatures.
(2) Literature suggests that the radial temperature gradient could introduce non-isothermal pressure loss terms that impact the effective draft of a chimney [53]. This pressure loss is associated with transverse gas flow from the hot centerline to the cooler walls.

The error introduced by calculating temperature-dependent chimney parameters with a centered probe at the base of the chimney could be significant ($> 20\%$ in many cases tested).

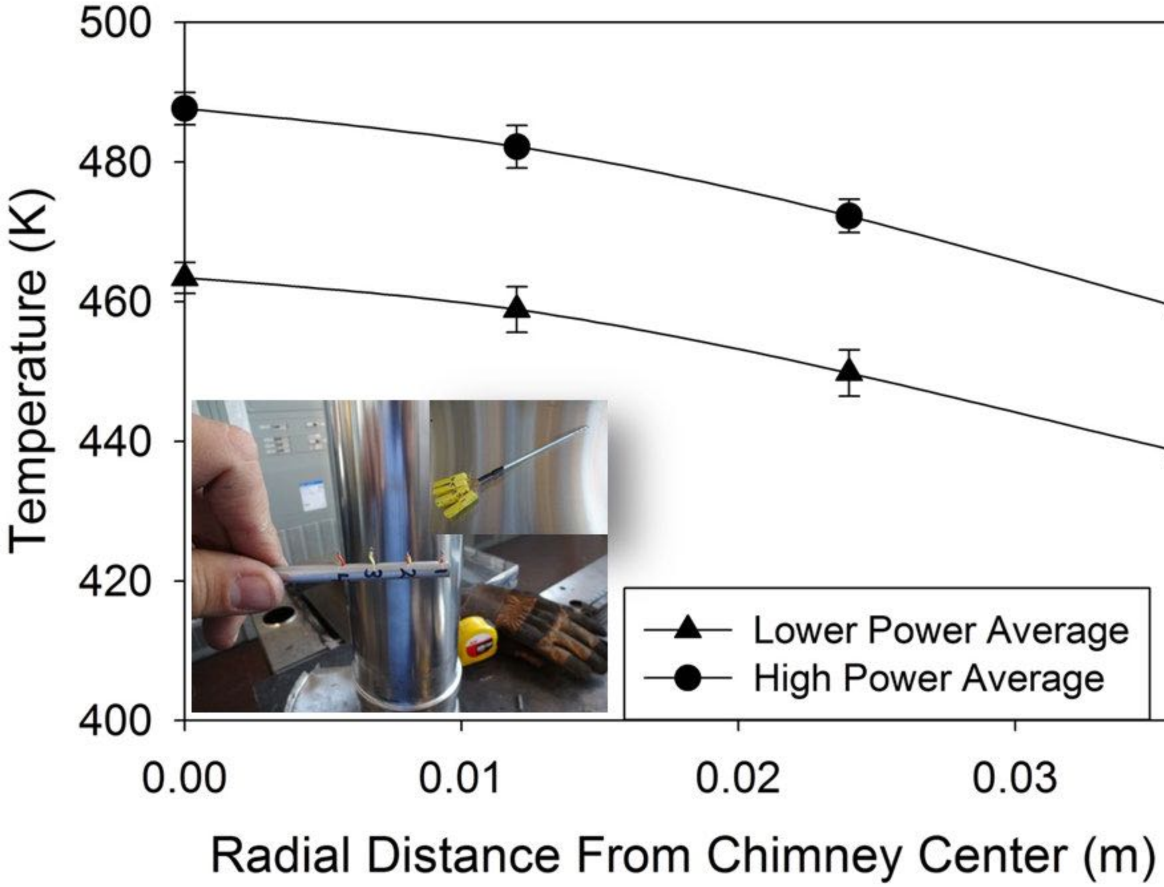


Figure 34. Steady-state radial temperature profile of gas flowing in 10 cm diameter chimney at low and high wood consuption rate/power. Bars represent standard deviation from 10 minute time average.

For the most accurate results, the temperature that should be used for calculations should be an axially and radially averaged value.

5.1.3. Chimney Wall Temperatures. In order to provide insights into the time scales for transient behavior as well as boundary conditions for elements in the numerical modeling, the temperature of the exterior wall of the chimney at several heights was measured. These temperatures were measured through thermocouples that were welded directly to the exterior wall of the chimney. Centerline gas temperatures at the same axial location were also measured for comparison and further heat transfer analysis. These centerline temperatures were measured with 1/16" OD k-type thermocouples.

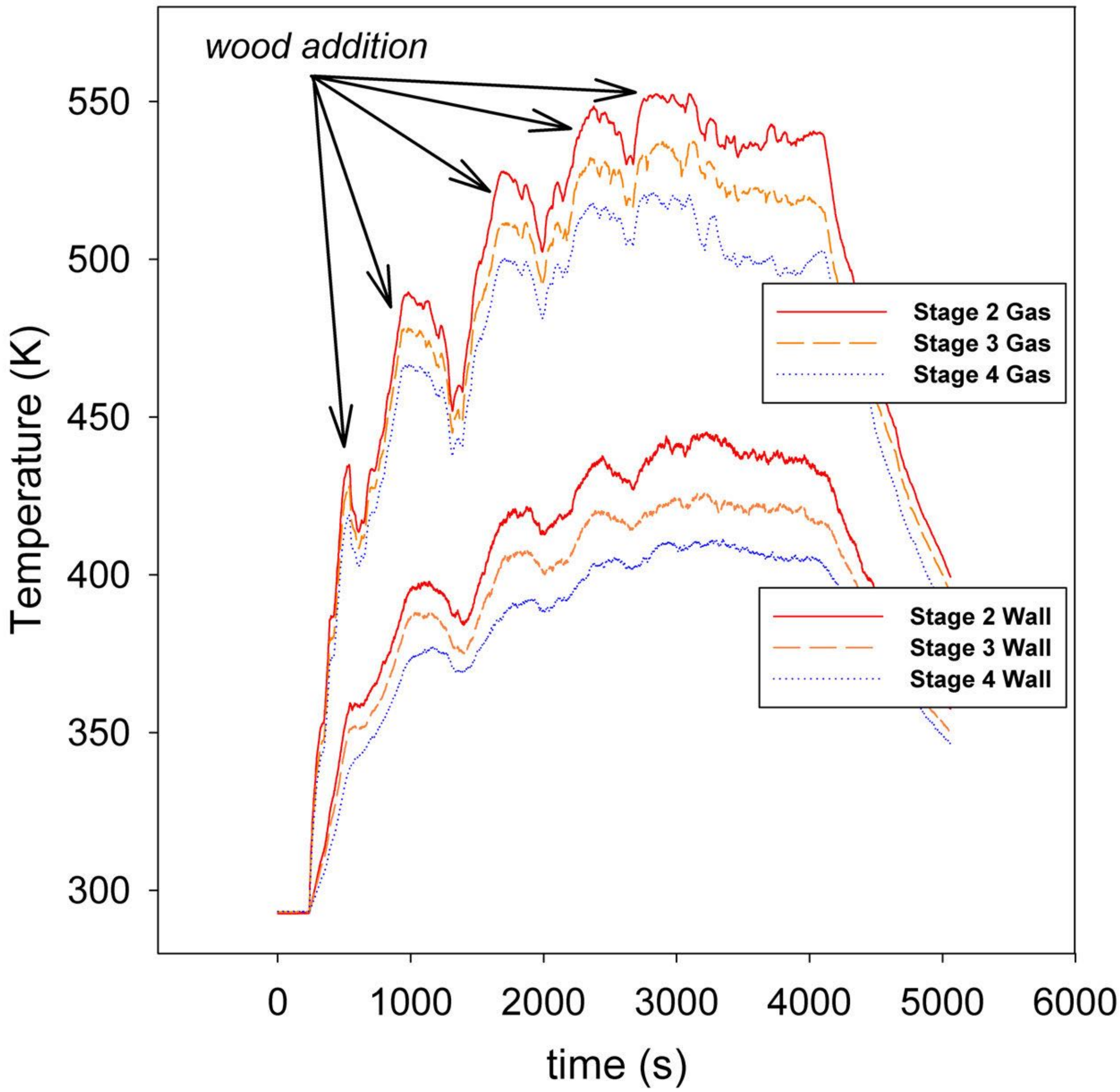


Figure 35. Wall temperatures and corresponding gas temperatures at three locations along the height of the chimney over a range of firepower. Data are from HM5000 stove with 2.27 m tall chimney.

Figure 35 provides several valuable insights. First, wood addition triggers immediate chimney temperature responses. Wood addition occurs at the inflection points shown in Figure 35. Temperature changes (due to combustion chamber activity) less rapidly at the chimney walls than at centerline of the chimney, as evidenced by the upward and downward slopes of the temperature spikes. This is intuitive, as the gas itself is responsible for the changing wall temperatures, and the mass of the chimney likely introduces thermal inertia. The response time will change with each stove as the path from flame to chimney varies for each stove. Secondly, the magnitudes of the temperatures at the chimney exterior wall points are considerably lower than the corresponding centerline gas temperatures. This provides usable data to compare against a calculated overall radial thermal resistance from centerline to exterior wall of the chimney through a thermal circuit analysis (see Section **??**).

From the center of the chimney to the exterior of the chimney wall, there are two major thermal resistances: that associated with convection from the gas to the interior chimney wall, and that associated with conduction through the chimney wall itself. It is of value to get a more detailed view of how the chimney gas is cooling. For this analysis experimental data and modeling results from the HM5000 stove will be used.

Over the temperature range in which the chimney operates (150-400 degrees C), the thermal conductivity of the stainless steel is approximately 17.5 $Wm^{-1}K^{-1}$ [95]. The chimney wall thickness is approximately 0.0005 meters. Thus, the resistance to heat transfer associated with conduction through the chimney can be approximated as:

$$R_{conduction} = \frac{L_{chim}}{k} \approx \frac{.0005m}{17.5Wm^{-1}K^{-1}} = 2.86X10^{-5}m^2KW^{-1} \tag{43}$$

where L_{chim} is the chimney wall thickness and k the thermal conductivity of the stainless steel chimney. The determination of an approximate resistance associated with convection is a bit more involved. First, the internal convection heat transfer coefficient can be expressed as:

$$h_i = \frac{Nu \cdot k_{gas}}{L} \quad (44)$$

where Nu is the Nusselt number, k_{gas} the thermal conductivity of the flue gas, and L the characteristic length. The Nusselt number for this cooling process can be related to the Reynolds and Prandtl numbers through the expression:

$$Nu \approx 0.023 Re^{0.8} \cdot Pr^{0.3} \quad (45)$$

provided that flow is turbulent [44]. Data and numerical modeling for the HM5000 indicate that flow inside the chimney is in a transition or turbulent flow regime ($3000 < Re < 4500$) under normal operating conditions (power between 2-12 kW). The Prandtl number was calculated to fall in the range of $0.67 < Pr < 0.73$ over the temperatures encountered in the chimney (100-300 degrees C). Therefor, the Nusselt number is expected to sit between ≈ 12 and 18. This leads to an expected range for h_i in the chimney to be 4- 8.5 $Wm^{-2}K^{-1}$. Thus:

$$R_{i,convection} = \frac{1}{h_i} \Rightarrow 0.12 < R_{i,convection} < 0.25 m^2 K W^{-1} \quad (46)$$

When comparing the magnitudes of the resistances expressed in Equations 43 and 46, it is clear that the resistance associated with convection is substantially higher than that due to conduction. Another approach for evaluation of the relative contributions of the convection and conduction heat transfer modes is to look as the Biot number (see Equation 3) within the chimney.

$$Bi_{i,chim} = \frac{h_i \cdot L_{chim}}{k_{chim}} \Rightarrow 0.00011 < Bi_{i,chim} < 0.00024 \tag{47}$$

where L_{chim} is the wall thickness of the chimney and k_{chim} the thermal conductivity of the stainless steel.

Over the operating range of the stove, this is considered a low Biot number system; convection resistance dominates and the chimney is 'thermally thin.'

5.2. Steady State Mass Flow Rate Testing

5.2.1. Mass Flow Rate Versus Gas Temperature. As has been described, the chimney attached to a stove acts as a pump, where the difference in mass between the column of hot air in the chimney and the equivalent column of ambient air is the 'motor' that allows the pump to function. This mass term is dependent on the chimney height and temperature through Equation 7. For a given chimney height then, the pumping power of a chimney is dependent on the difference between flue gas and ambient air temperature. As shown in Figure 36, the steady state total mass flow rate (fuel and air) increases with the average chimney temperature. The stove tested in this case is the HM5000. As shown, the shape of the mass flow curve is parabolic and is well captured by the numerical model.

The growth of the mass flow rate is dampened by the increasing viscous loss term that scales with velocity squared in accordance with Equation 8. At first, increasing temperature

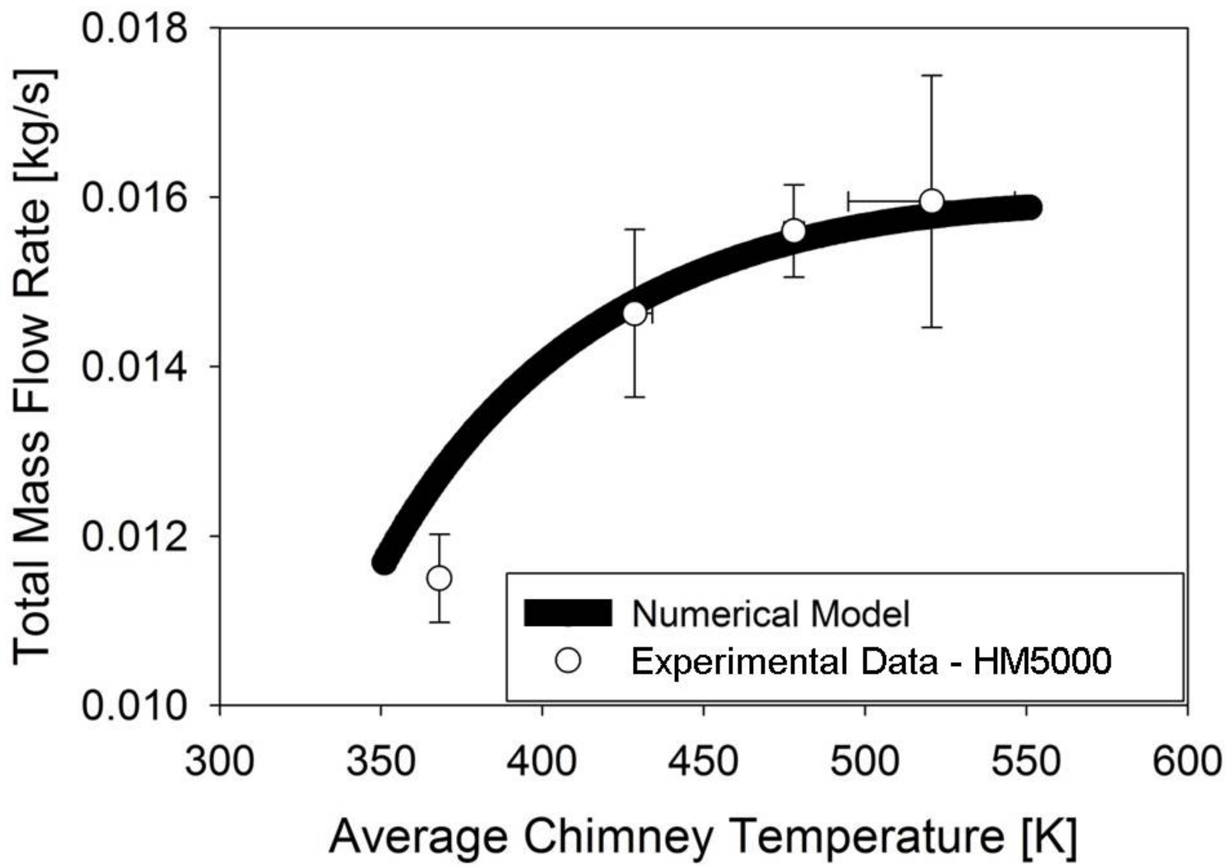


Figure 36. Total mass flow rate is shown to increase with average gas temperature, eventually reaching an asymptote as viscous losses compete with buoyant forces. Bars represent standard deviation from 5 minute averages.

leads to a rapid increase in mass flow. As the gas velocity increases, however, viscous losses approach the magnitude of the buoyant forces in accordance with Equation 8.

5.2.2. Exhaust Fan Equivalence Testing. Recently published literature indicating that increased air flow decreases the particulate matter production of a biomass cookstove [91, 92, 93]. It was of interest to determine whether chimneys are capable of producing air flows on par with forced draft cookstoves. To accomplish this, a small exhaust fan was powered through a variable AC power supply and attached to the top of the chimney, as described in Section 4.8.

Table 10. Comparison of Fan and A Buoyantly Driven Chimney

mass flow (g/s)	fan power (W)	ΔT in 2.27 meter tall chimney (K)
5.6	0.197	–
13.0	0.624	117
14.5	0.792	133
19.3	1.4	–

As shown in table 10 and Figure 37, a 2.27 meter tall chimney with a reasonable gas temperature can 'pump' at the same mass flow rate as a nominal 1 watt fan.

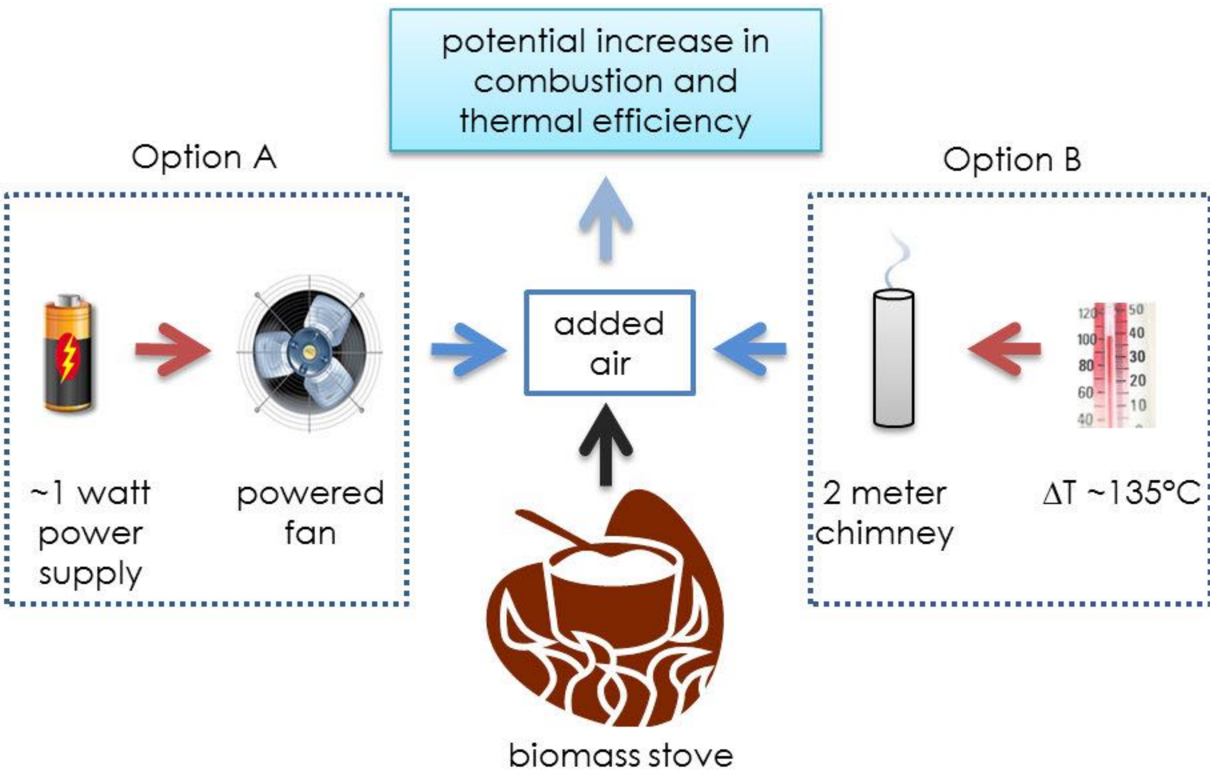


Figure 37. A two meter tall chimney was able to pull as much air into a stove system as a force draft stove sized fan when a modest temperature difference was created with a propane heater.

Similarly to what is seen in Figure 36 for a naturally-driven chimney, the mass flow through the chimney of the fan approaches an asymptote as power is increased. This effect can be seen in Figure 38. Similar to the behavior described in Section 5.2.1 this is likely due to an increasing proportion of viscous losses to pump pressure at higher velocities.

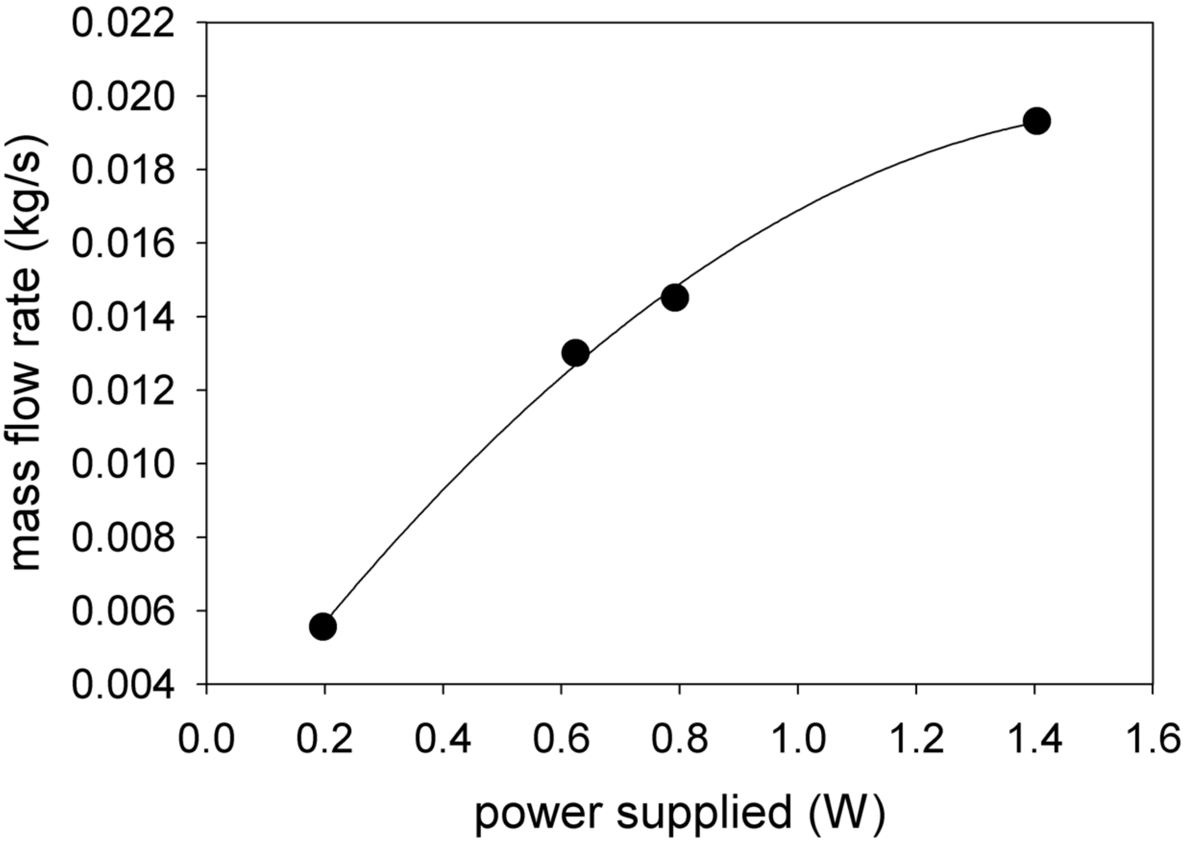


FIGURE 38. The mass flow of air drawn through a chimney with a powered fan. Ech point represents the steady state behavior from a single test.

5.2.3. OXIDATION OF CARBON MONOXIDE IN A CHIMNEY. Since chimneys theoretically provide increased residence time within a warm environment, there was interest in determining whether CO is further oxidized to CO_2 within a chimney. The author's field and laboratory data indicates that chimney temperatures generally fall within the range of 350-600 K, depending on the power and thermal efficiency of the stove. CHEMKIN-PRO was used to model two hypothetical scenarios to determine whether CO can be oxidized in chimneys under normal conditions. In the first scenario, gas flows from a 1500 K flame until reaching 600K where it is assumed to flow through an adiabatic chimney. In the second scenario, gas flows from a 1500K flame until reaching the 40 cm mark, where the gas is vented into cool ambient air.

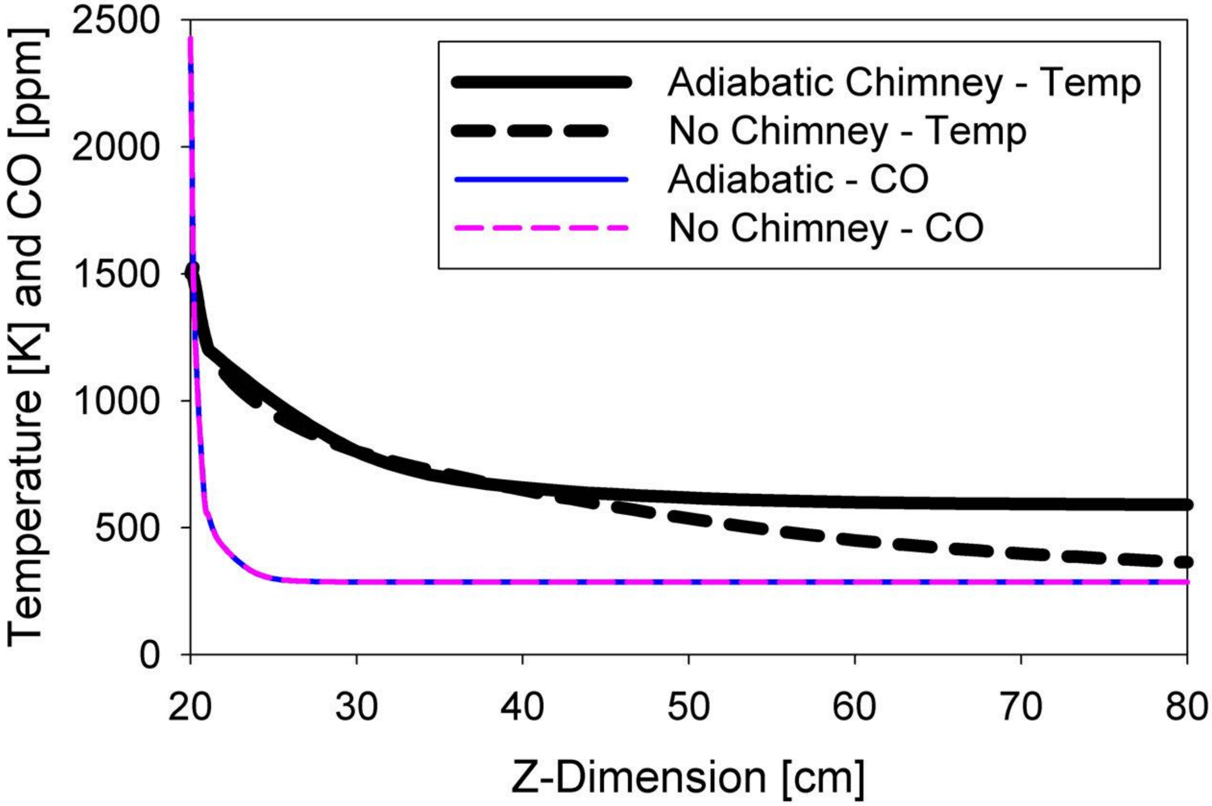


FIGURE 39. CHEMKIN-PRO results for hypothetical oxidation of CO in (a) an adiabatic chimney at 600K and (b) a direct emission of CO into the ambient air scenario.

As can be seen in Figure 39, even a very high temperature adiabatic chimney is not predicted to provide any oxidation advantage when compared to the exhaust-to-ambient scenario. The concentration of CO leaving the stove was identical between the two cases. Appreciable oxidation of CO appears to terminate at temperatures below 1200K, well above reasonable or safe chimney temperatures for residential stoves. This was an expected result, as literature kinetic rates will be extremely slow at the given chimney temperatures [96].

For a chimney to provide emissions reductions, it would need to include more advanced technologies such as catalyst inserts [10, 97].

5.3. Variable Draft Testing

The draft of a chimney stove is one of the only major 'knobs' that can be turned to alter the performance of that stove (another is firepower). Dampers allow users to adjust the draft of their stove during operation, but are difficult to model numerically. In order to capture the effects of different magnitudes of draft experimentally and computationally, draft was altered through the addition and subtraction of chimney sections as described in Chapter 4. Of particular interest in this work was understanding how the wood consumption rate, excess air, and emissions are affected by different magnitudes of draft. These results are discussed in the following sections.

5.3.1. Wood Consumption Rate.

One of the most important parameters of a stove is it's power (also called firepower), expressed by:

$$FP = \dot{m}_{fuel} \cdot LHV \tag{48}$$

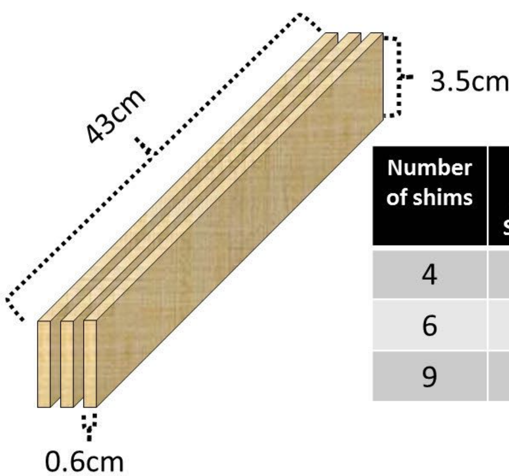
where $\dot{m}_{fuel}$ is the consumption rate of the fuel/wood and LHV the lower heating value of the fuel/wood.

Assuming the fuel type is held relatively constant, the fuel consumption rate becomes the only factor that controls the power output of the stove. For this reason, it is critical to understand what factors affect fuel consumption rate.

Literature, prior work, and first principles indicate that increasing fuel surface area will result in an increase in fuel consumption rate [71, 98]. Flames from wood combustion are a surface phenomenon. It logically follows that as more surface is available for reactions, more volatile gases can be released and ignited, releasing more heat.

The results shown in Figure 40 support this hypothesis. As described in Section 4.6.3, arrays of wooden shims composed of four, six, and nine standard shims were used to produce low, medium, and high power burns.

As shown in Figure 40, the average wood consumption rate scaled proportionately with the surface area of a given shim array. This effect was used to hold low, medium, and high power levels during testing, as described in Section 4.6.3.



Number of shims	Approximate Surface Area of Shim Array (cm^2)	Average Wood Consumption Rate (g/s)
4	1400	0.17 +/- 0.02
6	2100	0.30 +/- 0.004
9	3150	0.48 +/- 0.02

Figure 40. Wood consumption rate vs. surface area.

While surface area clearly affects wood consumption rate, the effect of increased air flow on wood consumption rate was less clear at the start of this work. Wood, like any fuel, requires oxidizer for combustion to occur. In high excess air scenarios, however, increased air may not add any boost to power and may just cool the reaction zone.

As shown in Figure 41, the consumption rate of wood was found to be relatively insensitive to the chimney draft. This data was collected at two (low and high) steady state firepowers with three different chimney heights, and two different stoves. In none of the cases did increasing draft appear to significantly elevate or decrease the consumption rate of wood.

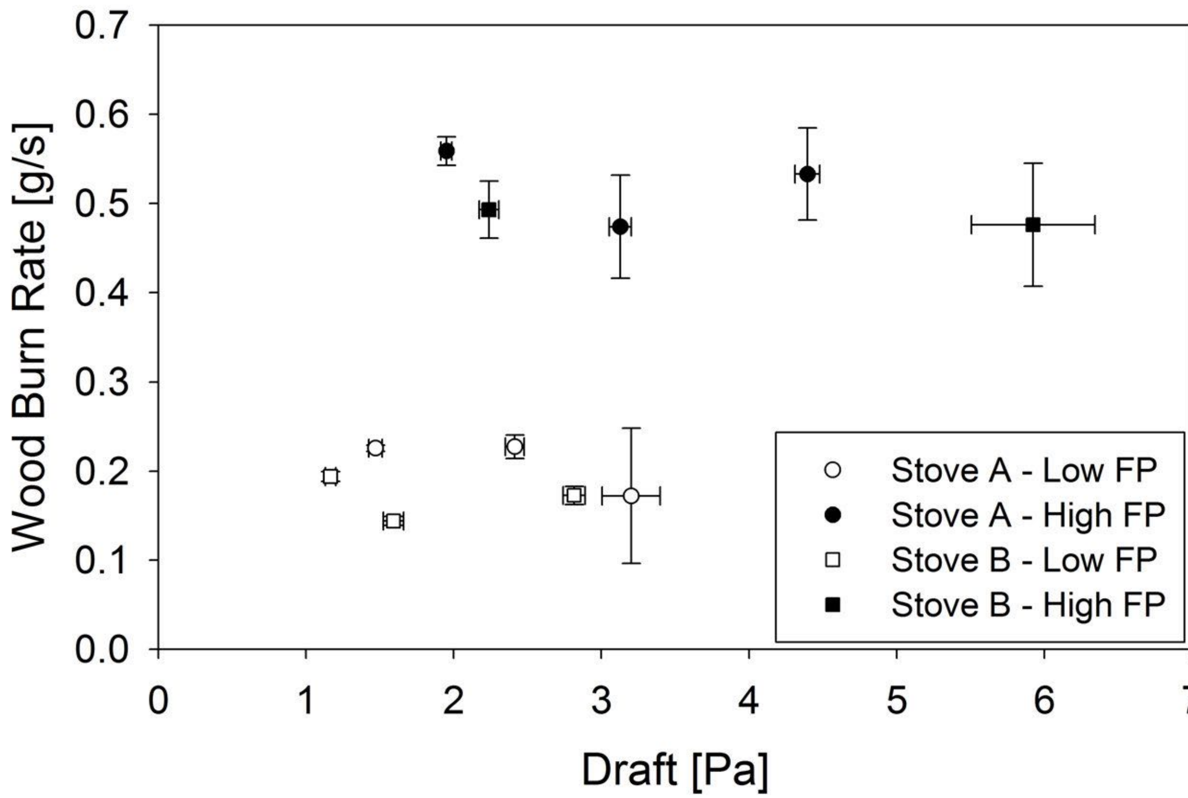


Figure 41. Wood consumption rate at several steady-state draft operation points. Draft was altered via chimney height, as described in Chapter 4, for Stove A (HM5000) and Stove B (Justa). Each point represents a single test. Error bars represent standard deviation over 90 second averages of draft (horizontal bars) and wood consumption rate (vertical bars).

Figure 41 shows a crucial finding in this work, having many implications to stove performance and design. Since higher draft results in a higher mass flow rate, but not a change in fuel consumption rate, draft is essentially a 'knob' for altering the flow rate of air. In other combustion systems (engines, boilers, etc.) altering the air-to-fuel ratio can have a significant effect on the efficiency and emissions of the system [99, 100, 101, 102]. This finding has important implications for the numerical model described in Chapter 3. Having the ability to decouple wood consumption rate from draft simplified the model greatly. In order to understand the implications of this controllable excess air more completely, it was necessary to first determine the amount of air that the chimney stoves in the study tend to operate with under nominal conditions.

5.3.2. Excess Air. Results from this study, shown in Figure 42, as well as previous work at the laboratory [58], indicate that some natural convection biomass stoves tend to operate with high excess air (typically $> 350\%$). The data in Figure 42 are from two stoves (the Justa and the HM5000) carried out in triplicate.

In Figure 42, 0 on the Y-axis represents stoichiometric combustion. As can be seen, the excess air from both Stove A (HM5000) and Stove B (Justa) fluctuates between $\approx 350\%$ and 1250% excess air. All six tests show a general downward trend in excess air from ignition to the twenty five minute mark. When the stoves first start, there is enough heat release to initiate a draft, which pulls in air, but the fuel is not yet burning fully. As the combustion chamber heats up and charcoal begins to accumulate, the wood consumption rate increases. The percent excess air continues to vary significantly throughout the test as fuel is added.

5.3.3. The Fuel Equivalence Ratio, Φ, and Overall Chimney Height. As described in Section 5.3.1, increasing chimney draft (through the addition of chimney sections) did not affect the consumption rate of wood. The increasing draft did result in a significant increase to the flow rate of air, thus altering the ratio of fuel to air as draft was changed. The

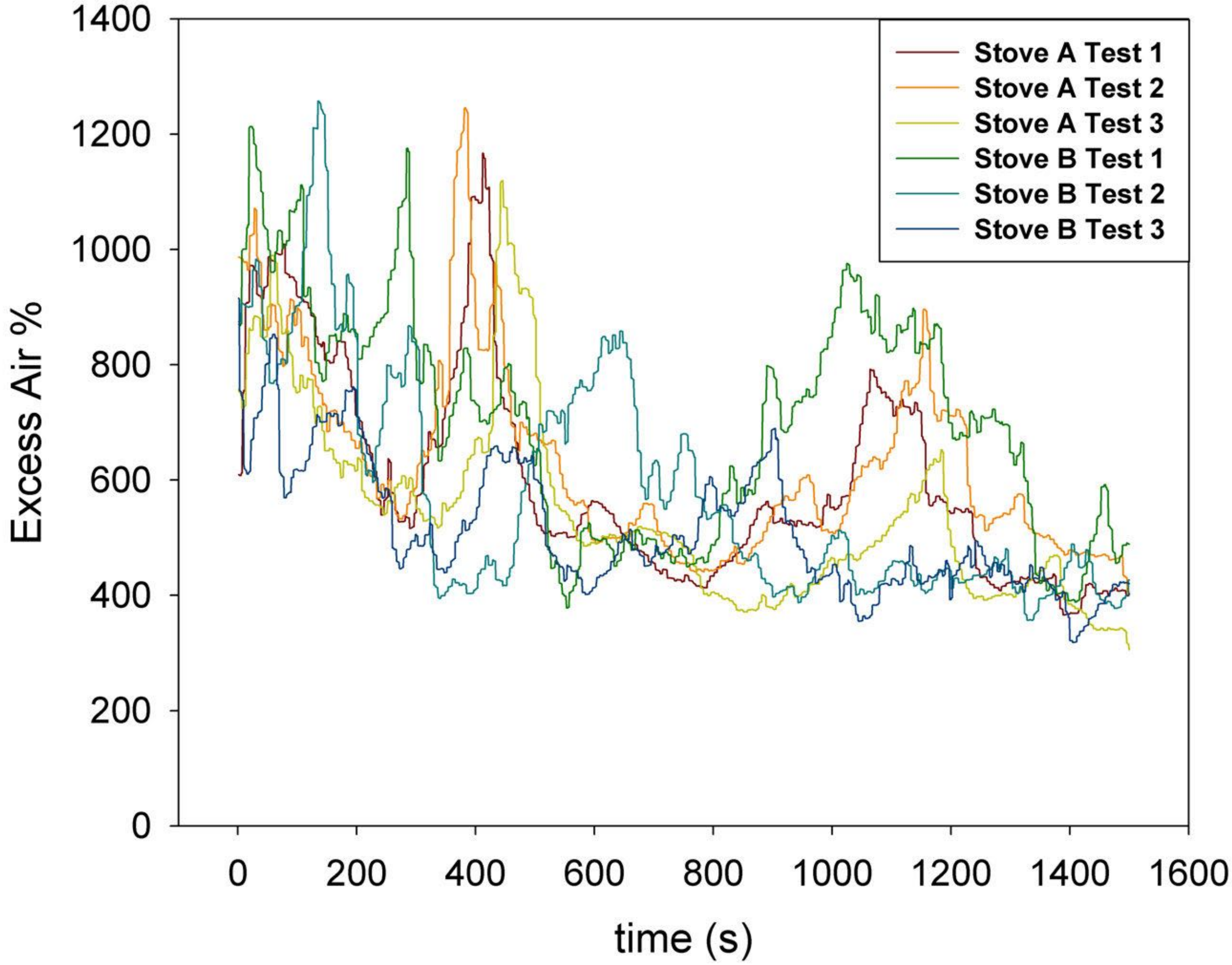


FIGURE 42. Excess air % over the first 25 minutes of simulated cooking cycle for Stoves A (HM5000) and B (Justa).

ratio of fuel to air can be described by the fuel equivalence ratio, Φ shown in the following equation:

$$\Phi = \frac{\left(\frac{A}{F}\right)_{stoich}}{\left(\frac{A}{F}\right)_{actual}} \tag{49}$$

Φ is a measure of how lean or rich the combustion reaction of fuel with air is in a given combustion system. As discussed in Section 5.3.2 and shown in Figure 42, certain natural convection stoves tend to operate far from stoichiometric air conditions, corresponding to

$\Phi << 1.0$. As chimney sections are removed, the air pulling capacity of the chimney is reduced. Thus, excess air is reduced, wood consumption rate remains fixed, and Φ increases. This dependence of Φ on total chimney height can be seen in Figure 43.

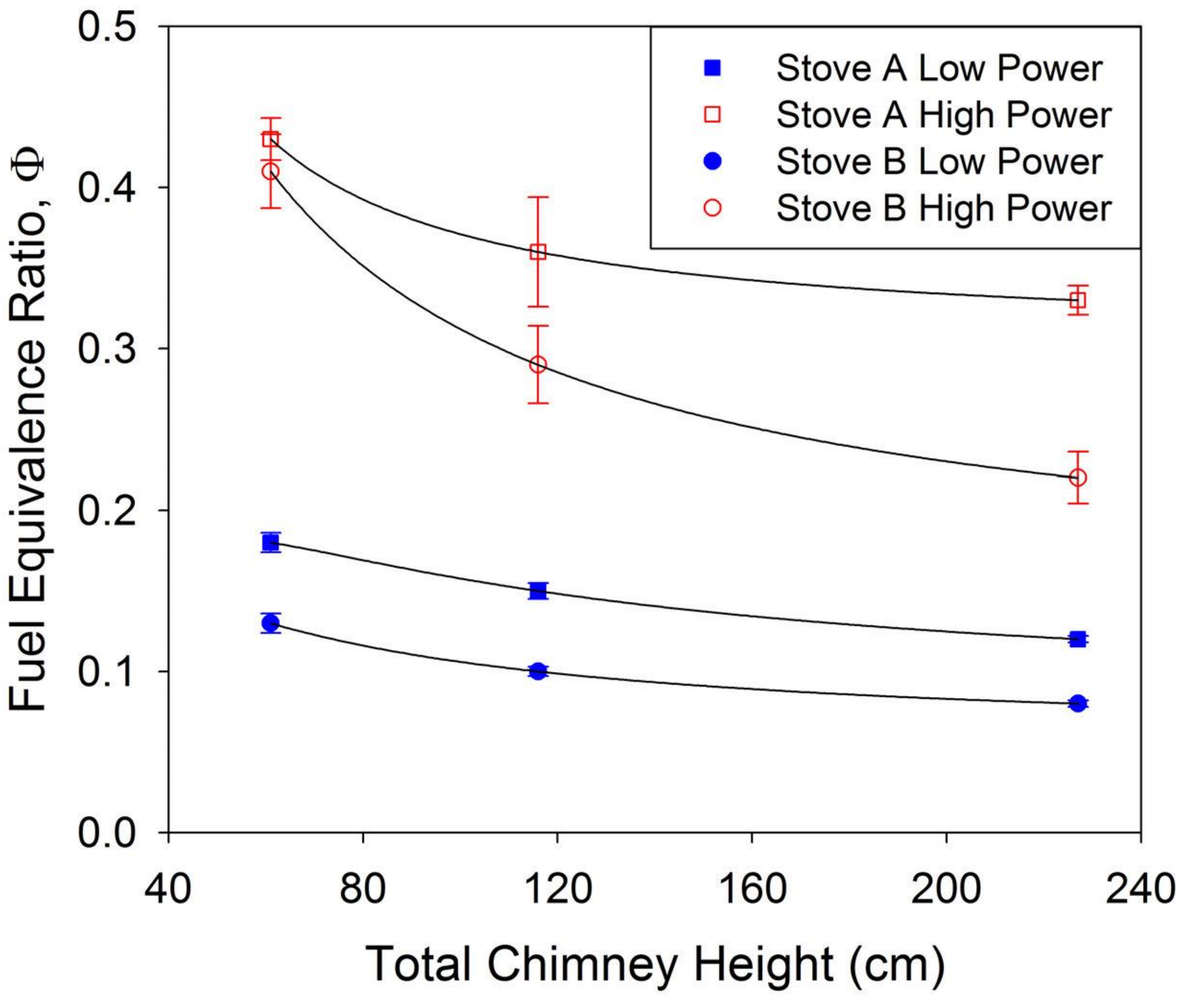


Figure 43. Steady-state fuel equivalence ratio, Φ, vs total chimney height for two different stoves (Stove A = HM5000, Stove B = Justa) at high and low power. Each data point represents a 90 second sample from a single test where the error bars represent standard deviation.

With two different stoves, Φ is shown to decrease with increasing chimney height. The shapes of these curves are different between stoves as each stove produces different relationships between draft and the resulting mass flow of air. These differences result from the unique flow resistance and heat transfer properties of each stove.

5.3.4. Laminar Diffusion Flames and Excess Air. The flames of biomass cookstoves are non-premixed diffusion flames. In such flames, insufficient air limits the amount of volatile gases that can be combusted. Too much air, on the other hand, pulls heat away from the combustion zone, limiting the amount of volatile gases that are released, and thus the heat output of the reaction. Given the results shown in Figure 42, obtained by testing two different griddle stoves with a 2.27 meter tall chimney, it was important to determine how combustion in Stoves A and B was impacted by varying chimney height and thus natural draft. Since these stoves are operating exclusively above stoichiometric air, any added draft pulls the reaction further away from stoichiometric conditions. This is especially true given the results shown in Figure 41, which indicate that draft simply increases air flow, leaving fuel flow fixed.

5.3.5. Modified Combustion Efficiency. In ideal combustion, carbon dioxide and water vapor are the only reaction products. In reality, not all carbon molecules are converted to carbon dioxide before the reaction terminates. The modified combustion efficiency (MCE) is used to describe the degree to which the carbon in hydrocarbon fuels is converted to CO_2. It is defined by:

$$MCE = \frac{[CO_2]}{[CO] + [CO_2]} \tag{50}$$

As can be seen while investigating Equation 50, high levels of CO decrease the magnitude of the MCE, indicating that some portion of the combustion reaction is incomplete. Incomplete combustion is generally the result of a combination of the following:

(1) insufficient oxidizer, such as in smoldering scenarios.

(2) insufficient mixing of fuel and oxidizer.

(3) excessive cooling of the reaction zone, essentially freezing chemical reactions before carbon in the fuel has been fully converted to CO_2.

As prior results indicated that chimney stoves run in operating regions of high excess air, insufficient oxidizer was not believed to be a likely culprit for carbon monoxide production. Too much air on the other hand, seemed plausible given the results shown in Figure 42.

The following observations were made regarding excess air:

- the two griddle stoves in this study ran with significant excess air in all cases tested
- more chimney height led to higher excess air (lower Φ) in all cases tested, as shown in Figure 43
- carbon monoxide was seen to peak when excess air was maximized in several tests

These observation made apparent the likelihood that excess air flow may be cooling the combustion zone, decreasing the modified combustion efficiency. Comparing the data for modified combustion efficiency versus Φ was undertaken. This was also an opportunity to exercise the chemical kinetics model discussed in Section 3.3.6.1. As shown in Figure 44, modified combustion efficiency does appear to increase with increasing Φ (decreasing excess air). The chemical kinetics model was shown to provide reasonable agreement with the experimental data, showing a sharp decrease in combustion efficiency near $\Phi \approx 0.12$.

While an explanation for this particular value of Φ is not available, both the data and model support the theory of excessive cooling of the combustion zone due to high excess air.

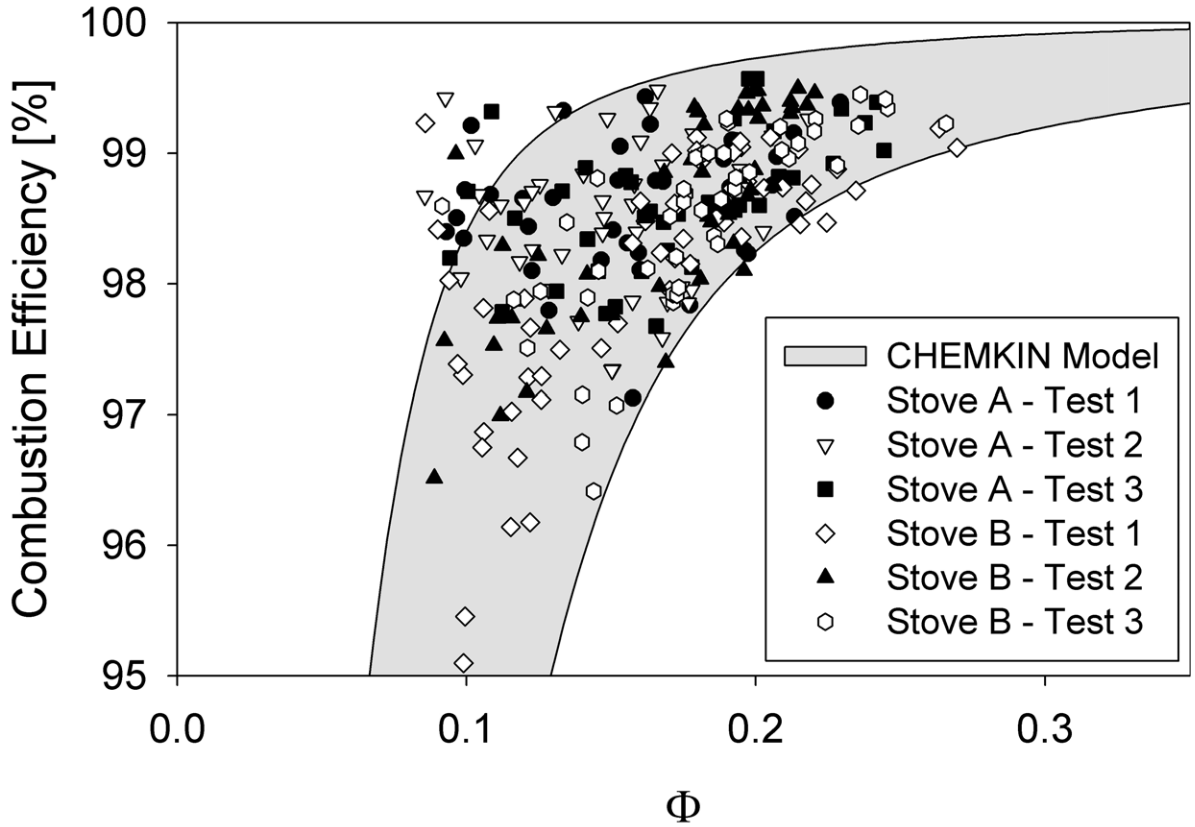


FIGURE 44. Both experimental data and simulation results from CHEMKIN-PRO model indicate that combustion efficiency increases with Φ. Each point represents data averaged over 90 seconds.

Having found that the wood burn rate was relatively insensitive to chimney draft, as shown in Figure 41, it was hypothesized that Φ could be altered by reducing the total mass flow rate allowed through the stove. It was believed that CO production could be reduced by confining a stove to a high-ϕ operating region, based on results shown in Figure 44. The total mass flow rate could be regulated through a variety of methods, but the simplest and most applicable appeared to be by reducing the diameter of the chimney. Adding a damper to the four inch chimney would add to the part count and cost of a stove. Swapping out a larger diameter chimney for a smaller diameter chimney, on the other hand, reduces materials and cost of a stove system (an essential requirement for all improved stoves for the developing world). A smaller diameter chimney should behave as a crude mass flow limiter through increased viscous loss terms. Pressure loss increases with inverse radius to the forth power, as described by Hagen-Poiseuille flow [45]:

$$\Delta P = \frac{8\mu L Q}{\pi r^4} \tag{51}$$

where ΔP is the pressure loss, L the pipe length, Q the volumetric flow rate, r the pipe radius, and π the mathematical constant (3.1415...).

As shown in Figure 45, Stove A was thrust into a higher-Φ operating region with the reduction to the chimney diameter. When comparing the two cases, there was a 38% reduction in CO emissions when the 10 cm ID chimney was replaced with a 7 cm ID chimney.

TABLE 11. Performance Comparison of Stove A With Two Chimney Diameters

Parameter	10 cm chimney	7 cm chimney
chimney inner diameter [cm]	10.12	7.01
average steady state wood consumption rate [g/s]	0.334	0.354
average steady state total mass flow rate [g/s]	13.29	8.33
excess air [%]	557	273
average steady state Φ	0.158	0.274
average steady state chimney draft [Pa]	4.38	3.91
overall thermal efficiency [%]	26.47	26.05
average steady state CO production rate [g/s]	0.00757	0.00466
percent reduction in CO	–	38%

It is important to note that the wood consumption rate of the two cases shown in Figure 45 and Table 11 was very similar, as was the overall draft and thermal efficiency. The major difference between the two cases was the total mass flow rate, and subsequently the

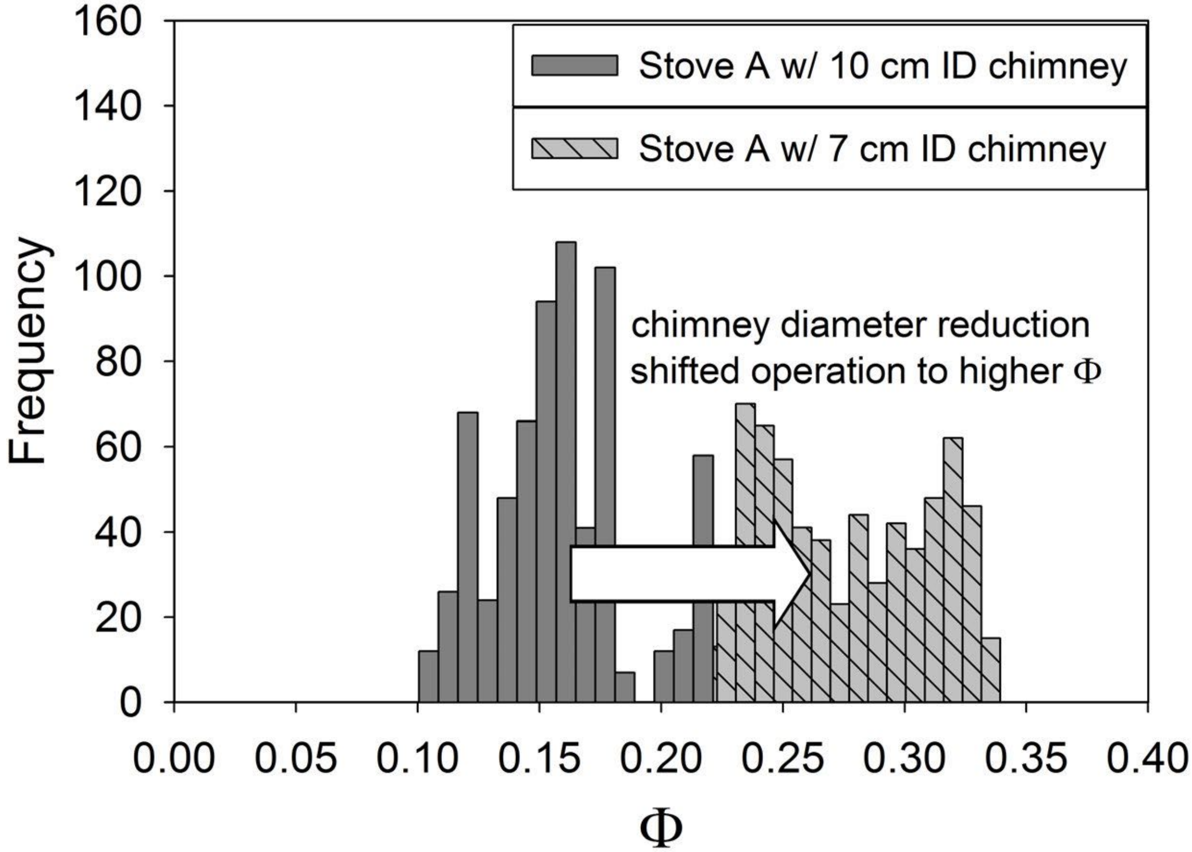


FIGURE 45. Stove A (HM5000) was successfully thrust into a higher Φ region by reducing the inner diameter of the chimney (presenting more resistance to gas flow). Each bar represents the amount of time spent at a certain equivalence ratio.

excess air, Φ, and carbon monoxide production. While total emissions from the stove were significantly reduced, a reduction in mass flow rate translates to a lower velocity of air into the front of the stove. This is an important trade-off to consider, as insufficient frontal velocity into the combustion chamber can lead to emissions of combustion products from the front of the stove.

5.4. Simulated Elevation Effects

Elevation is an often overlooked variable that has the potential to significantly change the performance of a chimney stove. Utilizing the numerical model described in Chapter 3, hypothetical experiments were run to determine the sensitivity of stove behavior to elevation. In Figure 46, three regions that have ongoing stove programs are identified by their elevation. Stoves in these three different regions would require chimneys of significantly different heights to achieve the same theroretical draft.

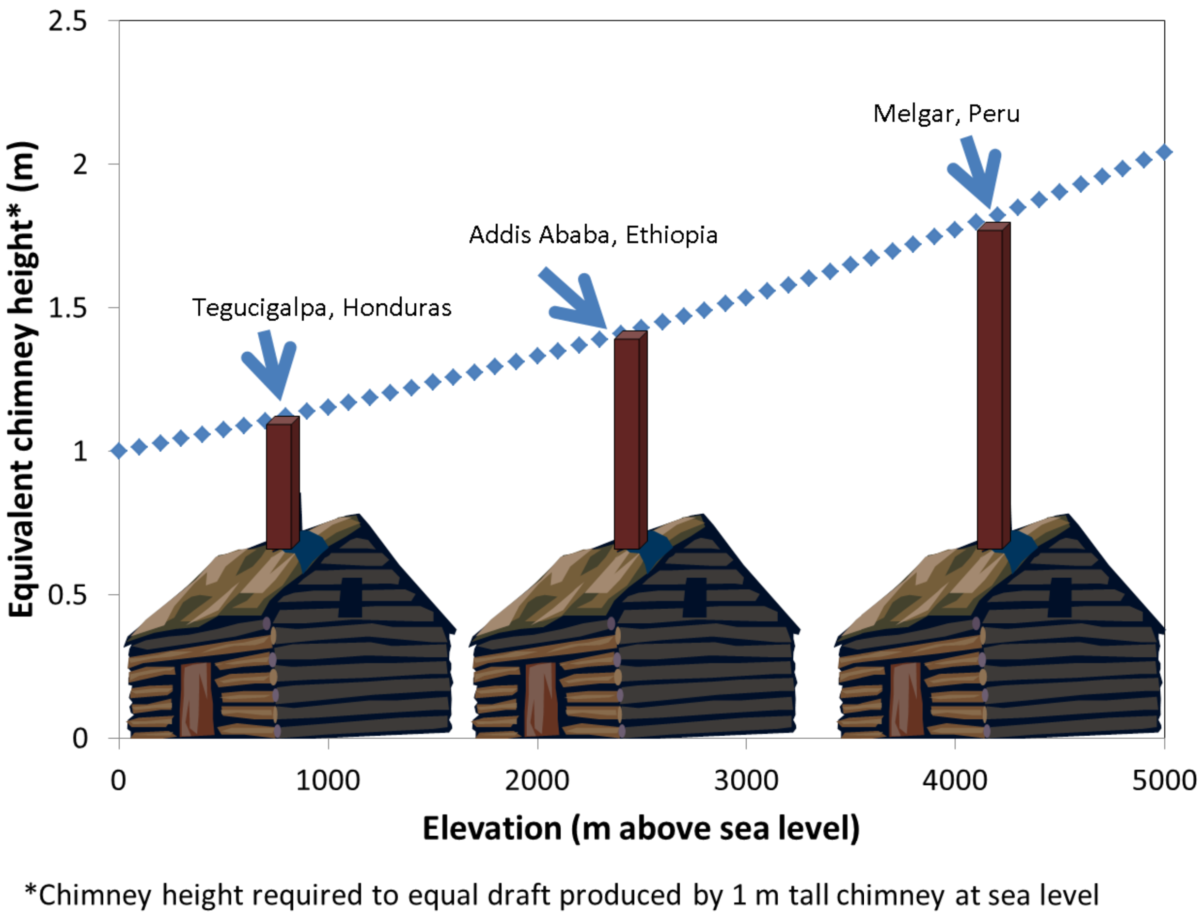


FIGURE 46. Chimney heights required for equivalent draft over a range of elevations.

The result shown in Figure 46 raises concerns about the common practice by international or national stove programs of distributing the same stove to regions which lie at different elevations without considering the potential for major differences in performance. To explore this further, the numerical model was used to investigate what would happen if a particular stove burning at 5 kW power was run at sea level and at an elevation of 4000 meters.

Table 12. Comparison of Theoretical Behavior of One Stove at Sea Level and 4000m

Parameter	Sea Level	4000 meters
firepower (kW)	5	5
chimney height (m)	2.2	2.2
mass flow of air (g/s)	12.2	6.7
fuel equivalence ratio (Φ)	0.16	0.35

As shown in Table 12, elevation can have a significant effect on the performance of a chimney cookstove. In particular, the mass flow of air is greatly diminished by the reduced density of gas at elevation. This, in turn, alters the fuel equivalence ratio, average gas temperature, and velocity of air entering the stove. This could have serious implications for the emissions formation, thermal efficiency, and fugitive emissions of a stove. It is important to note that these results are for one particular stove with one particular geometry at one particular firepower, but it is believed that most results would trend in a similar manner, given the physics at play.

5.5. Locating Optimization Points Using the Model

The main objective in the development of the chimney stove numerical and chemical models is to be able to optimize designs for new cookstoves. These models are tools that shed light on where efficiency can be maximized while minimizing emissions and allowing for adequate frontal velocity. The following sections describe these efforts in greater detail.

5.5.1. Carbon Monoxide Emissions.

Carbon monoxide is a product of incomplete combustion and is highly toxic to people [103]. The chemical model provided an approximate relationship between the carbon monoxide production rate and the fuel equivalence ratio, Φ, as shown in Figure 44. This relationship can be used to provide a contour map of combustion efficiency vs. firepower and air flow as shown in Figure 47.

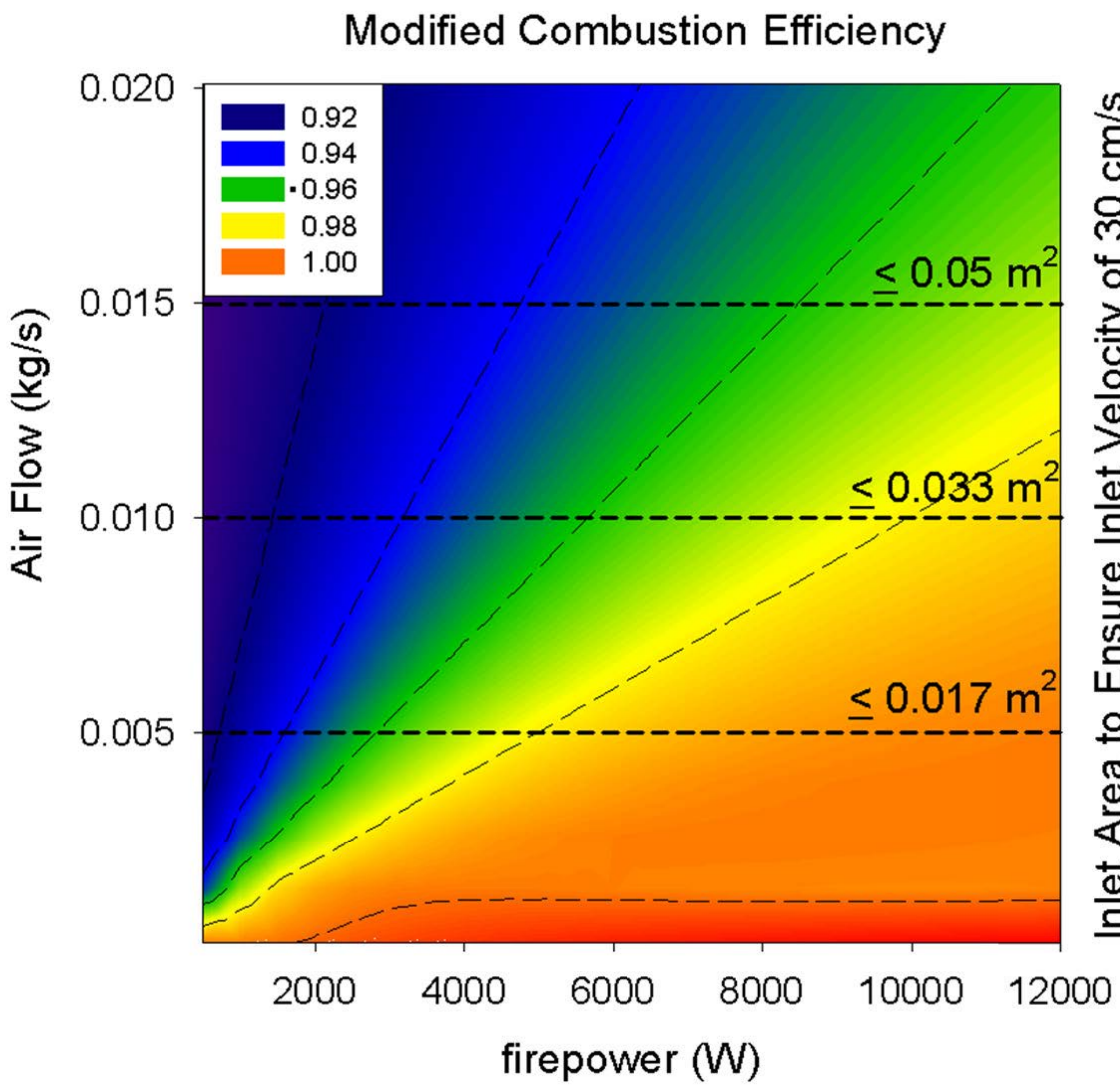


FIGURE 47. Modified combustion efficiency (MCE) contour. This contour uses the chemical kinetics model to predict MCE over a range of firepowers and air flow rates. The horizontal dashed lines indicate guidelines for combustion chamber cross sectional area to meet frontal velocity requirement of 30 cm/s at various air flow rates.

The numerical model was run over a range of firepowers and air flow rates (resulting in calculation of Φ) and made to calculate modified combustion efficiency using the results of the chemical kinetics model shown in 44. In agreement with previously discussed results, excess air is predicted to pull a stove away from the highest combustion efficiency, most likely by cooling the reacting combustion gases and effectively shortening the reaction zone. What is crucial to consider, however, is that too low of air flow can result in an inadequate frontal velocity. In regards to human health, a stove that produces less CO but allows more into the room occupied by the user is a more dangerous stove. Perhaps more serious yet are the implications to particulate matter; a properly operating stove should not allow any particulate matter to be released indoors. Figure 47 includes three guidelines for maximum combustion chamber area allowed to ensure a 30cm/s inlet velocity. While this velocity has not been recognized by any experts to be 'officially' safe, it is utilized here as a starting point, for it is slighlty higher than guidelines provided in the literature for wood burning appliances [104].

5.5.2. Thermal Efficiency. Another significant opportunity for optimization lies in the maximization of thermal efficiency. The numerical model was utilized to calculate the hypothetical operating map of a 10kW cookstove that has 0.5 m^2 of cooking surface area. A range of air flow and the hydraulic diameters (depth of gas path) were run through the model and made to calculate heat transfer to the cooking surface. As can be seen in Figure 48, excess air reduces the thermal efficiency. The drop in temperature degrades heat transfer far more than the higher velocity boosts it. That is to say that the increased air flow, which results in higher Reynolds number (and consequentially higher convection heat transfer coefficient), cools the gas too much to see any benefit.

5.6. HM5000 and L6040 Stove Development and Optimization

Two stoves were optimized as part of this overall work. The first, the HM5000 griddle stove has been tested extensively and is in production at the time of this publication. The second is the two-pot L6040, which underwent extensive testing but requires further work

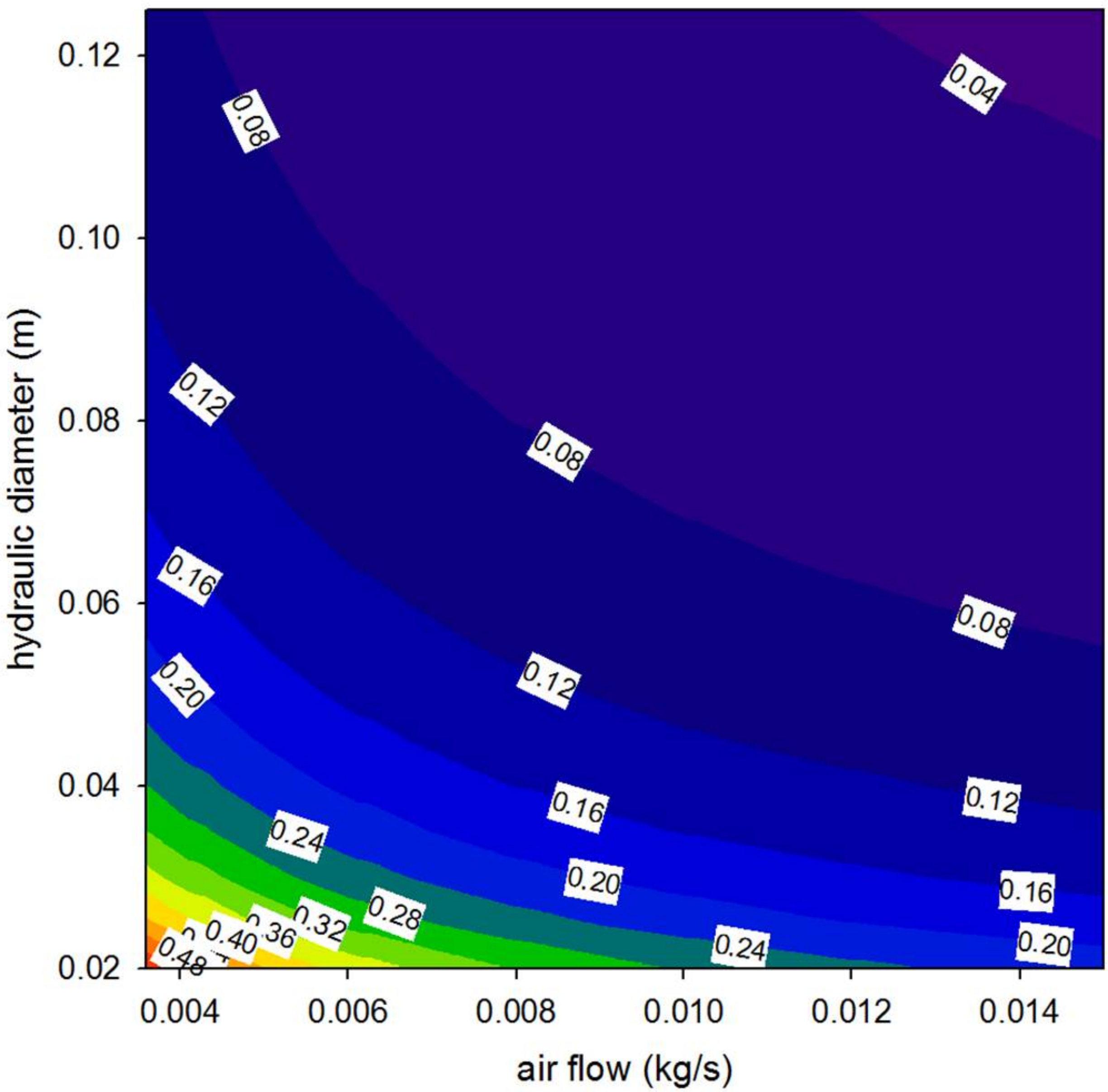


FIGURE 48. Thermal efficiency is shown to increase as air flow apporaches stoichiometric. It is also shown to increase as the hydraulic diameter is decreased. The case featured is for a 10kW burn with 0.5m^2 of cooking area.

to be ready for market. The optimizations and performance of these stoves are discussed in the next several sections.

5.6.1. Optimization of a Griddle Stove. Having developed (a) an understanding of several specifications that potential end-users would look for on a new griddle stove (b) an understanding of some of the fundamental relationships between draft, gas temperature, firepower, air-to-fuel ratio and (c) a numerical model that allows for rapid parametric sweeps of stove and chimney characteristics, there was an opportunity to optimize a griddle stove that would be efficient, clean, and well-liked by recipients.

The current version of the HM5000 is the result of more than a dozen full design revisions. The numerical model was being developed in parallel with these versions, so in many cases it was used to explain behavior encountered throughout testing in addition to driving decisions for next revisions. The stove development was funded by a commercial partner, Envirofit International, and was geared toward potential users in Honduras.

Several engineering techniques were used to develop early prototypes of the HM5000. As shown in Figure 49, design included analytical, computational, and experimental work. Select literature, such as Samuel Baldwin's seminal VITAE report "Biomass Stove," helped guide early design decisions.

5.6.1.1. *Heat Distribution*

When stove users in Honduras were asked what they did not like about their traditional stoves, a consistent concern was the non-uniform distribution of heat on the cooking surface. The plancha tends to send most heat directly above the combustion chamber and not enough elsewhere. With this being the case, a primary goal of the development of a new stove was to allow for more uniform heat distribution on the cooking surface.

To achieve this, several features were engineered to allow for lateral and front-to-back heat distribution. These features include, but are not limited to:

- A flared combustion chamber, as shown in Figure49, to promote lateral flame spread and radiation view factor

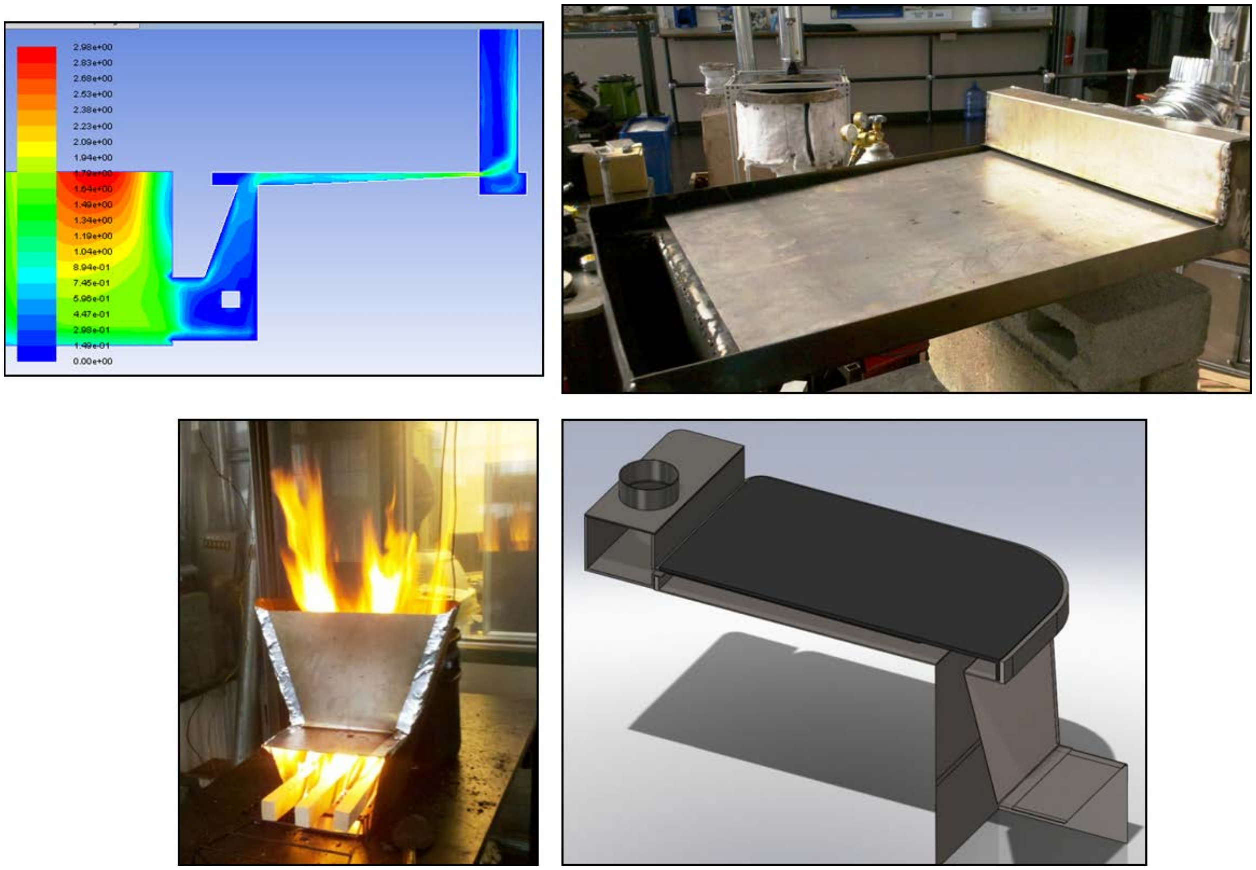


FIGURE 49. Optimization of the plancha stove involved analytical, computational, and experimental work.

- A sloped gas path floor to accelerate flow as it moved toward the chimney. This was meant to punch through the griddle's underside boundary layer and promote convective heat transfer toward the back
- A variable thickness griddle, with more material on the front of the stove to buffer heat directly above the combustion chamber
- Cast fins on the back two-thirds of the underside of the griddle to enhance surface area, increasing convective heat transfer

Much of the optimizations were made through iterative design, focusing on boosting the heat transfer to the sides and back of the griddle, since the front-center of the griddle was directly above the combustion chamber. As can be seen in Figure 50, the HM5000 is able to distribute heat considerably more effectively than the Justa.

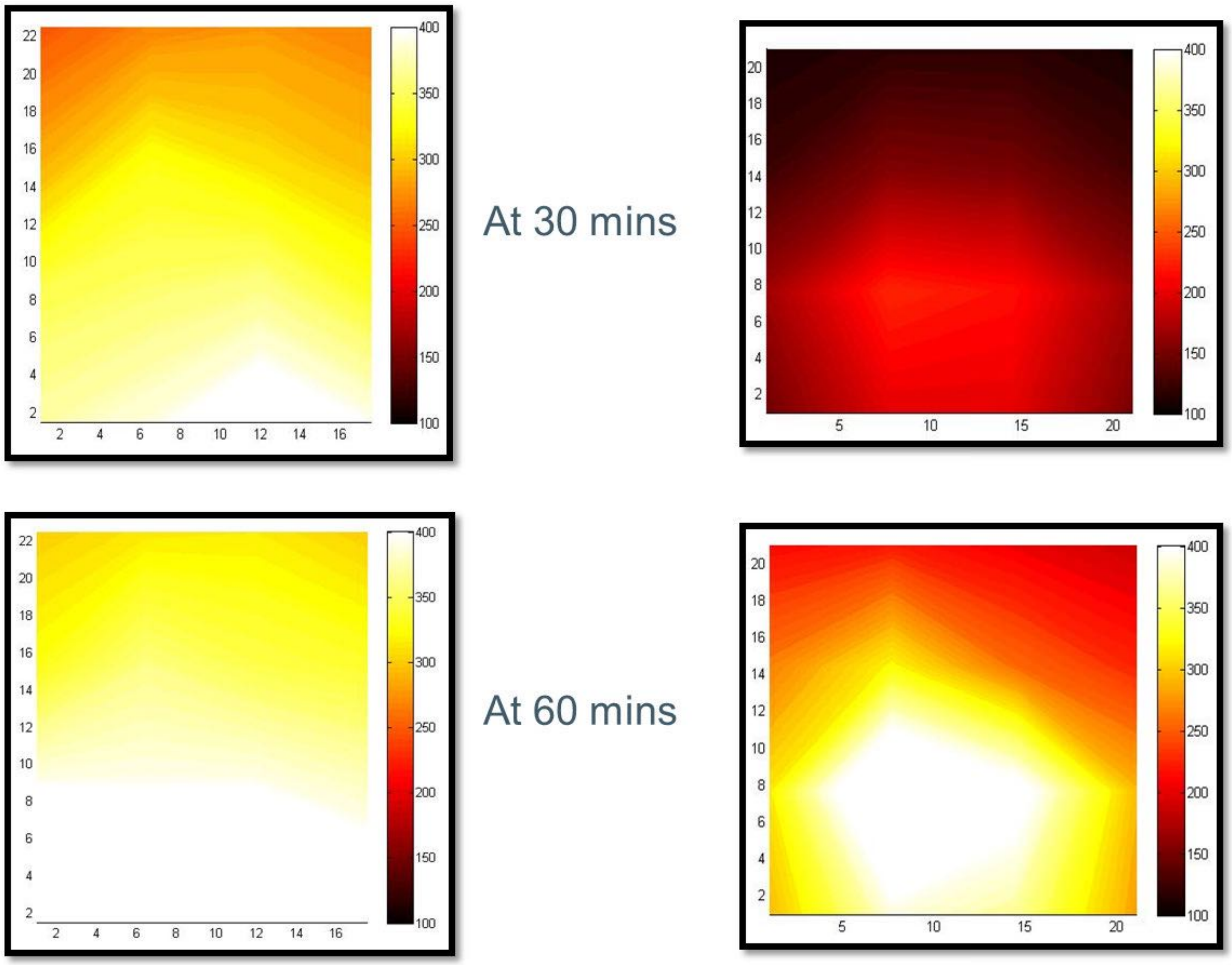


FIGURE 50. Heat distribution with optimized plancha stove versus traditional improved plancha.

But just spreading heat uniformly does not satisfy user requirements. The cooking surface must fall within a certain temperature range in order to be useful. Too low of a surface temperature and cooking takes too much time or food isn't cooked properly. Too high of a temperature and foods such as tortillas get burned. The ideal griddle stove heats up quickly, with as much of the cooking surface being usable as possible. The HM5000 was tuned (through a wide range of features) to produce cooking temperatures between 200 and

400 degrees Celsius, based on user feedback described in Chapter 1. Figure 51 shows the significant increase in useful area (surface area in which stove temperature is above 200 degrees C and below 400 degrees C) present with the HM5000 stove.

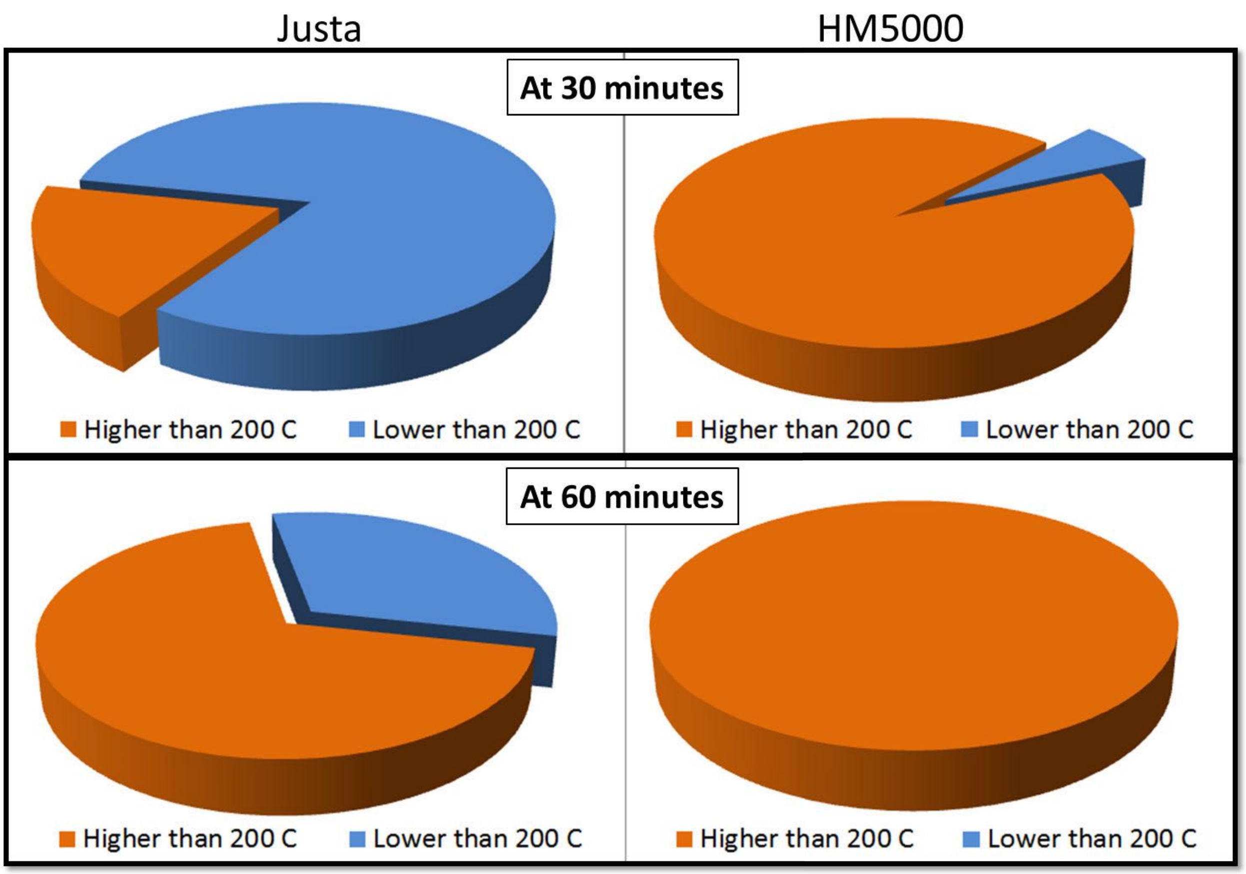


FIGURE 51. Useful area of the cookstove at 30 and 60 minutes: Justa VS HM5000.

5.6.1.2. *Thermal Efficiency*

Thermal efficiency is an extremely important performance metric for cookstoves since it influences wood use, time to boil, and total emissions from a stove. Efficient stoves make the most use of heat of combustion toward cooking operations. Less efficient stoves send heat into non-useful mass (such as the stove body) or out of the chimney. The thermal efficiency referred to in this work is defined as:

$$\eta_{thermal} = \frac{E_{useful}}{E_{total}} = \frac{E_{useful}}{m_{wood} \cdot LHV_{wood}} \tag{52}$$

where E_{useful} is a slightly subjective quantity describing the energy that is utilized for 'useful' purposes. If the only objective were boiling water in a sealed vessel, then:

$$E_{useful} = m_{water} \cdot c_p \cdot (T_{hot} - T_{cold}) \tag{53}$$

where m_{water} is the mass of water being heated, c_p the specific heat of water, T_{hot} the final heated temperature of the water, and T_{cold} the starting cold temperature of the water. When water is lost to evaporation that energy is generally counted as useful. When moist wood is used, the energy required to remove the water is counted as useful. If energy goes into the conversion of wood to charcoal, that may also be counted as useful energy. So, a more complete analysis includes multiple sub-terms in the $E_u seful$ term:

$$E_{useful} = E_{cooking} + E_{evaporation} + E_{fuelconversion} \cdots \tag{54}$$

The term described in Equation 54 is the one used in the determination of thermal efficiency in this work.

As can be seen in Figure 52, the HM stove achieved considerably higher thermal efficiency (average of 60 percent higher) than the Justa when using the modified WBT and rigid steel pots (1 in front of the griddle, 1 in back).

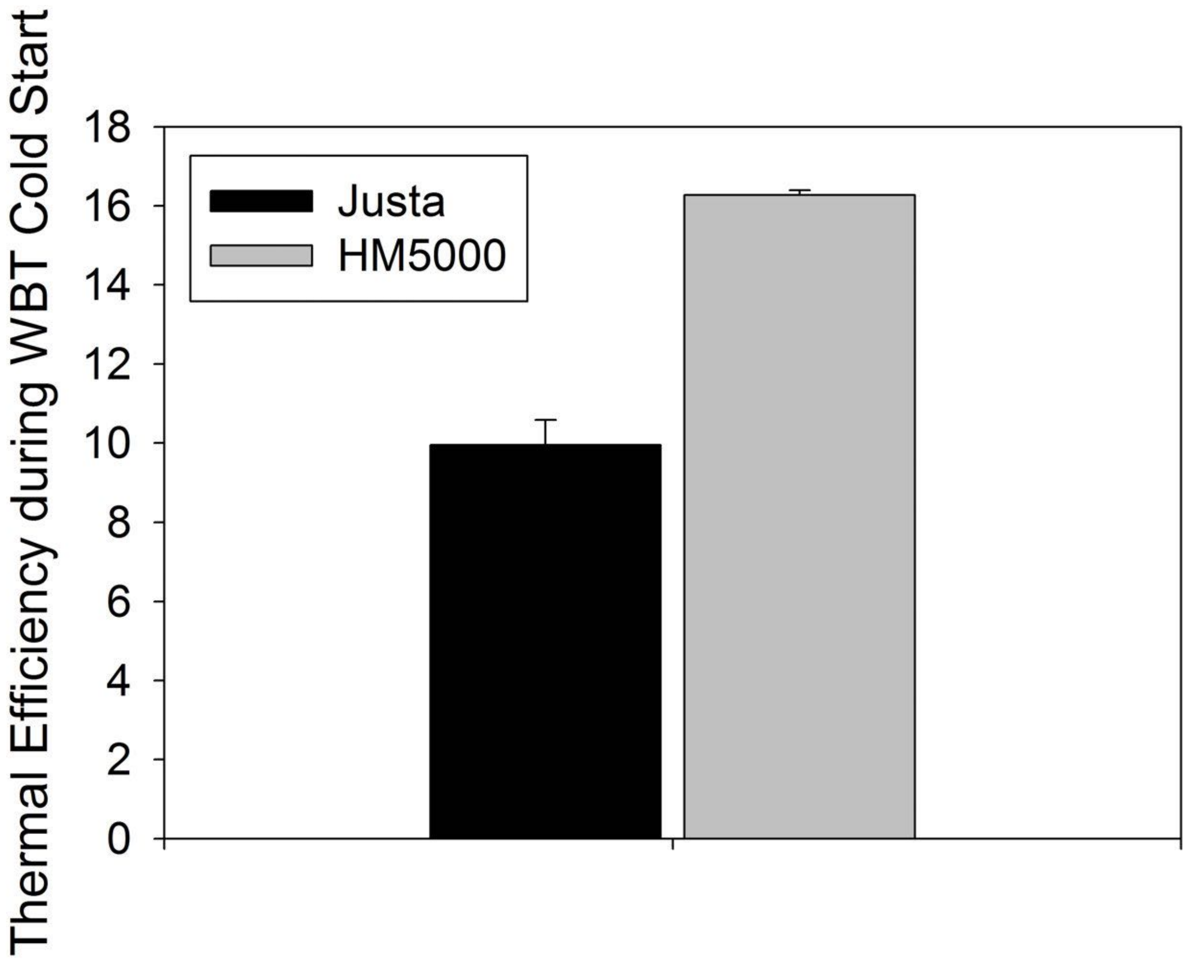


FIGURE 52. Thermal Efficiency for Justa vs. HM5000. Data are from three tests for the Justa and two tests for the HM5000. Bars represent standard deviation.

5.6.1.3. *Wood Use*

A direct effect of using a more efficient wood stove is that less wood is used during a standard cooking operation (in this case taking 5 liters of water from 15 degrees C to 90 degrees C). As shown in Figure 53, the HM5000 was shown to use approximately half (53 percent) of the wood required to complete the same task with the Justa. Both thermal efficiency and wood use improvements are believed to be the result of the following optimizations of the HM5000 stove:

- The combustion chamber is shaped to spread flue gas laterally into the gas path.

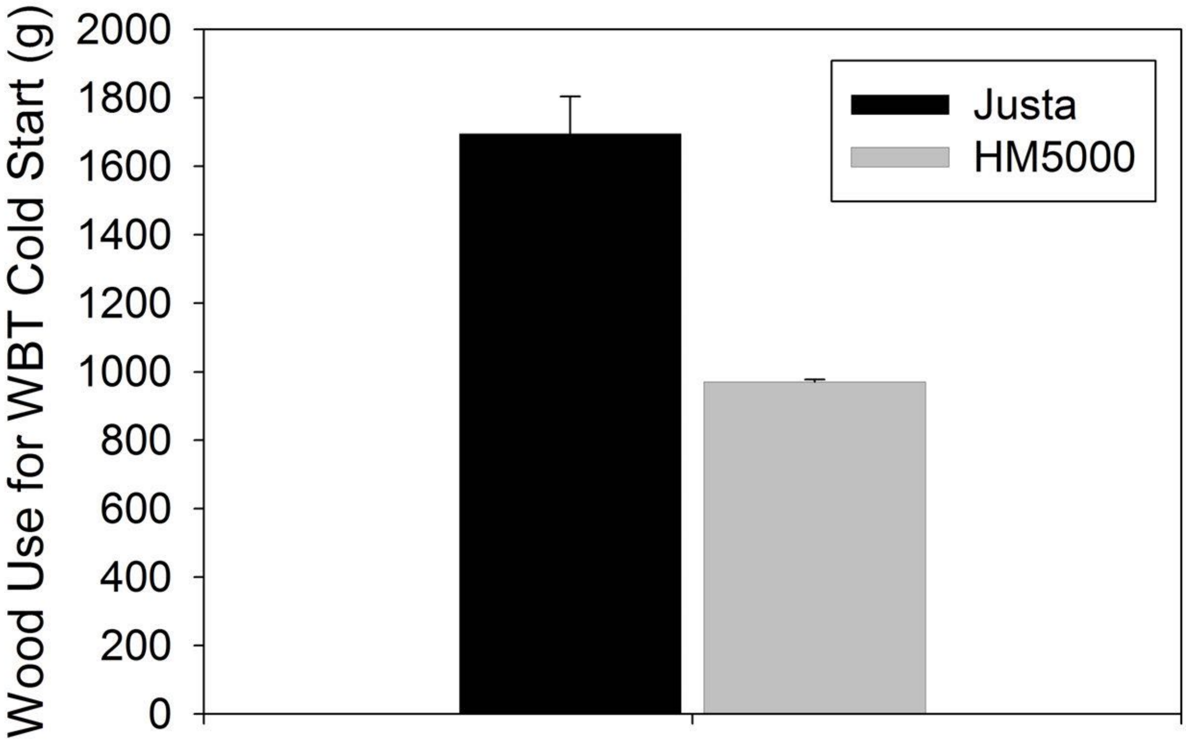


FIGURE 53. Fuel use required to complete cold start test for Justa vs. HM5000. Data are from three tests for the Justa and two tests for the HM5000. Bars represent standard deviation.

- The combustion chamber is composed of thin, low emissivity metal alloy, minimizing heat loss.
- The combustion chamber and gas path are insulated, minimizing heat loss.
- The gas path is thermally thin, allowing for higher convection transport from flue gas to griddle.
- The griddle possesses fins which boost convection heat transfer from an increase in wetted surface area.

5.6.1.4. *Carbon Monoxide*

Total carbon monoxide production is also substantially lower with the HM5000 stove compared to the Justa, as shown in Figure 54. The reduction in carbon monoxide is likely

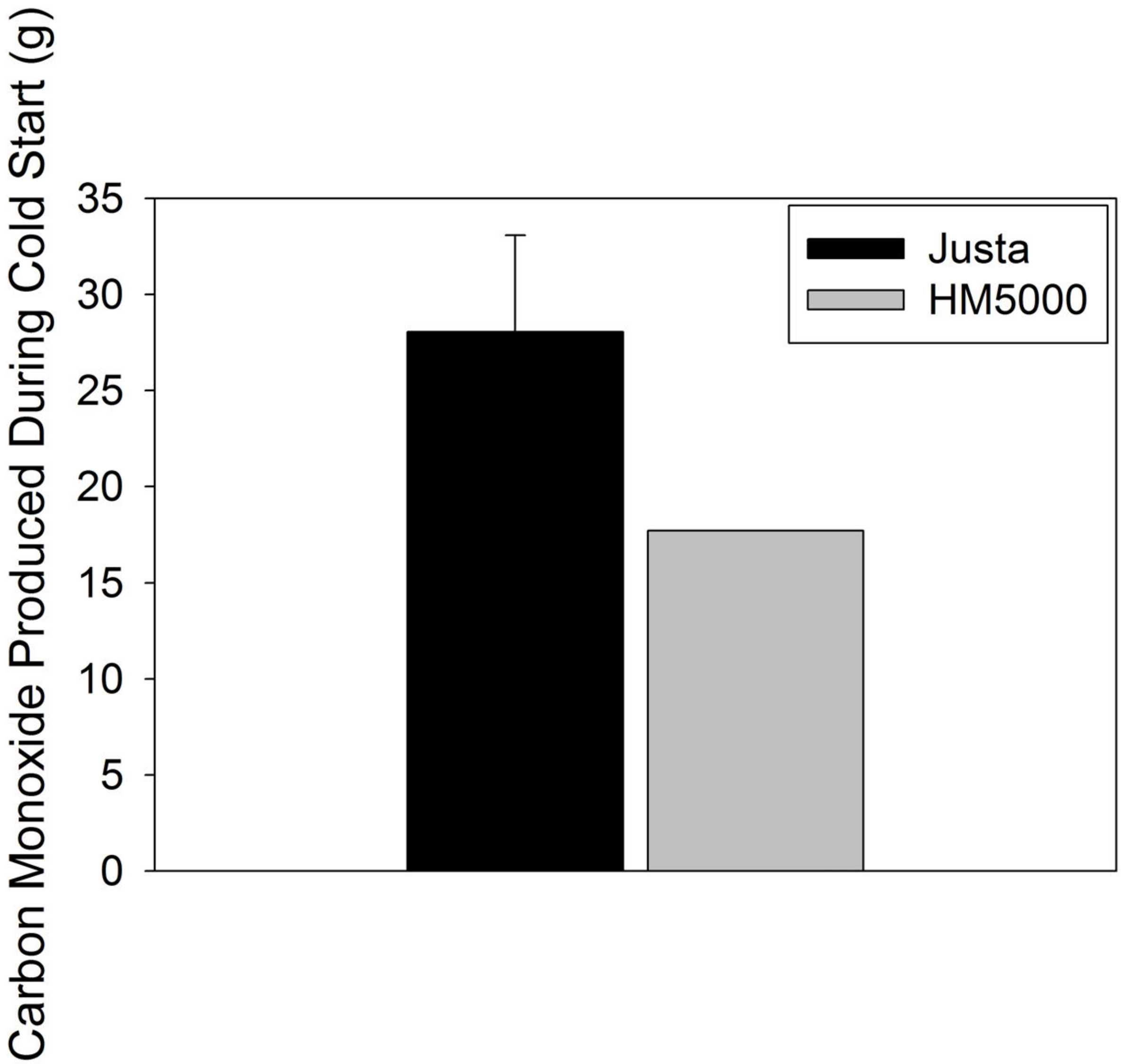


Figure 54. Carbon monoxide produced by Justa vs HM5000 during WBT cold start. Data are from three tests for the Justa and two tests for the HM5000. Bars represent standard deviation.

due to two factors:

- increased efficiency of the HM5000 means the stove runs for less time at the same firepower. Thus, less carbon monoxide is produced over the shorter period of time

- higher temperatures in the combustion chamber (from materials of construction and insulation) allow for more complete combustion

5.6.1.5. *Particulate Matter*

Particulate matter production was not improved when comparing the average performance of the HM5000 and the Justa, as shown in Figure 55. The production of particulate matter was not a specific objective of this work and as such, much work remains in order to understand how to reduce particulate matter. Preliminary evidence suggests that excess air may be beneficial in reducing particulate matter, even though it was shown to be detrimental in regards to carbon monoxide production.

5.6.1.6. *Frontal Velocity*

From the outset, the HM5000 was optimized for high thermal efficiency and low carbon monoxide production. Both of these objectives required measures that reduced draft (as excess air was shown to cool gas temperatures without increasing firepower). A reduction in draft, however, yields lower frontal velocities. For this reason, the combustion chamber inlet was reduced to compensate for lower total mass flow rate.

As shown in Figure 56, visible smoke is not released from the smaller combustion chamber when run with the same amount of wood as the larger chamber (where smoke is released when run with high resin pine at a high firepower).

5.6.1.7. *Field Evaluations*

At the current time, the HM5000 is in full production for distribution in Honduras. Several off-tooled units have been operating in the field for several months to collect user-feedback. Thus far, the stove has been well received; users are reporting significant reduction

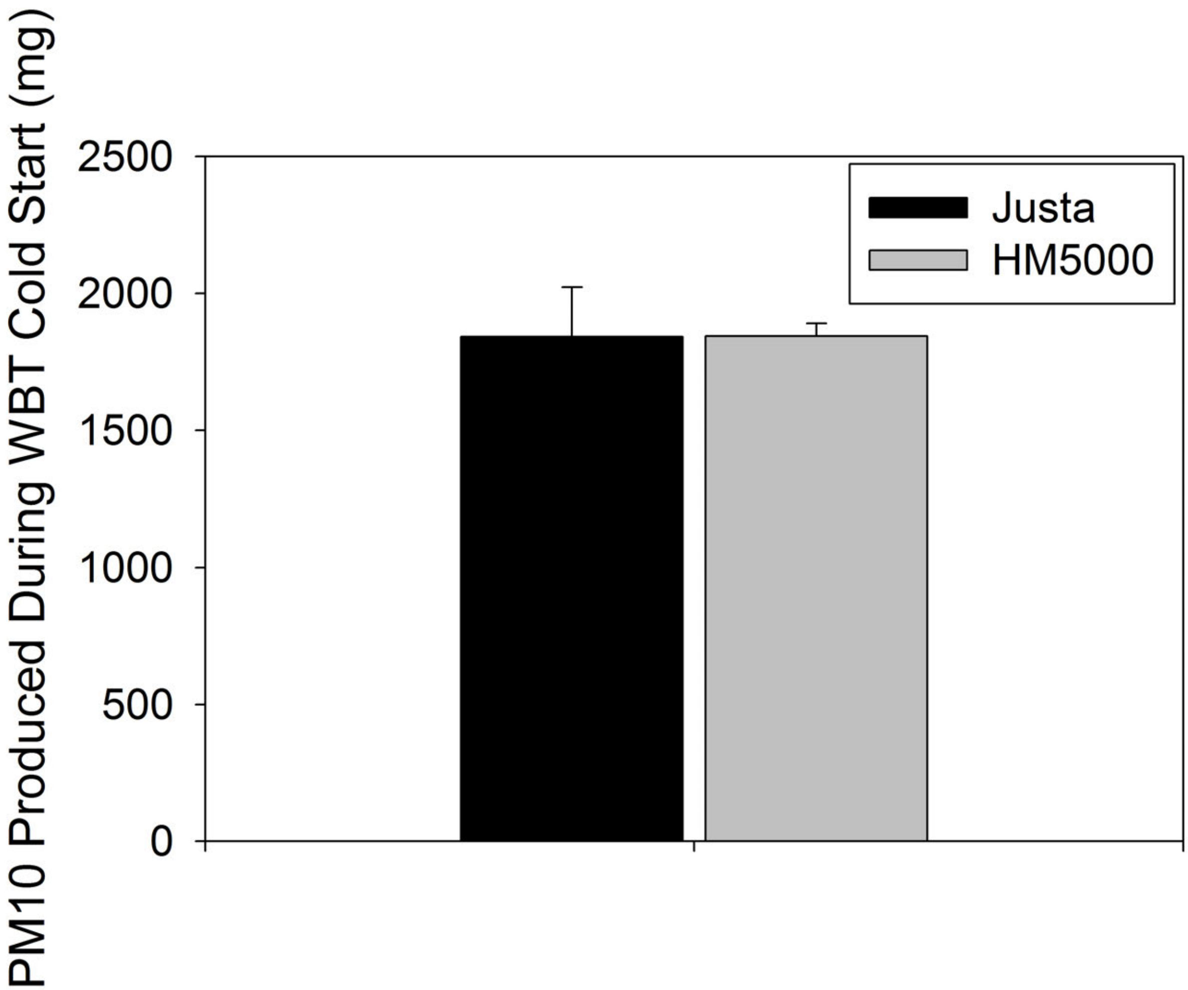


FIGURE 55. Particulate matter (10 micron and less) produced by Justa vs HM5000 during WBT cold start. Data are from three tests for the Justa and two tests for the HM5000. Bars represent standard deviation.

in wood use per month and greatly improved household air quality. As shown in Figure 57, users also seem to enjoy cooking on the newly developed stove.

5.6.1.8. *Insights from the Griddle Protocol Development*

As discussed in Section 4.10.1, contact resistance was seen as a major source of performance variability when running the water boil test on griddle stoves. The flatness, shape, size, and material of a testing pot and griddle has a large effect on heat transfer, thus, stove

FIGURE 56. Frontal velocity was increased by decreasing the cross sectional area of the combustion chamber inlet.

performance. For this reason, a new method is being developed that utilizes flexible bottom pots (made from transparent mylar) to reduce contact resistance.

In order to investigate how the thermal efficiency of a griddle stove changes with changes to the interface between the griddle and cooking pots, several tests were run with different combinations of cook pots and experimental flexible mylar pots. The three combinations tested were a) mylar pot in front, mylar pot in back b) mylar pot in front, rigid round pot in back, and c) rigid round pot in front and back. Each condition was tested in triplicate on the HM5000 stove at a wood burn rate of 20.8 +/- 2 g/s.

As shown in Figure 58, changes in cooking vessel type led to large differences in thermal efficiency. The two mylar bags, which produce a high degree of contact with the griddle surface, led to much higher thermal efficiency than the other conditions. This change in effective heat transfer has implications to other performance metrics as well. As shown in

FIGURE 57. Users interacting with the newly developed optimized plancha stove. All field trials were conducted in Honduras.

Figure 59, the time required to reach boiling was considerably lower with the mylar pot than with the rigid pot.

5.6.2. OPTIMIZATION OF TWO-POT STOVE. Given the field experiences described in Section 1.3.1, the author was motivated to optimize a two-pot style stove for higher efficiency and lower time to boil.

5.6.2.1. *Thermal Efficiency*

Information obtained through experimental (shown in Figure 60), analytical, and computational work as well as the literature [40] indicated that reducing the thickness of the gas path (on the sides of pots and underneath the pots) would lead to higher convection heat transfer.

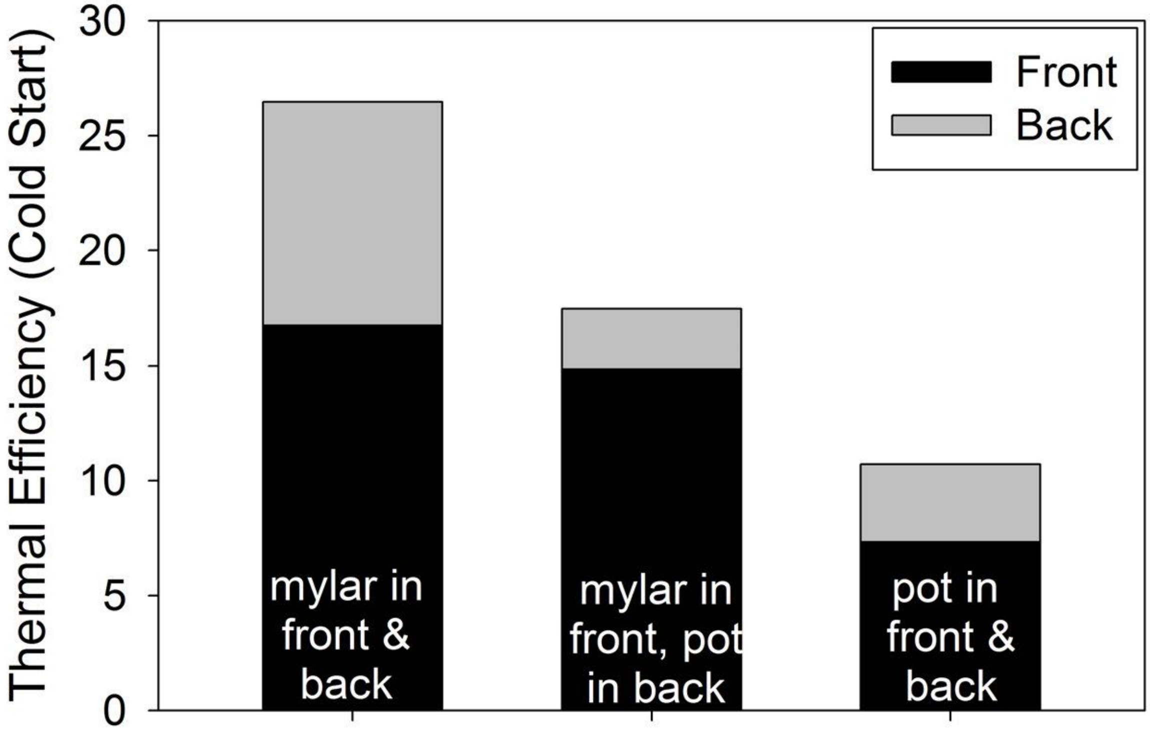


FIGURE 58. Thermal efficiency changes with different mylar bag/pot combinations. Data is from HM5000 testing. Each condition was tested in triplicate.

As can be seen in Figure 61, the HM stove achieved considerably higher thermal efficiency (average of 60 percent higher) than the Justa when using the modified WBT and rigid steel pots (1 in front of the griddle, 1 in back).

5.6.2.2. *Wood Use*

As was shown in Section 5.6.1.3, higher efficiency stoves use less wood to accomplish the same task when run at the same wood consumption rate. As shown in Figure 62, the L6040 prototype stove required 37 percent of the wood to required by the InkaWasi to complete the WBT cold start test.

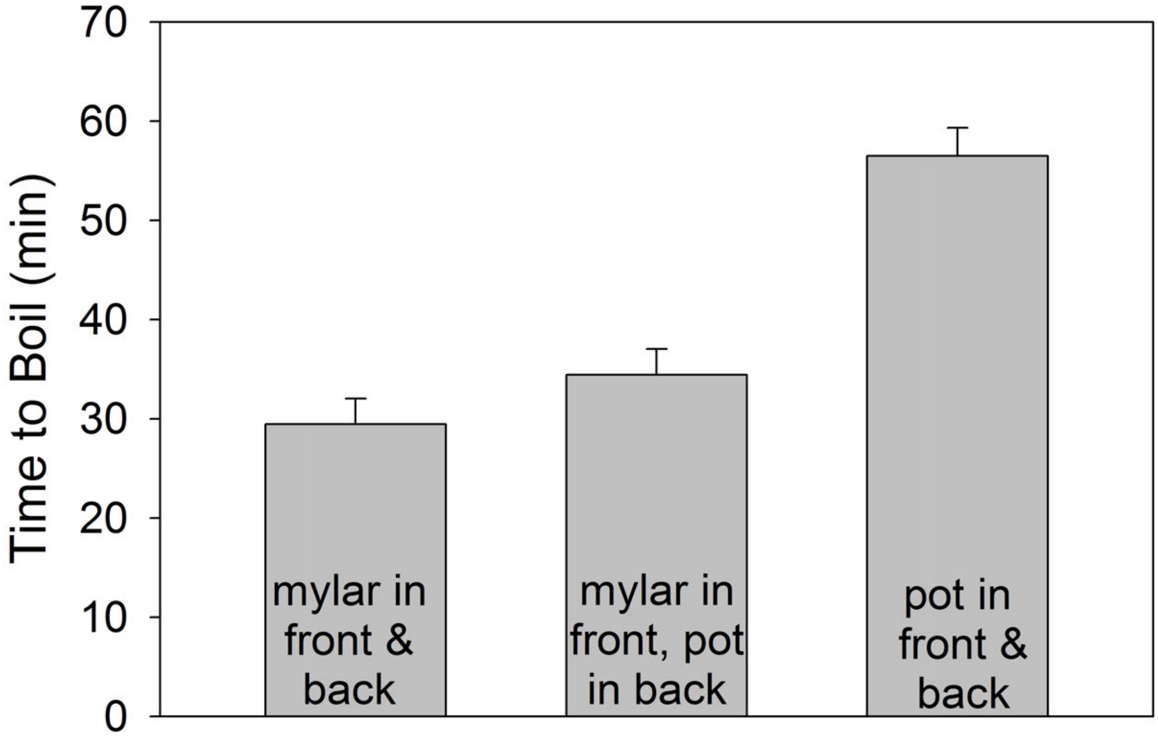


Figure 59. Time to boil changes with different mylar bag/pot combinations. Data is from HM5000 testing. Each condition was tested in triplicate. Bars represent standard deviation.

5.6.2.3. *Carbon Monoxide*

Total carbon monoxide production is also substantially lower with the L6040 stove compared to the InkaWasi, as shown in Figure 63. The reduction in carbon monoxide is likely due to hotter, more complete combustion in the low-thermal mass, insulated combustion chamber of the L6040.

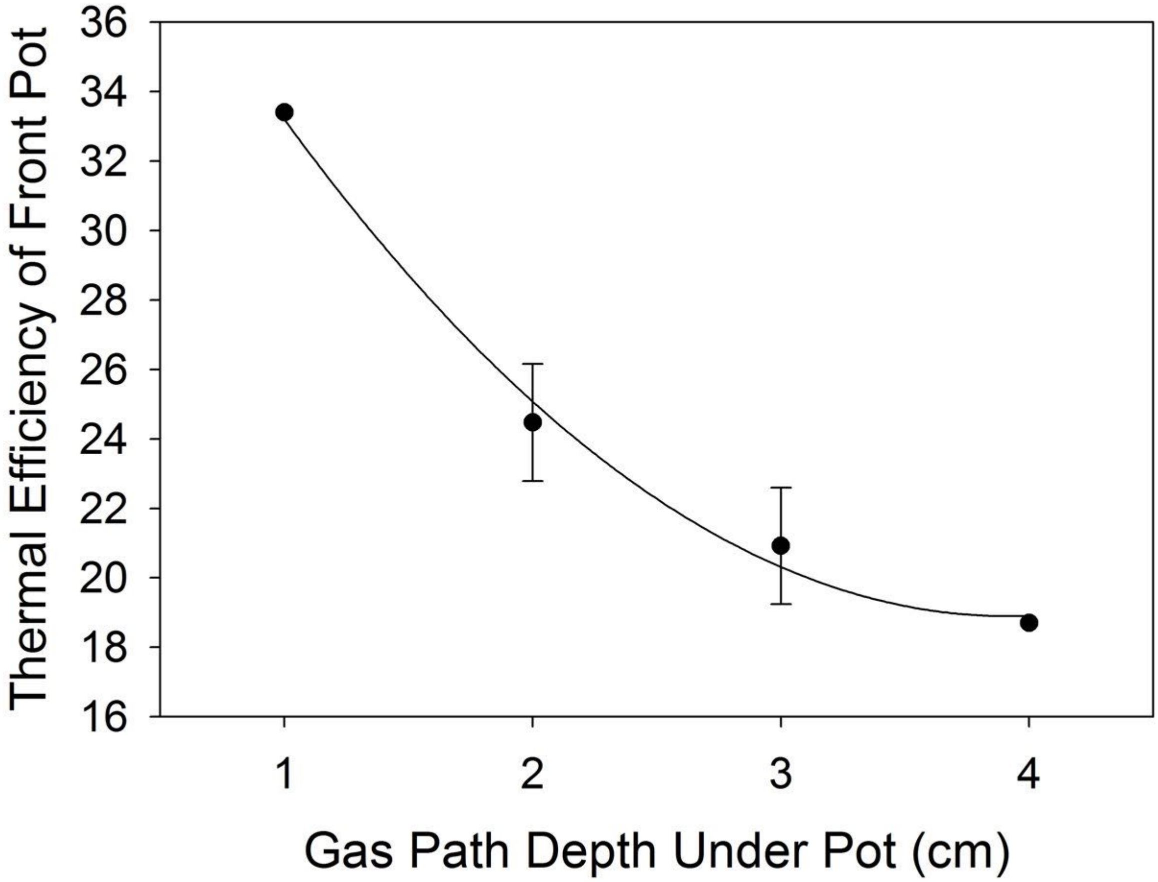


FIGURE 60. Thermal efficiency of primary pot vs pot gap. Bars represent standard deviation based on two tests.

5.7. General Considerations in the Optimization of Chimney Stoves

The analytical, experimental, and numerical modeling results all point to several common considerations when attempting to design a high performance biomass chimney stove. Many of these factors have been discussed in the literature for non-chimney stoves, but bear repeating here. Others are believed to be novel results/observations - made with the specific chimney stoves discussed in this work but applicable to ther chimney stoves as well.

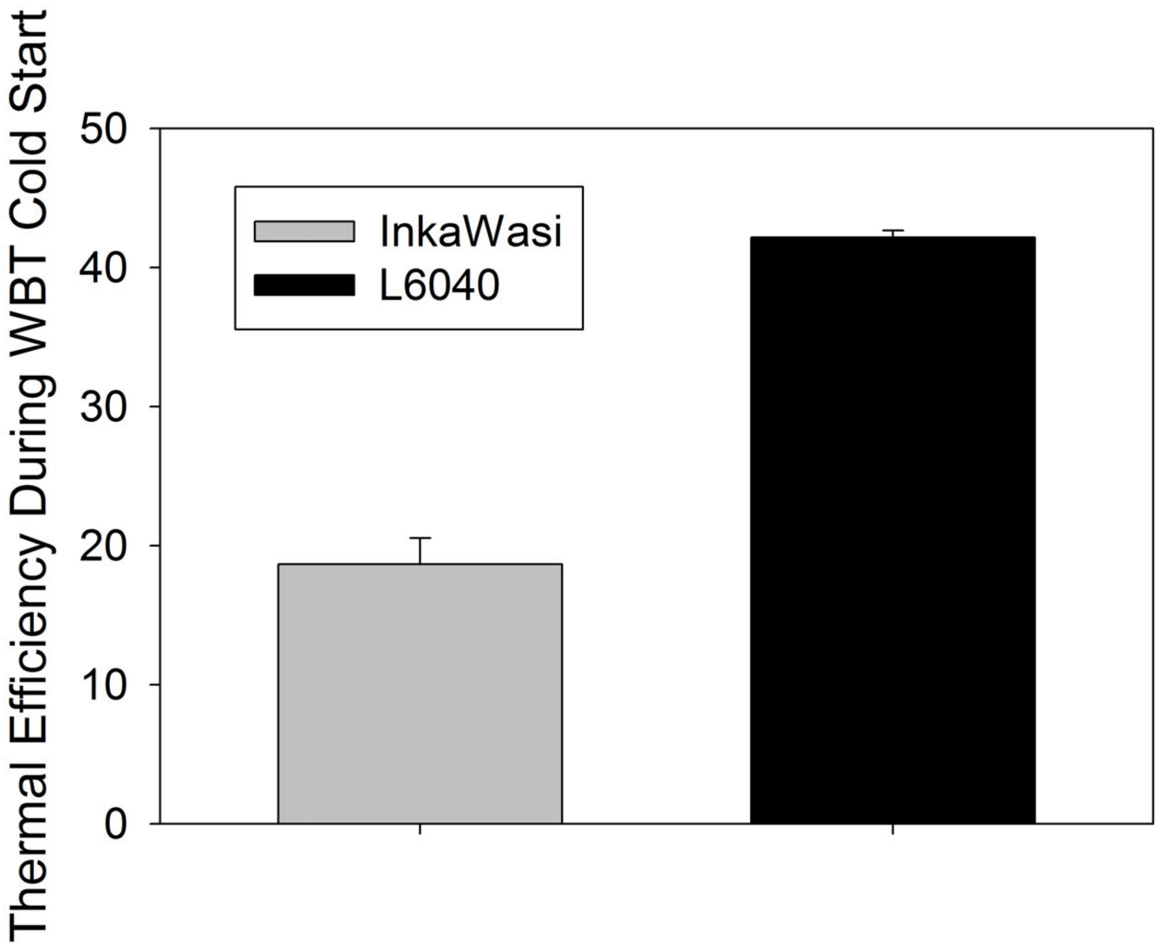


Figure 61. Thermal Efficiency for InkaWasi vs L6040 with WBT cold start. Two tests were carried out for each stove. Bars represent standard deviation.

- Chimneys have a large influence over the performance of the stove systems to which they are attached. They should be treated as an important element that deserves thoughtful design.
- Chimneys are capable of pulling relatively high amounts of air. Chimney stoves will often run with high excess air if the stove and chimney geometries have small loss coefficients.
- Related to the above point, chimney stoves tend to operate with low fuel-equivalence ratios, shown to be deleterious to combustion efficiency.

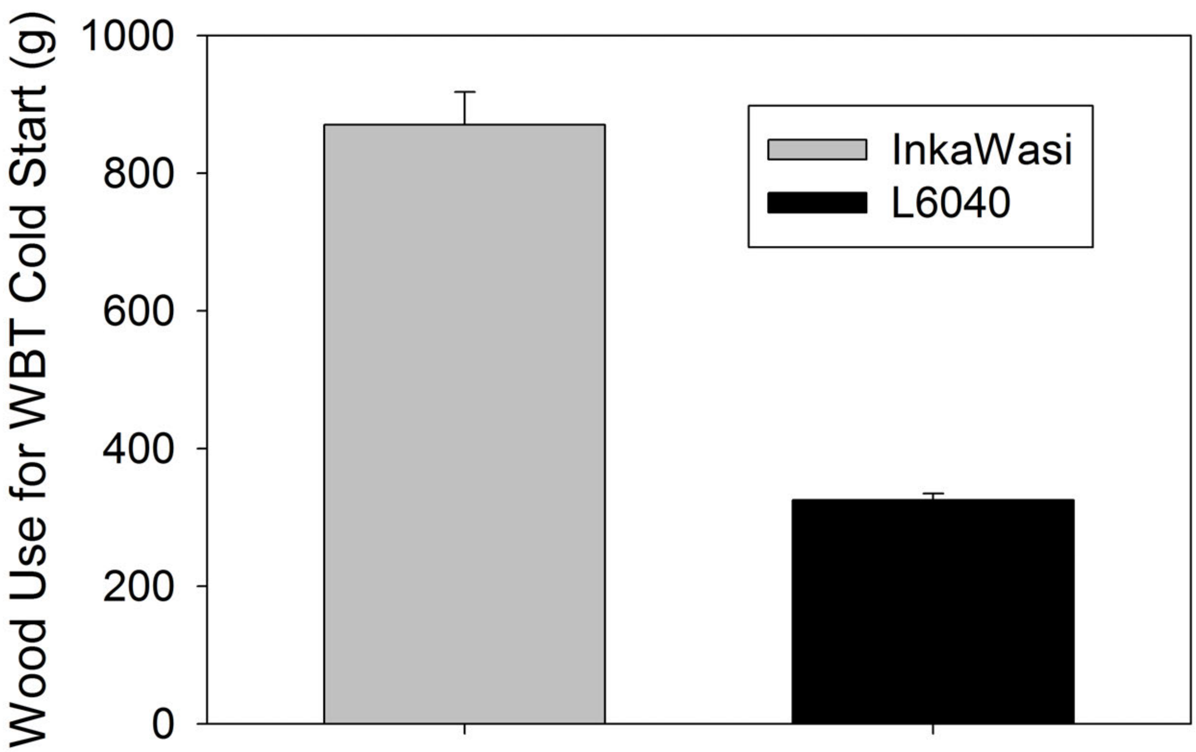


FIGURE 62. Fuel use for InkaWasi vs. L6040 for WBT cold start. Two tests were carried out for each stove. Bars represent standard deviation.

- Reducing the spacing in which flue gas flows by cooking surfaces will increase thermal efficiency to a certain point. Smaller than some minimum spacing (stove and firepower dependent), flow will be overly restricted by the narow channels, resulting in faulty operation of the stove (leaks, flame out of stove front, fire suppression from inadequate air, etc.).
- It serves several functions to keep the combustion chamber as hot as possible for a given firepower. Carbon monoxide production is reduced, thermal efficiency is increased, etc.
- Increasing the thermal efficiency of a stove for a given firepower offers several benefits
  - time to boil is reduced

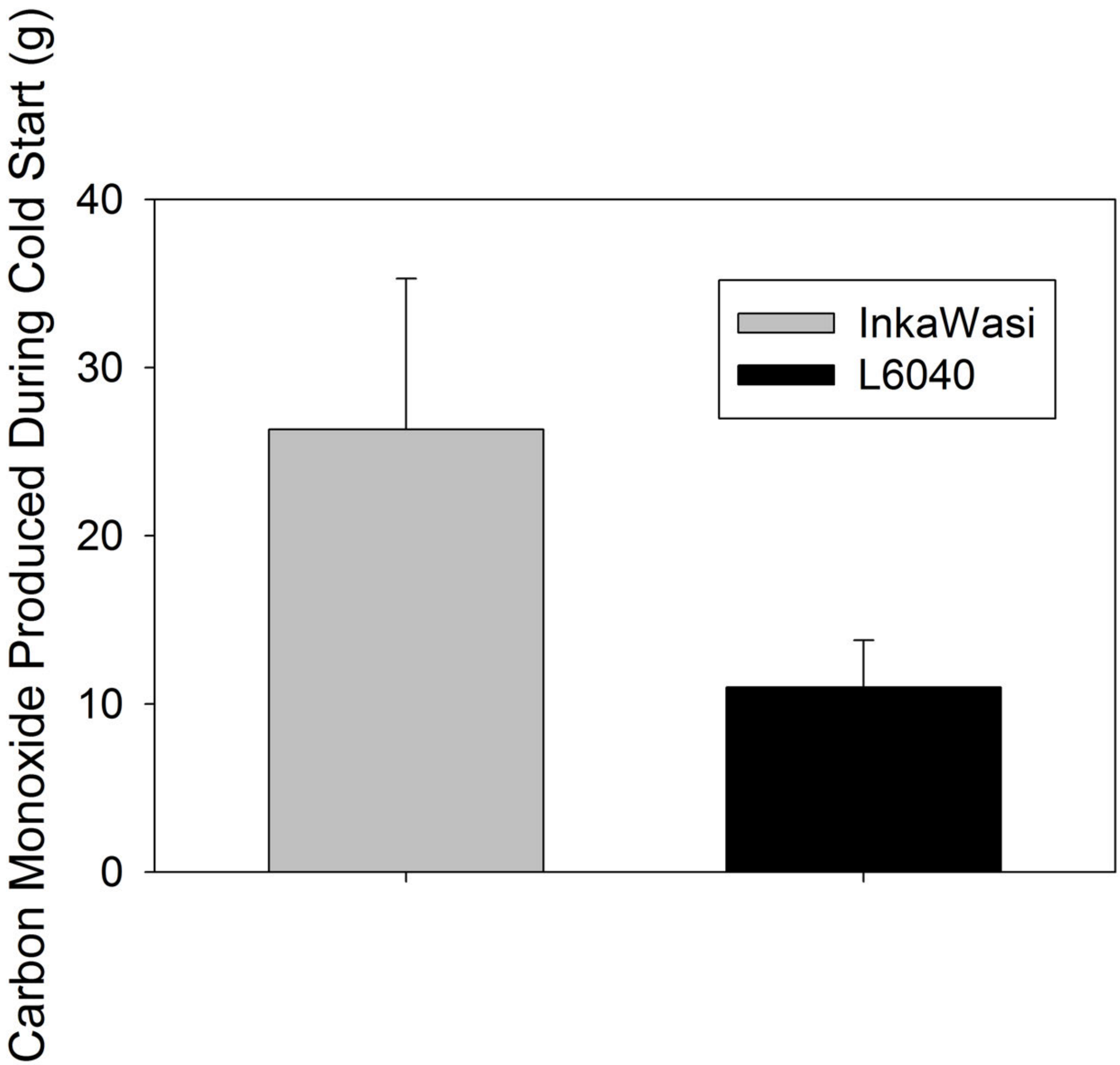


FIGURE 63. Carbon monoxide produced by Justa vs HM5000 during WBT cold start. Two tests were carried out for each stove. Bars represent standard deviation.

  - wood use is reduced
  - total emissions for a given task is reduced for a fixed emissions factor (same mass of CO produced per mass of wood consumed) since the stove is in use for less time

- Elevation can have a strong influence over the performance of a chimney stove

- Temperature loss in a single walled chimney can be significant. When attempting to understand chimney stove behavior with relatively high accuracy heat loss should be included.
- Firepower of a stove is highly dependent on surface area of the stove
- The frontal velocity (velocity of air entering the stove) is an important health consideration as it determines whether fugitive emissions will enter a home. It can be manipulated through draft and combustion chamber size.
- A chimney stove may be helpful to one person by venting emissions outdoors, but unhealthy to others who are exposed to this exhaust.
- For griddle stoves, the contact resistance between cooking apparatus (such as a pot) and heated surfaces has a significant effect on the performance of the stove.

In addition to looking toward improving the combustion environment to reduce emissions, efficiency is a means to expose users to less dangerous indoor environments. Efficient stoves use less fuel and fast stoves run for less time.

CHAPTER 6

Conclusion

6.1. Summary of Findings

Chimneys were found to have a large influence over the performance of the stove systems to which they were attached. Increased draft was shown to increase total mass flow rate. A crucial finding was the independent relationship of wood consumption rate to draft. With two different stoves, over a range of firepower, wood consumption rate was seen to change with surface area of wood within the combustion chamber, but not significantly with chimney draft. Increased draft, therefor was seen to increase the mass flow rate of air only, changing gas temperatures, the air-to-fuel ratio/Φ, and gas velocity. This laid the foundation for a simplified, lumped-parameter model of the chimney stove system.

In support of this work, a numerical model was developed in the MATLAB programming environment. The model was built to capture the interactions between heat transfer and buoyantly driven chimney flow. For simplicity and short run times, the model was set up to solve for physical parameters in one dimension (from the combustion chamber through the stove and out of the chimney). In most cases, this numerical model was shown to match experimental data with high accuracy. The model was then used to seek points of optimization for a given stove.

In experimental work combustion efficiency was shown to increase with increasing fuel equivalence ratio, Φ. Chemical kinetics simulations were run in CHEMKIN PRO by utilization of a pyrolysis gas mixture from the literature. The simulation results corroborated the experimental findings, showing optimal combustion efficiency as the air-to-fuel ratio shifted from lean toward stoichiometric.

A physical product of this work was the development of the HM5000 plancha stove. After a rigorous campaign of iterative design (including prototyping, laboratory testing, field testing, computational fluid dynamics, and numerical modeling) a wood-burning griddle stove was developed which achieves higher efficiency, lower emissions, and lower time-to boil than a popular stove in its category (Justa). During testing of this stove, it was made apparent that boiling water in standard pots on top of the plancha led to large sources of error. For this reason, a new protocol was developed for the testing of griddle stoves in collaboration with the Global Alliance for Clean Cookstoves that reduced testing error associated with pot-to-griddle contact.

A second chimney stove, the L6040 prototype, was also developed as part of this research. The improved two-pot stove showed significant efficiency gains over another improved stove in its category (the InkaWasi). This increased efficiency was achieved through optimization of the gas flow path and isolation of the cooking portion of the stove from areas with significant thermal mass. Considerable work remains in converting the L6040 from a prototype into a product.

6.2. Status of Original Goals

In Section 2.7, overall objectives for this research were described.

- Develop an experimental setup and procedures that allow for the collection of important information regarding the highly coupled behavior of natural convection chimney systems. *The Advanced Research Chimney (ARC) and associated equipment yielded important results that supported the overall understanding of the selected chimney stoves. The techniques developed to capture stove behavior (such as the* *griddle testing protocol) are expected to have continued utility within the cookstove community.*

- Develop a simplified numerical model that allows for quick estimation and optimization of chimney systems while capturing important real-world considerations, such as material properties, heat loss, fluid pressure loss, and varying power. *The numerical model developed as part of this work yielded information that proved to be accurate and useful in stove design. More complexity would be required to capture transient behavior.*
- Develop a metric to describe whether a chimney is performing well in its primary duty of ventilating combustion products out of user-occupied spaces. *Experiences from this work support the ongoing work by the Global Alliance for Clean Cookstoves to measure indoor and outdoor emissions separately for chimney stoves. The frontal velocity is believed to be the best quantifiable indicator to determine whether a stove is pulling emissions out of a chimney in a safe manner. This only works when a stove is well sealed (no leaks)*
- Develop a set of intuitive tools, such as graphical lookup charts, that aid stove designers in their development of clean, efficient, chimney stoves. *Many of the results found in Chapter 5 could be useful to designers of chimney stoves. See next item for support of this point.*
- Develop a new chimney stove that achieves superior performance in comparison to existing stoves utilizing the knowledge obtained throughout this work. *The HM5000*

and the L6040 were developed as part of this work. Both stoves were shown to provide large efficiency and emissions improvements over their traditional counterparts through laboratory testing.

The majority of the objectives set out at the beginning of this research were met. Many opportunities remain to bring further understanding and optimization strategies to chimney stoves for the developing world.

6.3. Recommended Future Work

6.3.1. Analytical. A natural extension of this work would be to develop a set of parameters that stove designers, installers, or evaluators could use to quickly estimate the performance of a particular chimney stove. Quick calculations for modified combustion efficiency and thermal efficiency based on stove geometry and firepower, for instance, would be a valuable resource for stove designers to have.

6.3.2. Modeling. One obvious choice for expansion to the current work would be to extend the numerical model into a two-dimensional domain. Particularly through more comprehensive heat transfer predictions, a two dimensional model would have increased utility for stove designers. The model should also be expanded to include stoves of different types such as two-pot and institutional stoves. Of interest is a drag-and-drop screen where designers could "build" a digital mock-up of the stove of interest; the software would then calculate estimates for the mass and heat transfer based on the virtual geometry provided.

In combination with more extensive experimental validation, it would be valuable to predict and/or describe the steady state firepower of a stove from easily measurable quantities such as fuel geometry, moisture content, and density. With this knowledge in hand, stoves could be run at their intended operating points through simple instructions on fuel selection/preparation and loading.

Another opportunity for modeling revolves around atmospheric considerations of chimney stoves. Having knowledge of the gas constituents, temperature, and velocity exiting a chimney could allow for interesting studies on local, regional, and global pollution modeling.

Computational fluid dynamics was not utilized extensively as part of this work due to (a) software access limitations for the intended global audience and (b) inability for models to be run quickly and simply. It would nevertheless be of interest to compare results of CFD simulations to the one-dimensional numerical model and experimental data.

6.3.3. Experimental.

6.3.3.1. *PM Minimization*

Several insights obtained during this work suggest the need for further experimental investigation into chimney systems to understand the overall performance of these systems. While strong correlations were found to exist between excess air and carbon monoxide emissions, particulate matter was found to follow less predictable trends. One of the issues involved a lack of reliable real-time particulate matter sensing. While an in-line nephalometer was utilized for the majority of tests, it produced results that varied greatly among replicates, suggesting issues with the instrument or a real variability in PM production from chimney stoves that would require significant further work to understand.

6.3.3.2. *Mixing Air*

As a form of pressure, draft can be utilized to produce higher volume lower pressure flow or lower volume higher pressure flow. The relatively open nature of the combustion chamber inlets tested in this work promotes lower Reynolds flow of air into the combustion chamber. Utilizing draft to inject less air into the combustion chamber at a higher velocity would increase the local Reynolds number in th combustion zone, promoting more efficient mixing of air and fuel without excessively cooling the combustion zone. This could provide significant benefits to combustion.

6.3.4. Stove Design.

6.3.4.1. *Developing World Domestic Fume Hood*

Perhaps the best way to address a global need for improved indoor air quality is to decouple ventilation from the cooking system. With a properly designed fume hood, a wide variety of stoves (traditional or improved) could be run indoors with assurance that pollutants were being exhausted from homes. Having a stove running under a fume hood could allow for stoves to run at lower excess air, perhaps increasing thermal efficiency and reducing carbon monoxide production in accordance with the results from this work. There is evidence in the literature of such systems being highly effective [105].

6.3.4.2. *Semi-gasifier*

Many of the semi-gasifier stoves that have been designed for the developing world and camping markets make use of powered fans to deliver primary and secondary air to the combustion chamber. As shown in this work, a chimney is capable of inducing flow that is of the magnitude of the fans that are used in these systems. Furthermore, semi-gasifiers can produce dangerous emissions during smoldering events primarily during start-up, shut-down, and fuel addition. A chimney-outfitted gasifier could allow for off-grid air addition to accomplish gasification with an exhaust to ensure indoor emissions remain low.

6.3.4.3. *Catalytic Chimney Stoves*

In the developed world advanced chimney technologies, such as noble metal catalysts, have been applied to wood burning appliances for decades [106, 107, 108]. Experts have been calling for the incorporation of this technology in developing world stoves for nearly as long [10], but there have been cost limitations. It is worth investigating whether a catalyst yet exists that could reduce emissions from biomass stoves without putting the stove cost out of reach of developing world users.

Bibliography

[1] B. Agarwal, "Diffusion of rural innovations: some analytical issues and the case of wood-burning stoves," *World Development*, vol. 11, no. 4, pp. 359–376, 1983.

[2] E. Boy, N. Bruce, and H. Delgado, "Birth weight and exposure to kitchen wood smoke during pregnancy in rural guatemala.," *Environmental Health Perspectives*, vol. 110, pp. 109–114, Jan. 2002.

[3] N. Bruce, J. McCracken, R. Albalak, M. A. Schei, K. R. Smith, V. Lopez, and C. West, "Impact of improved stoves, house construction and child location on levels of indoor air pollution exposure in young guatemalan children," *J Expo Anal Environ Epidemiol*, vol. 14, no. S1, pp. S26–S33, 0.

[4] M. Ezzati, D. Kammen, *et al.*, "Indoor air pollution from biomass combustion and acute respiratory infections in kenya: an exposure-response study," *Lancet*, vol. 358, no. 9282, pp. 619–624, 2001.

[5] D. G. Fullerton, N. Bruce, and S. B. Gordon, "Indoor air pollution from biomass fuel smoke is a major health concern in the developing world," *Transactions of the Royal Society of Tropical Medicine and Hygiene*, vol. 102, no. 9, pp. 843–851, 2008.

[6] W. J. Martin, R. I. Glass, J. M. Balbus, and F. S. Collins, "A major environmental cause of death," *Science*, vol. 334, pp. 180 –181, Oct. 2011.

[7] K. R. Smith, J. M. Samet, I. Romieu, and N. Bruce, "Indoor air pollution in developing countries and acute lower respiratory infections in children," *Thorax*, vol. 55, no. 6, pp. 518–532, 2000.

[8] G. W. Traynor, M. G. Apte, A. R. Carruthers, J. F. Dillworth, D. T. Grimsrud, and L. A. Gundel, "Indoor air pollution due to emissions from wood-burning stoves," *Environmental science & technology*, vol. 21, no. 7, pp. 691–697, 1987.

[9] L. S. Pheng, "Techniques for environmental control and structural integrity of buildings in ancient china," *Structural Survey*, vol. 22, no. 5, pp. 271–281, 2004.

[10] K. R. Smith, "Dialectics of improved stoves," *Economic and Political Weekly*, vol. 24, pp. 517–522, Mar. 1989.

[11] K. Dutta, K. N. Shields, R. Edwards, and K. R. Smith, "Impact of improved biomass cookstoves on indoor air quality near pune, india," *Energy for Sustainable Development*, vol. 11, no. 2, pp. 19–32, 2007.

[12] S. M. Hartinger, A. A. Commodore, J. Hattendorf, C. F. Lanata, A. I. Gil, H. Verastegui, M. Aguilar-Villalobos, D. Musezahl, and L. P. Naeher, "Chimney stoves modestly improved indoor air quality measurements compared with traditional open fire stoves: results from a small-scale intervention study in rural peru," *Indoor Air*, p. n/an/a, 2013.

[13] J. P. McCracken, K. R. Smith, A. Diaz, M. A. Mittleman, and J. Schwartz, "Chimney stove intervention to reduce long-term wood smoke exposure lowers blood pressure among guatemalan women," *Environmental Health Perspectives*, vol. 115, pp. 996–1001, July 2007.

[14] V. Joshi, C. Venkataraman, and D. R. Ahuja, "Emissions from burning biofuels in metal cookstoves," *Environmental Management*, vol. 13, no. 6, pp. 763–772, 1989.

[15] P. C. Roy, A. Datta, and N. Chakraborty, "Assessment of cow dung as a supplementary fuel in a downdraft biomass gasifier," *Renewable Energy*, vol. 35, no. 2, pp. 379–386,

2010.

[16] HERA, "Inkawasi uk stove technical brochure," 2012.

[17] G. L. Urban, K. M. Bryden, and D. A. Ashlock, "Engineering optimization of an improved plancha stove," *Energy for Sustainable Development*, vol. 6, no. 2, pp. 9–19, 2002.

[18] J. Kammerbauer and C. Ardon, "Land use dynamics and landscape change pattern in a typical watershed in the hillside region of central honduras," *Agriculture, ecosystems & environment*, vol. 75, no. 1, pp. 93–100, 1999.

[19] W. C. Flores, O. A. Ojeda, M. A. Flores, and F. R. Rivas, "Sustainable energy policy in honduras: Diagnosis and challenges," *Energy Policy*, vol. 39, no. 2, pp. 551–562, 2011.

[20] L. Tacconi, *Illegal logging: law enforcement, livelihoods and the timber trade*. Earthscan, 2007.

[21] G. G. Stevenson, "The production, distribution, and consumption of fuelwood in haiti," *The Journal of Developing Areas*, pp. 59–76, 1989.

[22] J. A. Carcamo, J. Alwang, and G. W. Norton, "On-site economic evaluation of soil conservation practices in honduras," *Agricultural Economics*, vol. 11, no. 2, pp. 257–269, 1994.

[23] D. Still and L. Winiarski, "Increasing fuel efficiency and reducing harmful emissions in traditional cooking stoves," *Boiling Point*, vol. 47, pp. 36–39, 2001.

[24] M. L. Clark, J. L. Peel, J. B. Burch, T. L. Nelson, M. M. Robinson, S. Conway, A. M. Bachand, and S. J. Reynolds, "Impact of improved cookstoves on indoor air pollution and adverse health effects among honduran women," *International journal*

of environmental health research, vol. 19, no. 5, pp. 357–368, 2009.

[25] C. Roden, T. Bond, S. Conway, B. Osorto Pinel, and N. Maccarty, "Factors leading to variability of emission factors, single scattering albedo, and elemental carbon fraction from biofuel emissions," in *AGU Fall Meeting Abstracts*, vol. 1, p. 0985, 2006.

[26] B. D. Saatkamp, O. R. Masera, and D. M. Kammen, "Energy and health transitions in development: fuel use, stove technology, and morbidity in jar cuaro, m xico," *Energy for Sustainable Development*, vol. 4, no. 2, pp. 7–16, 2000.

[27] D. F. Barnes, K. Openshaw, K. R. Smith, R. Van der Plas, and B. Mundial, *What Makes People Cook with Improved Biomas Stoves?* Banco Mundial, 1994.

[28] I. Jan, "What makes people adopt improved cookstoves? empirical evidence from rural northwest pakistan," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 5, pp. 3200–3205, 2012.

[29] M. Pinnell, "Work in progress-when service-learning is a failure," in *Frontiers in Education, 2005. FIE'05. Proceedings 35th Annual Conference*, pp. F4F–16, IEEE, 2005.

[30] P. G. Burnet, N. G. Edmisten, P. E. Tiegs, J. E. Houck, and R. A. Yoder, "Particulate, carbon monoxide, and acid emission factors for residential wood burning stoves," *Journal of the air pollution control association*, vol. 36, no. 9, pp. 1012–1018, 1986.

[31] K. Wallmo, S. K. Jacobson, *et al.*, "A social and environmental evaluation of fuel-efficient cook-stoves and conservation in uganda," *Environmental Conservation*, vol. 25, no. 2, pp. 99–108, 1998.

[32] R. D. Peacock, "Chimney fires: Intensity and duration," *Fire technology*, vol. 22, no. 3, pp. 234–252, 1986.

[33] M. D. Mumford, "Social innovation: ten cases from benjamin franklin," *Creativity research journal*, vol. 14, no. 2, pp. 253–266, 2002.

[34] P. L. Marks, *Chimneys and Flues: Domestic and Industrial*. Schauffler Press, 2008.

[35] H. Shoub, *Survey of Literature on the Safety of Residential Chimneys and Fireplaces*, vol. 252. US Government Printing Office, 1963.

[36] G. NFPA, "211-standard for chimneys," *Fireplaces, Vents, and Solid Fuel-Burning Appliances*.

[37] L. Cottone and E. Messer, *Test Method Evaluations and Emissions Testing for Rating Wood Stoves*. US Environmental Protection Agency, Air and Energy Engineering Research Laboratory, 1987.

[38] W. Funk, "When smoke gets in your eyes: Regulatory negotiation and the public interest-epa's woodstove standards," *Envtl. L.*, vol. 18, p. 55, 1987.

[39] J. F. Kowalczyk and B. J. Tombleson, "Oregons woodstove certification program," *Journal of the Air Pollution Control Association*, vol. 35, no. 6, pp. 619–625, 1985.

[40] S. F. Baldwin, *Biomass stoves: engineering design, development, and dissemination*. Volunteers in Technical Assistance, 1987.

[41] M. Johnson, R. Edwards, C. Alatorre Frenk, and O. Masera, "In-field greenhouse gas emissions from cookstoves in rural mexican households," *Atmospheric Environment*, vol. 42, no. 6, pp. 1206–1222, 2008.

[42] R. W. Allen, S. Leckie, G. Millar, and M. Brauer, "The impact of wood stove technology upgrades on indoor residential air quality," *Atmospheric Environment*, vol. 43, no. 37, pp. 5908–5915, 2009.

[43] B. Gebhart, Y. Jaluria, R. L. Mahajan, and B. Sammakia, “Buoyancy-induced flows and transport,” 1988.

[44] F. P. Incropera, A. S. Lavine, and D. P. DeWitt, *Fundamentals of heat and mass transfer*. John Wiley & Sons Incorporated, 2011.

[45] M. J. Moran, H. N. Shapiro, B. R. Munson, and D. P. DeWitt, *Introduction to Thermal Systems Engineering*. John Wiley and Sons, Inc,, 2003.

[46] A. F. Mills and A. Mills, *Basic heat and mass transfer*, vol. 2. Prentice hall Upper Saddler River, NJ, 1999.

[47] D. D. Gray and A. Giorgini, “The validity of the boussinesq approximation for liquids and gases,” *International Journal of Heat and Mass Transfer*, vol. 19, no. 5, pp. 545–551, 1976.

[48] F. Incropera and D. DeWitt, “Introduction to heat transfer,” 1985.

[49] S. K. Saarikoski, M. K. Sillanpää, K. M. Saarnio, R. E. Hillamo, A. S. Pennanen, and R. O. Salonen, “Impact of biomass combustion on urban fine particulate matter in central and northern europe,” *Water, Air, and Soil Pollution*, vol. 191, no. 1-4, pp. 265–277, 2008.

[50] P. R. Achenbach, “Physics of chimneys,” *Physics Today*, vol. 2, p. 18, 1949.

[51] P. Achenbach and D. Cole, “Performance of fourteen masonry chimneys under steady state conditions,” *ASHVE Transactions*, vol. 55, p. 147, 1949.

[52] W. Brown and W. Colborne, “Fundamentals of chimney performance,” *Canadian Journal of Technology*, vol. 34, 1956.

[53] W. G. Brown and C. Wachmann, “Draft performance of chimneys,” *ASHRAE Journal*, vol. 2, no. 9, pp. 49–54, 1960.

[54] L. Schmitt and R. Engdahl, "Performance of residential chimneys," *Heating, Piping, Air Condng*, vol. 20, no. 11, pp. 111–118, 1948.

[55] V. I. Hanby, *Combustion and pollution control in heating systems.* Springer-Verlag, 1994.

[56] C. Cortés and A. Campo, "Rapid computation of the exit temperature of hot combustion gases flowing inside chimneys," *Applied thermal engineering*, vol. 19, no. 9, pp. 969–990, 1999.

[57] U. Lacoa and A. Campo, "Teaching technique for internal forced convection flows through tubes cooled or heated by external natural convection. ii. vertical orientation," *Computer Applications in Engineering Education*, vol. 5, no. 3, pp. 153–160, 1997.

[58] J. N. Agenbroad, "A simplified model for understanding natural convection driven biomass cooking stoves," Master's thesis, Colorado State University, 2010.

[59] D. J. Zube, "Heat transfer efficiency of biomass cookstoves," Master's thesis, Colorado State University, 2010.

[60] *2012 Ashrae Handbook: Heating, Ventilating, and Air-Conditioning Systems and Equipment: Inch-Pound Edition.* ASHRAE, June 2012.

[61] L. F. Moody, "Friction factors for pipe flow," *Trans. Asme*, vol. 66, no. 8, pp. 671–684, 1944.

[62] P. K. Swamee and A. K. Jain, "Explicit equations for pipe-flow problems," *Journal of the hydraulics division*, vol. 102, no. 5, pp. 657–664, 1976.

[63] M. Z. Jacobson, *Fundamentals of atmospheric modeling.* Cambridge University Press, 2005.

[64] C. Fitzsimmons, "New developments in chimneys and flues," *National Fire Protection Association Quarterly*, p. 6, 1944.

[65] J. P. Catchpole and G. Fulford, "Dimensionless groups," *Industrial & Engineering Chemistry*, vol. 58, no. 3, pp. 46–60, 1966.

[66] E. L. Keating, *Applied combustion.* CRC Press, 2007.

[67] B. Jenkins, L. Baxter, T. Miles Jr, and T. Miles, "Combustion properties of biomass," *Fuel processing technology*, vol. 54, no. 1, pp. 17–46, 1998.

[68] A. Demirbas, "Combustion characteristics of different biomass fuels," *Progress in energy and combustion science*, vol. 30, no. 2, pp. 219–230, 2004.

[69] F. L. Browne, *Theories of the Combustion of Wood and Its Control: A Survey of the Literature.* Forest Products Laboratory, 1963.

[70] S. B. Kausley and A. B. Pandit, "Modelling of solid fuel stoves," *Fuel*, vol. 89, pp. 782–791, Mar. 2010.

[71] K. Ragland, D. Aerts, and A. Baker, "Properties of wood for combustion analysis," *Bioresource Technology*, vol. 37, no. 2, pp. 161–168, 1991.

[72] D. A. Tillman, *Wood Combustion: Principle, Processes, and Economics.* Academic Press, 1981.

[73] D. D. Miller-Lionberg, "A fine resolution cfd simulation approach for biomass cook stove development," Master's thesis, Colorado State University, 2011.

[74] E. Ranzi, A. Cuoci, T. Faravelli, A. Frassoldati, G. Migliavacca, S. Pierucci, and S. Sommariva, "Chemical kinetics of biomass pyrolysis," *Energy & Fuels*, vol. 22, pp. 4292–4300, Nov. 2008.

[75] J. J. Manya, E. Velo, and L. Puigjaner, "Kinetics of biomass pyrolysis: a reformulated three-parallel-reactions model," *Industrial & Engineering Chemistry Research*, vol. 42, pp. 434–441, Feb. 2003.

[76] T. Hosoya, H. Kawamoto, and S. Saka, "Cellulosehemicellulose and celluloselignin interactions in wood pyrolysis at gasification temperature," *Journal of Analytical and Applied Pyrolysis*, vol. 80, pp. 118–125, Aug. 2007.

[77] R. Radmanesh, Y. Courbariaux, J. Chaouki, and C. Guy, "A unified lumped approach in kinetic modeling of biomass pyrolysis," *Fuel*, vol. 85, pp. 1211–1220, June 2006.

[78] G. A. Ban-Weiss, J. Chen, B. A. Buchholz, and R. W. Dibble, "A numerical investigation into the anomalous slight no¡ sub¿ x¡/sub¿ increase when burning biodiesel; a new (old) theory," *Fuel processing technology*, vol. 88, no. 7, pp. 659–667, 2007.

[79] G. Barozzi, M. Imbabi, E. Nobile, and A. Sousa, "Physical and numerical modelling of a solar chimney-based ventilation system for buildings," *Building and environment*, vol. 27, no. 4, pp. 433–445, 1992.

[80] A. Gosman and E. Loannides, "Aspects of computer simulation of liquid-fueled combustors," *Journal of Energy*, vol. 7, no. 6, pp. 482–490, 1983.

[81] M. Jureczko and M. Pawlak, "Optimisation of wind turbine blades," *Journal of Materials Processing Technology*, vol. 167, no. 2, pp. 463–471, 2005.

[82] J. Gill, "Improved stoves in developing countries: A critique," *Energy Policy*, vol. 15, no. 2, pp. 135–144, 1987.

[83] Y. A. Cengel, M. A. Boles, and M. Kanoğlu, *Thermodynamics: an engineering approach*, vol. 5. McGraw-Hill New York, 2011.

[84] E. Toolbox, "Air-absolute and kinematic viscosity." Accessed: 2013.

[85] C. Ryu, Y. B. Yang, A. Khor, N. E. Yates, V. N. Sharifi, and J. Swithenbank, "Effect of fuel properties on biomass combustion: Part i. experimentsfuel type, equivalence ratio and particle size," *Fuel*, vol. 85, no. 7, pp. 1039–1046, 2006.

[86] T. R. Melton, F. Inal, and S. M. Senkan, "The effects of equivalence ratio on the formation of polycyclic aromatic hydrocarbons and soot in premixed ethane flames," *Combustion and flame*, vol. 121, no. 4, pp. 671–678, 2000.

[87] F. Inal and S. M. Senkan, "Effects of equivalence ratio on species and soot concentrations in premixed n-heptane flames," *Combustion and flame*, vol. 131, no. 1, pp. 16–28, 2002.

[88] J. H. Chen, "Petascale direct numerical simulation of turbulent combustionfundamental insights towards predictive models," *Proceedings of the Combustion Institute*, vol. 33, no. 1, pp. 99–123, 2011.

[89] M. S. Day, X. Gao, and J. B. Bell, "Properties of lean turbulent methane-air flames with significant hydrogen addition," *Proceedings of the Combustion Institute*, vol. 33, no. 1, pp. 1601–1608, 2011.

[90] D. S. ROSS, "Welders' metal fume fever," *Occupational Medicine*, vol. 24, no. 4, pp. 125–129, 1974.

[91] N. MacCarty, D. Ogle, D. Still, T. Bond, and C. Roden, "A laboratory comparison of the global warming impact of five major types of biomass cooking stoves," *Energy for Sustainable Development*, vol. 12, no. 2, pp. 56–65, 2008.

[92] D. Champier, J. Bedecarrats, M. Rivaletto, and F. Strub, "Thermoelectric power generation from biomass cook stoves," *Energy*, vol. 35, no. 2, pp. 935–942, 2010.

[93] J. J. Jetter and P. Kariher, “Solid-fuel household cook stoves: characterization of performance and emissions,” *Biomass and Bioenergy*, vol. 33, no. 2, pp. 294–305, 2009.

[94] C. C. P. L’Orange, “Testing methodologies for biomass cook stoves and their effects on emissions,” Master’s thesis, Colorado State University, 2009.

[95] J. Sweet, E. Roth, and M. Moss, “Thermal conductivity of inconel 718 and 304 stainless steel,” *International journal of thermophysics*, vol. 8, no. 5, pp. 593–606, 1987.

[96] I. Glassman, *Combustion*. Academic press, 1997.

[97] P. M. Fine, G. R. Cass, and B. R. Simoneit, “Chemical characterization of fine particle emissions from the wood stove combustion of prevalent united states tree species,” *Environmental Engineering Science*, vol. 21, no. 6, pp. 705–721, 2004.

[98] P. Thomas, M. Bullen, J. Quintiere, and B. McCaffrey, “Flashover and instabilities in fire behavior,” *Combustion and Flame*, vol. 38, pp. 159–171, 1980.

[99] F. Ma, Y. Wang, H. Liu, Y. Li, J. Wang, and S. Zhao, “Experimental study on thermal efficiency and emission characteristics of a lean burn hydrogen enriched natural gas engine,” *International Journal of Hydrogen Energy*, vol. 32, no. 18, pp. 5067–5075, 2007.

[100] V. Kouprianov and V. Tanetsakunvatana, “Optimization of excess air for the improvement of environmental performance of a 150 mw boiler fired with thai lignite,” *Applied energy*, vol. 74, no. 3, pp. 445–453, 2003.

[101] X. Jun, X. Sun, S. Hu, and D. Yu, “An experimental research on boiler combustion performance,” *Fuel Processing Technology*, vol. 68, no. 2, pp. 139–151, 2000.

[102] L. Johansson, C. Tullin, B. Leckner, and P. Sjövall, “Particle emissions from biomass combustion in small combustors,” *Biomass and Bioenergy*, vol. 25, no. 4, pp. 435–446,

2003.

[103] R. F. Coburn, "Mechanisms of carbon monoxide toxicity," *Preventive medicine*, vol. 8, no. 3, pp. 310–322, 1979.

[104] R. L. Stone, "Fireplace operation depends upon good chimney design," *ASHRAE Journal*, vol. 63, 1969.

[105] J. Ramakrishna, M. Durgaprasad, and K. R. Smith, "Cooking in india: the impact of improved stoves on indoor air quality," *Environment International*, vol. 15, no. 1, pp. 341–352, 1989.

[106] P. Burnet, "The northeast cooperative woodstove study," *Volume I, EPA-600/7-87-026a, and*, vol. 2, 1987.

[107] R. C. McCrillis, R. R. Watts, and S. H. Warren, "Effects of operating variables on pah emissions and mutagenicity of emissions from woodstoves," *Journal of the Air & Waste Management Association*, vol. 42, no. 5, pp. 691–694, 1992.

[108] E. Karlsvik and O. K. Sønju, "Emissions from wood stoves and fireplaces," *Advances in Thermochemical Biomass Conversion*, pp. 690–707, 1993.

APPENDIX A

Additional Data and Results

1.1. The Issue of Ocote

An unexpected challenge related to the development of the HM5000 plancha stove involved users in the field fueling it with pitchy pine. In Honduras a wood type, regionally referred to as ocote, is commonly used as kindling. In the US, this wood is commonly referred to as fatwood. The wood is high in resin, resulting in extremely smoke fires. Some users in Honduras use this wood as their main fuel, choosing to trade air quality for easy start up.

An earlier iteration of the HM5000 had smaller gas path gaps to optimize heat transfer. During field trials, stoves would begin to clog after only a few days of use. Ocote was identified as the culprit. As seen in Figure 64, the underside of the plancha and gas path had significant deposits of ocote particles which restricted flow to the chimney.

Figure 64 reveals an important reality of stove design: People will burn the fuel that is available and convenient to them. This required a complete redesign of the stove geometry to allow for ocote particles to accumulate for much longer without restricitng flow. This required a small drop in thermal efficiency, but allowed for a much more usable stove to a large population of Hondurans.

1.2. Further Elevation Modeling

As shown in Figure **??**, the mass flow rate induced by the chimney effect is heavily dampened by increasing elevation. This is expected given the drop in barometric pressure discussed in Section 2.3.3.

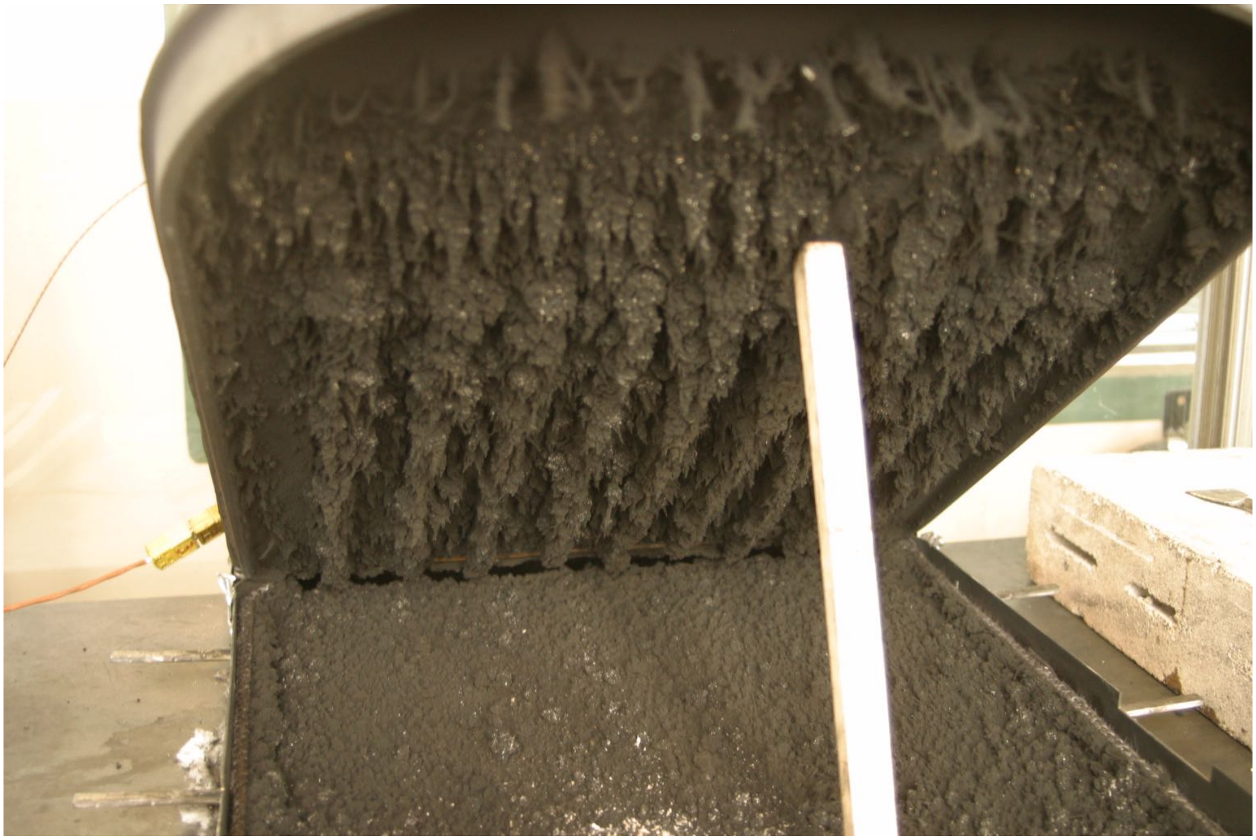


FIGURE 64. Use of pitchy pine in previous version of the HM5000 after several hours of use

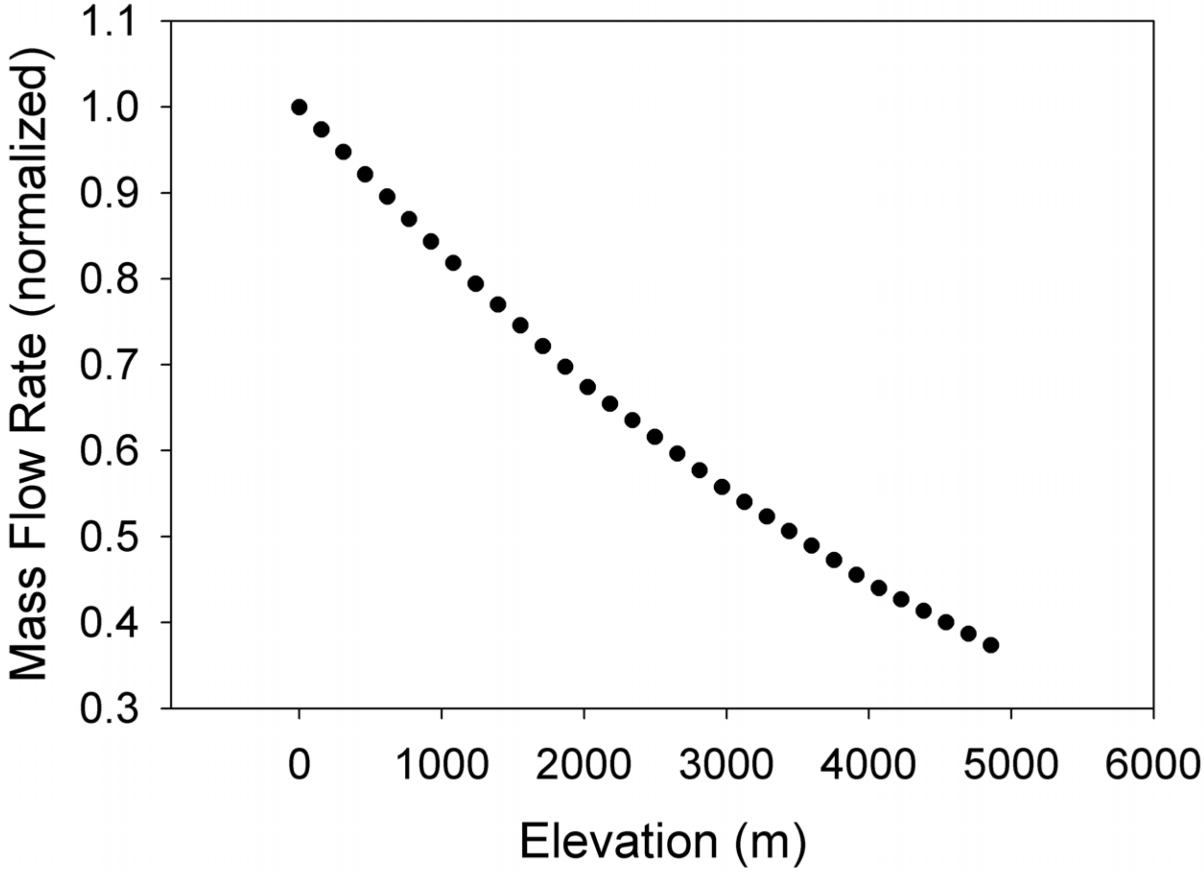


FIGURE 65. The modeled effect of elevation on total masss flow.

APPENDIX B

Matlab Scripts for Numerical Model

2.1. Matlab Scripts

The following contains one version of the script developed for stove modeling and optimization. Many of the parameters listed in the selected script change according to the stove being modeled.

```
%This is a program to model the performance of a solid fuel
%chimney outfited system
clear all
clc

% CONSTANTS
%Constants
g = 9.81; %gravity m/s^2
e_sb = 5.67*10^-8; %stefan boltzmann constant, W/(m^2K^4)
R_univ = 8314; %universal gas constant
emiss_fire = 1; %stand in value for emissivity of fire for
%radiation calc

MW_flue = 29; % molecular weight of flue gas from Hanby
%eventually dependent on fuel, moisture content, A/F, etc.

MW_air = 28.84; % molecular weight of air
```

```
% SYSTEM-SPECIFIC VALUES
%Chimney Variables
%Z = input('Enter chimney height (in meters):');
Z = 2.18; %ARC chimney height in meters
ZV = 0:.001:Z; %vector of Z discretized for integral
r_i = 0.05; %chimney radius in meters
D_chim = 2*r_i; %chimney diameter in meters
THwall = .0005; % thickness of chimney wall in meters
D_e = 2*r_i + 2*THwall; %external diameter of chimney
A_cross_chim = pi*(r_i^2); %internal cross-sectional
%area of the duct, m^2

A_chim_wall = 2*pi*r_i*Z; %surface area of the interior
% chimney wall, m^2;

A_chim_outwall = 2*pi*(D_e/2)*Z; %surface area of the
% exterior chimney wall, m^2;

k_chim = 18; %stainless steel W/m K from engineer toolbox


Pr = 0.74; %actually temperature dependent cp*mu/k, but
```

```
% value taken from Hanby to initiate model,
%temp dependent version follows

cp_fg = 1050; %flue gas specific heat. Temp dependent
%in relaity, this is J/kg K at 300 C from Cengel Thermo
%tables, temp dependent version follows


%Plancha Variables for HM5000
D_stove = 0.025; %average channel height under plancha, m
W_stove = 0.438; %approximate width of plancha channel, m
L_stove = 0.55; %length of sub-plancha channel, m
A_cross_stove = D_stove*W_stove; %approximate cross
%sectional area of sub-plancha channel, m^2

TH_plancha = .00635; %average thickness of the plancha, m
Per_plancha = 2*(D_stove + W_stove); %wetted perimeter
% of the plancha channel

Dh_plancha = 4*A_cross_stove/Per_plancha; %hydraulic
%diameter of the plancha
```

```
%Combustion Chamber
W_HM_cc = .16; %width of the HM5000 combustion chamber
% in meters

H_HM_cc = 0.11; %height of the HM5000 combustion
% chamber in meters

Per_HM_cc = 2*(W_HM_cc+H_HM_cc); %perimeter of the
% combustion chamber, m

A_HM_cc = W_HM_cc*H_HM_cc; %frontal cross sectional
%area of the HM5000's c.c. Doesn't include effect
% of adding wood and reducing area.
Dh_cc = 4*A_HM_cc/Per_HM_cc;

TH_firebrick = 0.015; %thickness of chamber tile, m

A_HM_bottomcc = 0.10*0.10; %area of combustion chamber
% bottom face, m^2

k_firebrick = 1.4; % thermal conductivity at 500C
```

```
%Cooking Surface
A_cooking = W_stove*L_stove; %surface area
%available for cooking, m^2

k_plancha = 70; %thermal conductivity of cast iron
%from engineer toolbox, W/m k

A_mylar = 2*.11354; %area occupied by 2 mylar bags, m^2


%Fuel specific information
LHVwood = 17500; %lower heating value of pine wood,
% kJ/kg

 moisture_wood = 0.07;  %not yet being utilized.
 %Placed as reminder for future model expansion

 w_fuel = 0.025; %width in m
 h_fuel = 0.05; %height in m
 l_fuel = 0.3; %length of sticks in m
 sticks = 5; %number of sticks burning at once
 area_sticks = sticks*h_fuel*w_fuel; %cross sectional
 % area occupied by sticks in the combustion chamber, m^2
```

```
%USER INPUTS
%Inputs
Elev = input('Enter elevation (in meters above sea level):');
T_amb = input('Enter ambient temperature (in K):');
firepower = input('Enter steady state firepower (in kW):');
%eventually add approximate wind speed, V_wind = input
%('Enter approximated wind speed (in m/s):');

%Heat Loss from the Stove
T_coal = 1000; %temp of coals in kelvin
T_fire = 1400; %flame temp approximation in kelvin

Q_cond_loss = k_firebrick*A_HM_bottomcc*...
    (T_coal-T_amb)/TH_firebrick;
Q_rad_loss = .5*firepower*1000;% eventually use  alternative
%of the form e_sb*(A_HM_cc-area_sticks)*emiss_fire*
%(T_fire^4-T_amb^4); %crude estimate for radiation heat loss
%with a view factor of chamber minus wood

HeatLossFactor = (Q_cond_loss+Q_rad_loss)/(1000*firepower);
%estimate for heat loss from combustion chamber in watts

```

```
%CALCULATED PARAMETERS
  %WOOD MASS FLOW RATE (BASED ON FIREPOWER)
mdot_wood = firepower/LHVwood; %kg/s wood

    % Barometric Pressure Calc
P_ref = 101325; %reference pressure in Pa
Elev_ref = 7000; %reference elevation in meters
P_loc = P_ref*exp(-(Elev/Elev_ref));
%local barometric pressure (Pa)

    %ambient gas props
kin_visc_air = 0.000000123.*(T_amb-273.15) + 0.000009571;
%kinematic viscosity of ambient air

rho_amb = (P_loc*MW_air)/(R_univ*T_amb);
%ambient air density kg/m^3

%GUESSES FOR MODEL INITIATION

%OVERALL MASS FLOW RATE (BASED ON FIREPOWER)

%OVERALL FLUID LOSS COEFFICIENT, K
%(use roughness, Reynolds, diameter,
```

```
%and Swamee-Jain equation and guesses based
%on ASHRAE tables
k_elbow = .75;
k_inlet = 0.75;
k_outlet = 0.25;
n_elbow = 2;
roughness_stove = .00026; % from thermal sciences
%for cast iron in meters

roughness_chim = .00015; % from thermal sciences
% for galv iron in meters

k_fric = k_inlet + n_elbow*k_elbow + k_outlet; %frictional
%coefficient for minor losses

F_stove = .01; %initial guess for friction factor of stove

k_stove = F_stove*L_stove/D_stove; %frictional coefficient
%for major losses through stove

F_chim =  .01;%initial guess for friction factor of chimney
k_pipe = F_chim*Z/D_chim; %frictional coefficient for major
%losses through chimney
```

```
k_overall = k_stove+k_pipe+k_fric; %overall frictional
% coefficient



 %Initial Guesses to Start Model
mdot_total = .014;
%initial guess for total mass flow rate in kg/s

mdot_air = mdot_total - mdot_wood;
%mass flow rate of air in kg/s

kin_visc_fg = 0.000000123*(500-273.15) + 0.000009571;
%calculated guess for temp dependent kinematic viscosity

rho_flue = .6;%initial guess for flue gas density, kg/m^3
V_chim = 2; %initial guess for gas velocity m/s
Re_chim = 3500; %initial guess for average reynolds
%number in the chimney

k_fg = .04; %initial guess for thermal conductivity
%of the flue gas
```

```
V_stove = 2; %initial guess for average gas velocity
% in the sub-plancha channel
Re_stove = 5000; %%initial guess for average reynolds
%number in the gas path

V_HM_cc = 1; %initial guess for average velocity of air
% flowing into the combustion chamber, m/s

Re_HM_cc = 2000; %initial guess for average reynolds
%number of air flowing into combustion chamber

stoich_air = 6.125*mdot_wood; %based on
%Applied Combustion text and used in Chemkin Model

phi = stoich_air/(mdot_air-stoich_air); %initial guess
%for fuel equivalence ratio

Nu_chim = 25;%initial guess for average Nusselt
%number within chimney
Nu_stove = 25;%initial guess for average Nusselt
%number within stove

h_stove = 75;%initial guess for convection heat
```

```
%transfer coefficient within stove

h_chim = 10;%initial guess for convection heat transfer
% coefficient within chimney

h_o = 15; %initial guess for average convective
%coefficient for cooling of the chimney

h_stovetop = 10; %initial guess for average convective
% coefficient for cooking surface

U_chim = 15; %initial guess for average overall heat
% transfer coefficient for the chimney

U_stove = 100; %initial guess for average overall heat
%transfer coefficient for gas within the stove

T_out_cc = 1000; %initial guess for combustion chamber
% outlet temp, K

T_in_plancha = T_out_cc; %initial guess for sub-plancha
% inlet gas temp, K

```

```
T_out_plancha = 650; %initial guess for sub-plancha
%gas path outlet temp, K

T_plancha_avg = (T_in_plancha+T_out_plancha)/2;
%initial guess for avergage sub-plancha gas temp, K

T_in_chim = T_out_plancha; %initial guess for chimney
% inlet temp, K

T_out_chim = 450; %initial guess for chimney outlet temp, K
T_chim_avg = (T_in_chim+T_out_chim)/2; %initial guess for
%combustion chamber outlet temp, K

T_chim_avglin = 550; %initial guess for combustion chamber
% outlet temp, K

T_chim (1:length(ZV))= 500; %initial guess for combustion
%chamber outlet temp, K

DRAFT_theor = 8; %initial guess for theoretical draft, Pa
DRAFT_LOSS = 4; %initial guess for pressure loss, Pa
DRAFT_actual = DRAFT_theor-DRAFT_LOSS;
Q_cooking = h_stove.*A_mylar.*(T_plancha_avg-318);
```

```
%calculated initial guess for convection power to cooking

thermalefficiency=.10; %initial guess for thermal
%efficiency of stove
%intcon = (U_chim*2*pi*r_i)/(mdot_total*cp_fg);
intT = 1000; %inital guess for integral used to
%solve average temperature function

Nu_chim_alt = 20;
F_chim_alt = .05;

%WHILE LOOP - run until convergence criteria is met
%(TEMPERATURE AND/OR MASS FLOW)
resid_T_chim_avg = 100; %initial guess for difference
%between chimney temp guess(1) and chimney temp guess(0)
index = 1;

while resid_T_chim_avg>=.0000001


%CALCULATED TEMPERATURE DEPENDENT PARAMETERS
kin_visc_fg(index+1) = 0.000000123*(T_chim_avg(index)-...
    273.15) + 0.000009571;
```

```
%approximate gas kinematic viscosity from Hanby

rho_flue(index+1) = (P_loc*MW_flue)/(R_univ.*...
    T_chim_avg(index));    % flue gas density (kg/m^3)
k_fg(index+1) = 0.02442+0.6992*10^-4*(T_chim_avg(index)-...
    273.15); %thermal conductivity of the gas
cp_fg(index+1) = -5.35E-07*T_chim_avg(index)^3 + ...
    6.88E-04*T_chim_avg(index)^2 + 2.75E-02*...
    T_chim_avg(index) + 1.00E+03;
%heat capacity of air, equation created from table values

Pr(index+1) = -7E-10*T_chim_avg(index)^3 + 1E-06*...
    T_chim_avg(index)^2 - 0.0007*T_chim_avg(index) + ...
    0.7809; %Prandtl number equation created from
    %table values for cp, mu, and k.

%Reynolds number in the chimney
 V_chim(index+1) = mdot_total(index)/(rho_flue(index+1)...
     *A_cross_chim);
 %Average velocity of fg in the chimney, m/s

 Re_chim(index+1) = V_chim(index+1)*D_chim/kin_visc_fg...
     (index+1); %Average reynolds number of chimney flow
```

```
 %Reynolds number in the stove
V_stove(index+1) = mdot_total(index)/(rho_flue(index+1)...
    *A_cross_stove);
%Average velocity of fg in the sub-plancha channel, m/s

Re_stove(index+1) = (V_stove(index+1)*Dh_plancha./...
    kin_visc_fg(index+1));
%Average reynolds number of sub-plancha channel flow
%alternative Re_plancha =
%((mdot_total/(rho_plancha*A_cross_stove))*Dh_plancha)/nu;

%Velocity and Reynolds number in the CC
V_HM_cc(index+1) = mdot_total(index)/(rho_amb*A_HM_cc);
%Average velocity of air entering HM5000
%combustion chamber, m/s

Re_HM_cc(index+1) = (V_HM_cc(index+1)*Dh_cc)/kin_visc_air;
%Average reynolds number of flow into combustion chamber


 %Fluid Loss terms
```

```
F_stove(index+1) = 96/Re_stove(index+1);
%table value for friction factor for parallel plate flow

%alt F_chim(index+1) =  0.25/((log10(roughness_chim/
%(3.7*D_chim)+(5.74./(Re_chim(index+1)^0.9)))^2));
%friction factor, solved using Swamee-Jain Equation

F_chim(index+1) = (0.79*log(Re_chim(index+1))-1.64)^-2;
%friction coefficient for pipe, from Incropera

k_fric = k_inlet + n_elbow*k_elbow + k_outlet;
%estimation of geometrical minor losses

k_stove(index+1) = F_stove(index+1)*L_stove/D_stove;
%loss coefficient for stove

k_pipe(index+1) = F_chim(index+1)*Z/D_chim;
%loss coefficient for chimney

k_overall(index+1) = k_stove(index+1)+k_pipe(index+1)+k_fric;
%overall system loss ceofficient

%Calculation of Average Nusselt Numbers
```

```

if Re_chim(index+1) >= 3000
   Nu_chim(index+1)= ((F_chim(index+1)/8)*(Re_chim(index+1)...
       -1000)*Pr(index+1))/(1+12.7*((F_chim(index+1)/8)...
       ^0.5)*((Pr(index+1)^.66)-1));
   % correlation from Incropera, alternative 0.26*
   %(Re_chim(index+1)^.6)*(Pr(index+1)^0.3);

else
   Nu_chim(index+1) = 0.023*(Re_chim(index+1)^.8)*...
       (Pr(index+1)^0.4); %Dittus-Boelter correlation
end

 if Re_stove(index+1) >= 3000
   Nu_stove(index+1) = 9;
   % Within parallel plate flow, Nu is shown to vary
   % between 4-10, depending on boundary conditions.
else
   Nu_stove(index+1) = 9;% same as previous cond,
   %but may utilize low Re correlation in future such as
   %alternative Nuss_plancha = 7.54+((0.03*(Dh_plancha/L)
   %*Re_plancha*Pr)/(1+0.016*((Dh_plancha/L)*Re_plancha*Pr)
   %^(2/3)));
```

```
end


    h_stove(index+1) = Nu_stove(index+1)*(k_fg(index+1)...
        /D_stove); %convection heat transfer coefficient
     %for stove
    h_chim(index+1) = Nu_chim(index+1)*k_fg(index+1)/...
        D_chim;
    %convection heat transfer coefficient for chimney

    h_o = 50;%eventually replace with function showing
    %indoor convective cooling and outdoor wind cooling

    h_stovetop = 38.8; %based on h*A*DT calculation knowing
    %efficiency is 27% This will change with cooking
    %load, radiation, etc.

    U_chim(index+1) = 1/((1/h_chim(index+1))+...
        (THwall/k_chim)+(1/h_o)); %add radiation term
    U_stove(index+1) = 1/((1/h_stove(index+1))+...
        (TH_plancha/k_plancha));%+(1/h_stovetop));
    %may add linearized radiation term

```

```
%COMPUTE AXIAL PLANCHA TEMPERATURE PROFILE
%ARRIVE AT GUESS FOR CHIMNEY INLET TEMPERATURE,
%VELOCITY, REYNOLDS NUMBER
T_out_cc(index+1) = T_amb+((1-HeatLossFactor)*...
    firepower*1000/(mdot_total(index)*cp_fg(index+1)));
%estimate for temperature of gas leaving the combustion
%chamber. Since the combustion zone is far from
%adiabatic, heat loss term is introduced.

T_in_plancha(index+1) = T_out_cc(index+1);
T_out_plancha(index+1) = T_amb + (T_in_plancha(index+1)...
    -T_amb)*exp(-((U_stove(index+1)*A_cooking)/...
    (mdot_total(index)*cp_fg(index+1))));
%temperature exiting plancha, solution to heat diff eq.

T_plancha_avg(index+1) = (T_in_plancha(index+1)+...
    T_out_plancha(index+1))/2;
%linear average of sub-plancha channel gas temp

%COMPUTE AXIAL CHIMNEY TEMPERATURE PROFILE AND
%CALCULATE AVERAGE CHIMNEY TEMPERATURE

```

```
    %COMPUTE UPDATED GUESS FOR MASS FLOW RATE INTO
    %STOVE FROM ASHRAE DP RELATION

     T_in_chim(index+1) = T_out_plancha(index+1);
     T_out_chim(index+1) = T_amb + (T_in_chim(index+1) ...
         -T_amb)*exp((-U_chim(index+1)*A_chim_wall)/...
         (mdot_total(index)*cp_fg(index+1)));
     %temperature exiting chimney, solution to heat diff eq.

% To produce axial chimney temperature profile for
%i=1:length(ZV)
     T_chim(index+1,1:length(T_chim)) = T_amb + ...
         (T_in_chim(index+1)-T_amb)*exp((-U_chim(index+1)...
         *(2*r_i*pi*ZV)/(mdot_total(index)*cp_fg(index+1))));
%
    %For Eventual True Average Chimney Temp (Non-linear)
    %intcon(index+1) = (U_chim(index+1)*2*pi*r_i)/
    %(mdot_total(index)*cp_fg);

    %intT(index+1) = (T_amb*Z)+(T_amb+T_chim_in)*
    %((exp(-intcon(index+1)*Z))/(intcon(index+1)))
    %+((T_amb-T_in_chim(index+1))/intcon(index+1));

```

```
    %intT(index+1) = (T_amb*Z)+((exp(-intcon(index+1)
    %*Z))/(intcon(index+1)))+(1/intcon(index+1));

    %intT(index+1) = trapz(T_chim(index+1,:));
     %T_chim_avg(index+1) = (1/Z)*intT(index+1);
     % T_chim_avg(index+1) = T_chim_avg;
     T_chim_avg(index+1) = (T_in_chim(index+1)+...
         T_out_chim(index+1))/2; % a crude linear average
     %for now, can use average value theorem with
     %integral eventually.


%COMPUTE predicted DP based on ideal DP minus loss
%(delta rho*g*h - k*rho*V^2/2)
DRAFT_theor(index+1) = Z*g*P_loc/(R_univ/MW_flue)*...
    ((1/T_amb)-(1/T_chim_avg(index+1)));
%theoretical draft of chimney

DRAFT_LOSS(index+1) = (0.5)*(k_pipe(index+1)+...
     k_outlet)*rho_flue(index+1)*(V_chim(index+1)^2);
%estimated loss of draft from chimney

DRAFT_actual(index+1) = DRAFT_theor(index+1)-...
```

```
         DRAFT_LOSS(index+1); %estimated net draft, should be
 %compared to experimental DP value

%estimate mass flow rate based on density difference from
%Kincead Capacity Equation
    mdot_total(index+1) = A_cross_chim*((2*g*Z/...
        (k_pipe(index+1)+k_outlet))^0.5)*rho_flue(index+1)...
        *(rho_amb-rho_flue(index+1));
    %ASHRAE Kincaid Fireplace Capacity equation;

    mdot_air(index+1) = mdot_total(index+1) - mdot_wood;

%estimate fuel equivalence ratio, Phi
    phi(index+1) = stoich_air/(mdot_air(index+1)-...
        stoich_air); %fuel equivalence ratio

%estimate thermal efficiency
Q_cooking(index+1) = h_stove(index+1)*A_mylar*...
    (T_plancha_avg(index+1)-318); %calling average cold
%side temperature half way to 90 degrees from 15 degrees

thermalefficiency(index+1) = Q_cooking(index+1)/...
    (firepower*1000); %not intended to be highly accurate,
```

```
  %just approximate for optimization analysis

  %Iterative statements
      if index>1
  %resid_mdot(index) = abs(mdot_total(index+1)-
  %mdot_total(index));
    resid_T_chim_avg(index) = abs(T_chim_avg...
        (index+1)-T_chim_avg(index)); %convergence criteria
     end
  index = index+1;
 end
 %END OF WHILE LOOP
```

2.2. Gas Property Equations

Polynomial functions for several temperature dependent properties were derived from table values. These functions were used in the numerical modeling.

	cp	mu	k	Pr
100	1.01E+03	2.26E-05	3.14E-02	7.28E-01
125	1.02E+03	2.34E-05	3.32E-02	7.16E-01
150	1.02E+03	2.42E-05	3.49E-02	7.06E-01
175	1.03E+03	2.49E-05	3.67E-02	6.97E-01
200	1.03E+03	2.57E-05	3.84E-02	6.89E-01
225	1.04E+03	2.65E-05	4.02E-02	6.83E-01
250	1.04E+03	2.72E-05	4.19E-02	6.78E-01
275	1.05E+03	2.80E-05	4.36E-02	6.74E-01
300	1.06E+03	2.88E-05	4.54E-02	6.70E-01
325	1.07E+03	2.95E-05	4.71E-02	6.67E-01
350	1.07E+03	3.03E-05	4.89E-02	6.65E-01
375	1.08E+03	3.11E-05	5.06E-02	6.63E-01
400	1.09E+03	3.18E-05	5.24E-02	6.61E-01
425	1.10E+03	3.26E-05	5.41E-02	6.60E-01
450	1.10E+03	3.33E-05	5.59E-02	6.59E-01
475	1.11E+03	3.41E-05	5.76E-02	6.59E-01
500	1.12E+03	3.49E-05	5.94E-02	6.58E-01
525	1.13E+03	3.56E-05	6.11E-02	6.58E-01
550	1.14E+03	3.64E-05	6.29E-02	6.58E-01
575	1.14E+03	3.72E-05	6.46E-02	6.58E-01
600	1.15E+03	3.79E-05	6.64E-02	6.58E-01
625	1.16E+03	3.87E-05	6.81E-02	6.58E-01
650	1.16E+03	3.95E-05	6.99E-02	6.58E-01
675	1.17E+03	4.02E-05	7.16E-02	6.57E-01
700	1.17E+03	4.10E-05	7.34E-02	6.57E-01
725	1.18E+03	4.18E-05	7.51E-02	6.56E-01
750	1.18E+03	4.25E-05	7.69E-02	6.55E-01
775	1.19E+03	4.33E-05	7.86E-02	6.54E-01
800	1.19E+03	4.41E-05	8.04E-02	6.53E-01

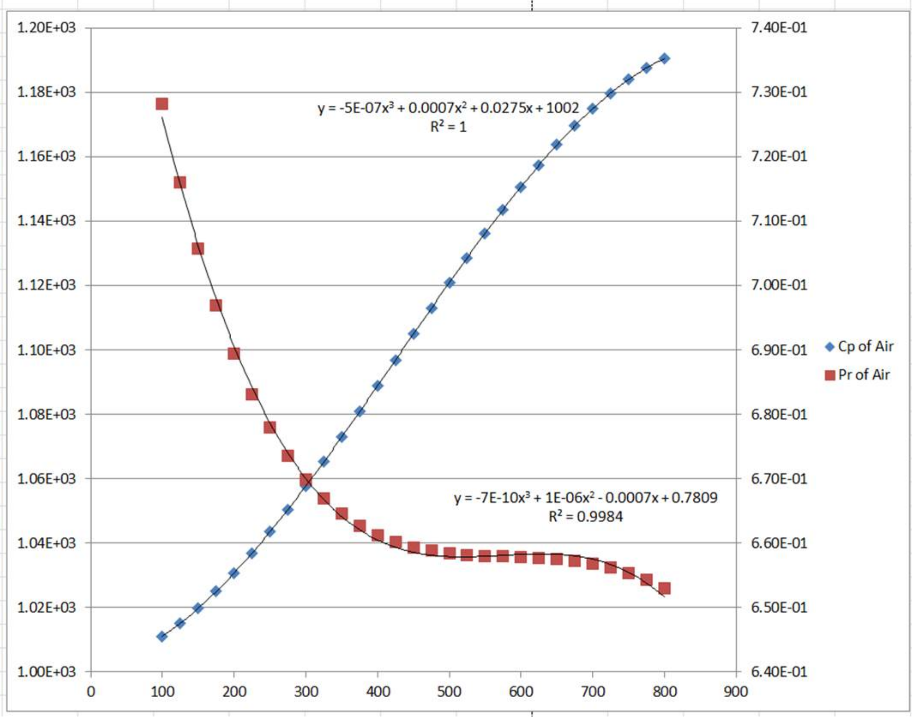


Figure 66. Derivation of Temperature Dependent Prandtl Number and Specific Heat Equations from Table Data.

APPENDIX C

Supplementary Material for Chapters 1,2, and 4

3.1. Baseline data for Peru field work

The following data was gathered by the author in one of three trips to Peru in support of this work. As can be seen in Figure 67, nearly all of the stoves tested were able to boil the

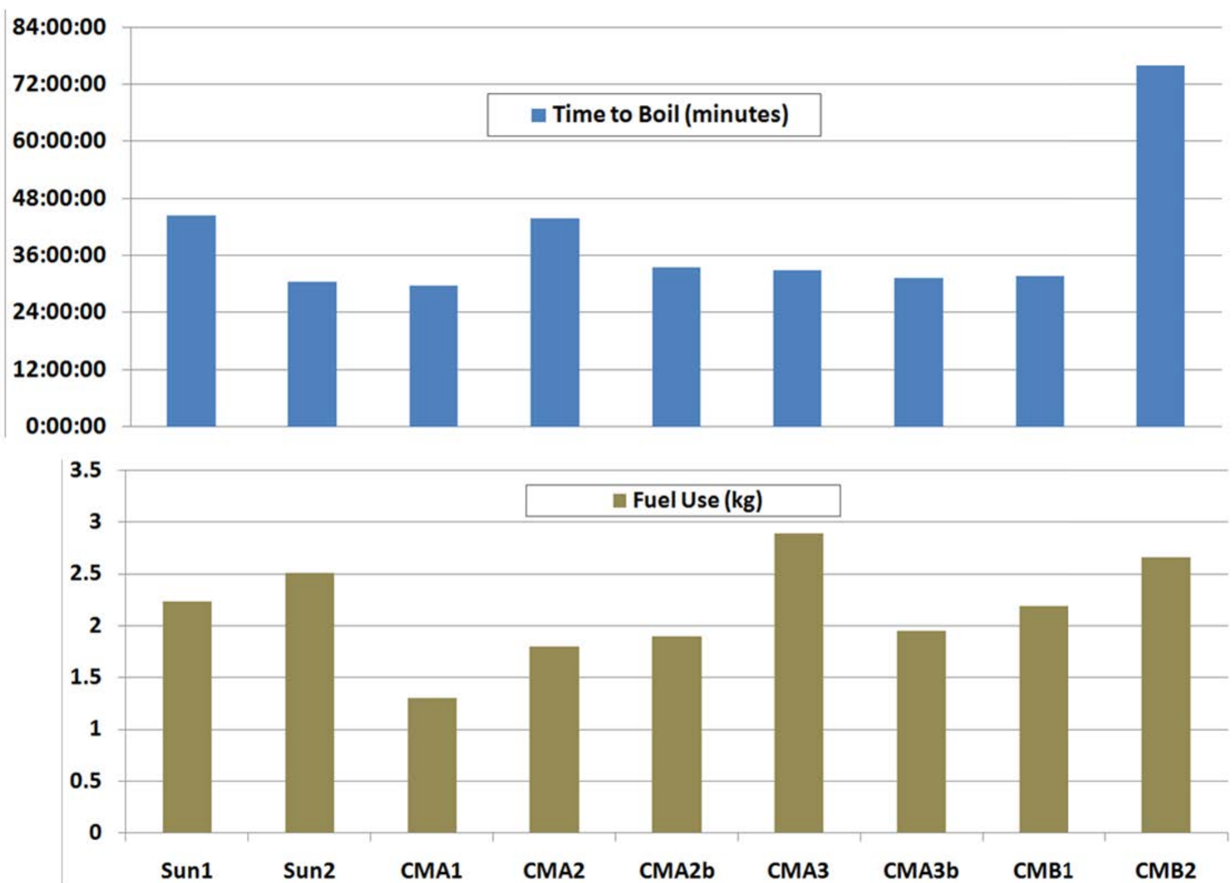


Figure 67. Time to boil and fuel use of several traditional Peruvian dung-stoves. The water boiling test was used to standardize testing.

water in less than 45 minutes. All used more than 1.25 kg of fuel, which shows that these tradtional stoves are fast but inefficient. These results helped guide the design of the L6040 2-pot stove described throughout this work.

A labVIEW SCADA was custom-built for this work. Figure 68 shows the wiring diagram or 'back-panel' of this program

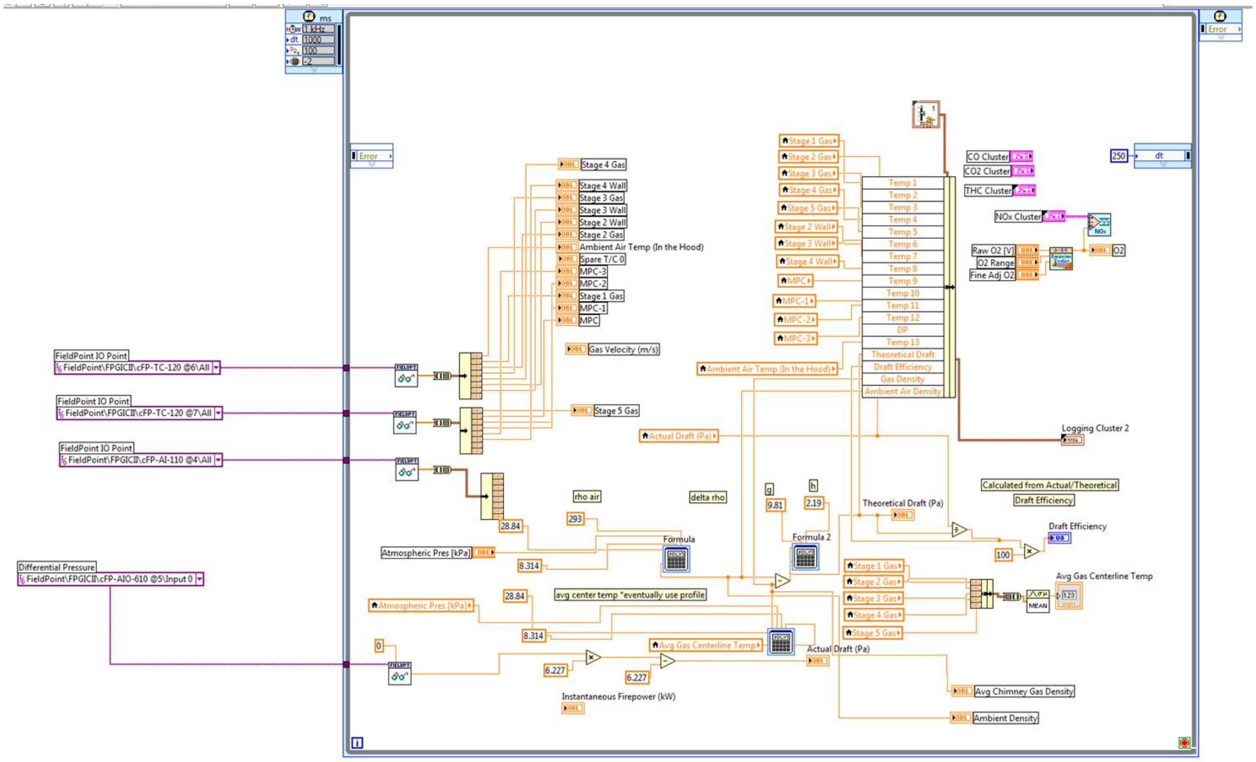


Figure 68. The back panel of the LabVIEW program developed for this research.

3.3. Condensed Step By Step Instructions for Flexible Bottom Pots Used in Plancha Protocol

Plancha Test Protocol with Mylar Pots (Jason Prapas, Sean Babbs, James Tillotson, and John Mizia) The following items will be needed:

- clear mylar, thickness:
- measuring device
- cutting device
- water and heat resistant tape

- 1” tall aluminum barstock, length to be determined by stove size

3.3.1. Background. To more accurately capture the useful heat and thermal efficiency of a plancha stove, a standard sized round pot is impractical and covers only a small amount of the total area. It was determined, therefore, that rectangular pots should be used, as the majority of plancha type stoves are rectangular. The pots will be made specifically for the stove, and will be made of Mylar material. It was deemed necessary to cover 70% of the area of the plancha surface, as the test still needed to accommodate rectangular pots on a circular plancha surface. The test itself is run similarly to an EPTP, the only major difference being only a CS and HS will be run, and thermal efficiency data will be calculated for the HS. The efficiencies of the two phases will be averaged.

3.3.2. Flexible Pan Fabrication. To create the pots, follow the steps below:

(1) Calculate the plancha surfaces total area. Then calculate 70% of that area. item Determine the aspect ratio (width to length) of the griddle. Determine the shape of the pan using the same aspect ratio but at 70% of the total area to determine the dimensions of the two pots. The two pots should be identical.
(2) Determine the side wall height needed to hold 5L of water, and add at least an inch to every side so that they can be folded over (it is advisable to also add and inch over the required side wall height so that it is easier to carry without spillage).
(3) Mark the required dimensions on the flat Mylar sheet, making sure to take into account walls on all four sides. It is advisable to use a large straight edge to maximize precision. Then cut this out.

(4) Mark the dimensions of the bottom of the pot and fold the walls up at these marks. Bring the corners to a point, and then fold the corner back on one side and attach to that wall (see photos).

(5) Create a rim out of flatstock that will fit around the pot securely. Make sure the height of the rim is smaller than the final wall height, since the rim should not be touching the plancha surface during the test.

(6) Cut the corners down an inch, so that they can be folded over the rim. Attach the rim to the folded over Mylar. *Note: Make sure that the pot/rim apparatus can support 5L of water safely.

(7) Repeat Steps 1-7 to create a second pot.