Design, Development and Performance Evaluation of a Rocket Stove with Skirt for Household Use

Frew Gebretsadik Gebremariyam

A Thesis Submitted to

The Department of Mechanical Engineering

School of Mechanical, Chemical and Materials Engineering

Presented in Partial Fulfillment of the Requirement for the Degree of Master of Science in Thermal Engineering

Office of Graduate Studies

Adama Science and Technology University

June 2023

Adama, Ethiopia

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DECLARATION

I hereby declare that this Master Thesis entitled "Design, Development and Performance Evaluation of a Rocket Stove with Skirt for Household Use" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Frew Gebretsadik Gebremariyam	______________	______________
Name of student	Signature	Date

RECOMMENDATION

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled **“**Design, Development and Performance Evaluation of a Rocket Stove with Skirt for Household Use**”** was prepared under my guidance by Frew Gebretsadik Gebremariyam and submitted in partial fulfilment of the requirements for the degree of Mater’s of Science in Thermal Engineering. Therefore, I recommend the submission of the revised version of the thesis to the department following the applicable procedures.

Dr. Dawit Gudeta (Associate Professor)	____________	____________
Major Advisor	Signature	Date

APPROVAL SHEET

I, the advisor of the thesis entitled “Design, Development and Performance Evaluation of a Rocket Stove with Skirt for Household Use” and developed by Frew Gebretsadik Gebremariyam, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Dr. Dawit Gudeta (Associate Professor)	________________	________________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Frew Gebretsadik Gebremariyam have read and evaluated the thesis entitled “Design, Development and Performance Evaluation of a Rocket Stove with Skirt for Household Use” and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfilment of the requirement of the degree of Master of Science in Thermal Engineering.

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Finally, approval and acceptance of the thesis are contingent upon the submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

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ACRONYMS

ABS	Advanced biomass stoves
CCT	Controlled cooking test
GDP	Gross domestic product
IAP	Indoor air pollution
ICS	Improved cookstoves
PM	Particulate matter
NGO	Non-governmental organizations
RMS	Rocket mud stove
SFC	Specific fuel consumption
TLUD	Top-lit updraft gasifier
TSF	Three stone fires
TSOFS	Three-stone open fire stoves
WBT	Water boiling test
WHO	World health organization

NOMENCLATURE

h_{ci}	Convective heat transfer coefficient for inner wall of the stove (W/m^2°C)	Q_{ac}	Supplied heat by the fuel combustion (J)
h_{co}	Convective heat transfer coefficient for outer wall of stove (W/m^2°C)	Q_{fl}	Heat gain by flue in zone (J)
h_{ri}	Radiative heat transfer coefficient for inner wall (W/m^2°C)	Q_{loss}	loss through combustion wall (J)
h_{roc}	Radiative heat transfer coefficient of char from outer side (W/m^2°C)	Q_{rad}	Heat transfer by radiation from flame to pot (J)
h_{rof}	Radiative heat transfer coefficient of flame for inner wall (W/m^2°C)	$Q_{moisture\ loss}$	moisture loss (J)
h_{chr}	Char radiative temperature	ε_{fl}	Emissivity of flue gas
h_{rfl}	Radiative heat transfer coefficient of flue gas (W/m^2°C)	Cp	Specific heat of air/flue gas (kJ/kg K)
m_{flue}	kg of flue produced per kg of dry fuel burnt	$\dot{m}_f$	fuel burn rate (kg of dry fuel/s)

h_{ro}	Radiative heat transfer of outer surface (W/m^2°C)	Gr	Gras Hoff's number
h_s	Enthalpy of superheated steam at atmospheric pressure (kJ/kg of steam)	L	length (m)
L_b	Characteristic length	k	Thermal conductivity (W/m K)
Re	Reynolds number	v	Kinematic viscosity of air/flue gas (m^2/s)
T_f	Flam temperature	α_{fl}	Absorptivity of flue gas
T_{wi1}	Inner wall temperature of combustion chamber	μ	Dynamic viscosity of flue gas (kg/m s)
g	Gravity (m/s^2)	ρ_g	Density of flue gas (kg/m^3)
ρ_a	Density of atmospheric air (kg/m^3)	$\Delta P_{chimney}$	Chimney draught (N/m2)

ABSTRACT

Biomass wood is a vital energy source for cooking in developing nations like Ethiopia, particularly in rural areas. However, inefficient use of biomass wood fuel for cooking leads to socioeconomic and environmental problems. To address this, a study aims to design, develop, and test a locally-made rocket stove with a variable combustion chamber height. The rocket stove's geometrical parameters were designed using a principle from the Aprovecho Research Center, integrating locally accessible stove bodies and insulating materials. Two height variations for the combustion chamber one with 36 cm height and the second with 24 cm were developed and tested to investigate the performance of the stove. Experimental investigations were conducted to study the performance of the designed model. Water boiling tests were carried out using 2.5 kg of water and local Eucalyptus globulus wood logs with 10.53% of moisture content as feedstock. For a 36 cm combustion chamber height, the average firepower input was 6.156 kW, the average time to boil was 9.83 minutes, the burning rate was 19.6 g/min, the specific fuel consumption was 79.15 g/liter, and the thermal efficiency was 30.23%. For the 24 cm combustion chamber height, the average firepower input was 5.44 kW, the average time to boil was 11.42 minutes, the burning rate was 17.33 g/min, the specific fuel consumption was 79.48 g/liter, and the thermal efficiency was 28.51%. The results showed that the combustion chamber with a height of 36 cm performed better than the one with a height of 24 cm. the designed rocket stove showed considerable improvement over recently developed improved biomass stoves in Ethiopia, and the results suggest that the new stove has the potential to significantly reduce the socio-economic and environmental problems associated with biomass wood fuel for cooking in Ethiopia.

Key words; Rocket stove, Improved cookstove, Fuel consumption, Biomass wood

CHAPTER ONE

1. Introduction

1.1. Background of the study

Many people on the planet who reside in developing nations are unable to access modern energy sources necessary for their economic and social growth (Smith, 1993). In countries like Ethiopia wood is a major source of energy utilizing it for different purposes like cooking lighting and heating. Biomass fuels (firewood, agricultural residues, animal wastes, and charcoal) account for up to 90 percent of the energy supply of Ethiopia (Idiata et al., 2013). A sizable number of houses lack access to electricity from the grid (Association, 2012).

Despite its relatively small contribution to the global primary energy mix, wood remains an essential energy source for many people in developing countries, with approximately 2.8 billion people worldwide relying on it as a fuel source. In Sub-Saharan Africa, up to 70% of households depend on wood energy, and in some countries, it makes up as much as 90% of the household energy mix and contributes up to 3.5% of GDP. Efficient use of wood as an energy source is crucial in these regions where alternative energy sources are not yet widely available (Dewes, 2016).

Indoor air pollution resulting from the use of stoves with poor combustion design can have a significant impact on the health of household members, particularly women and children (Smith, 1993). Exposure to smoke and pollutants like carbon monoxide, benzene, and formaldehyde can cause health problems, and it's estimated that indoor air pollution is responsible for an additional two million deaths of women and children in poor countries each year (Bruce et al., 2000; Nahar et al., 2016). Additionally, using solid biofuels for cooking has a large worldwide influence on the emissions of greenhouse gases and black carbon, which make up 1-3% of all human-caused global warming (Smith et al., 2013).

1.2Biomass cookstove

A biomass cookstove is a structure that uses air-fuel combustion to generate heat and direct it towards a cooking surface. Stoves have been used throughout human history and have evolved to accommodate various cultures and cuisines. The traditional stove, also known as the three-stone fire, has remained largely unchanged for over 12,000 years and is still prevalent in rural settings in many African, Asian, and Latin American countries, despite being phased out in Europe in the 18th century. (Kshirsagar and Kalamkar, 2014; Westhoff and Germann, 1995).

1.3 Biomass cookstove improvements

The Improved Cookstove (ICS) is designed using scientific principles to enhance combustion, heat transfer, efficiency performance, and reduce emissions. It may incorporate modern building materials to achieve these goals while maintaining affordability and usability. The Rocket and Gasifier stoves are two popular types of ICS that address the limitations of traditional stoves. (Kshirsagar and Kalamkar, 2014).

Improved cookstoves are designed to increase cooking efficiency and decrease pollutant emissions while meeting the cooking energy needs of rural residents in developing countries. By using biomass more efficiently, households can reduce their fuel consumption. When designing an ICS, it's essential to consider the needs and requirements of the users. (Schirnding, 2001).

The stove's design should be; (Ram et al., 1984)

- ✓ Built using materials and equipment that are easily accessible locally.
- ✓ Able to sustain a year's worth of heavy use without cracking, possibly longer.
- ✓ Affordable compared to using open fires.

Presently, different types of Improved Cooking stoves are being developed and disseminated for societies living in rural and urban cities in Ethiopia by governments and NGOs. For instance, Lakech stoves, Charcoal stoves, Tikikil stoves, and Metal stoves.

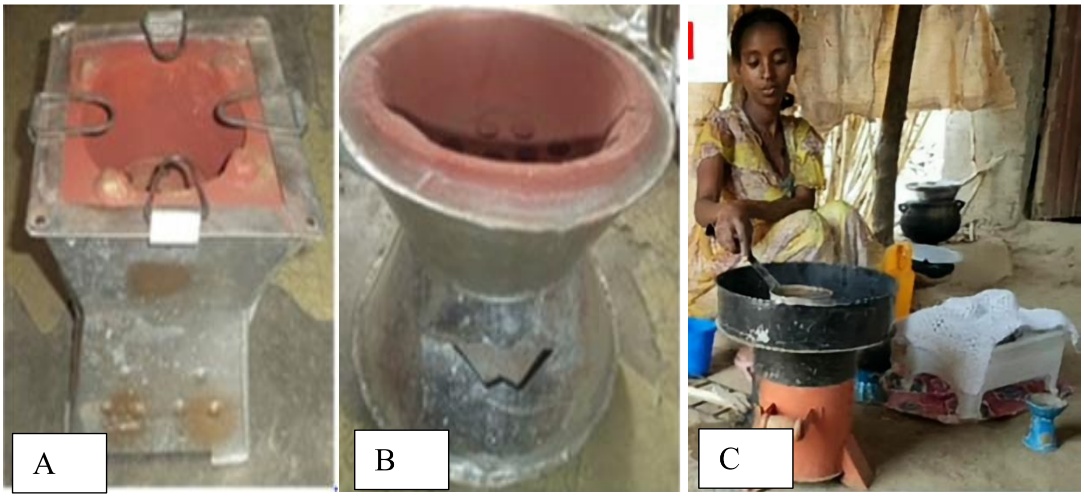


Figure 1.1 Pictures of (A) *Mirchaye*, (B) *Lakech* (C) *Tikikil* (Mamuye et al., 2018; Manaye et al., 2022)

For small diameter fuel rocket stoves are an efficient and hot burning stoves, in rocket stoves before the flame reach the cooking surface, the fuel is burned in a straightforward combustion chamber with a vertical chimney, which ensures almost complete combustion (Teshome et al., 2019).

To increase energy security in developing nations, particularly in rural regions, efforts are being made to encourage the use of rocket stoves that are more effective and sustainable as well as the adoption of contemporary cooking methods and technologies. from those technologies Rocket stove combustion systems deserve attention for a few reasons (Kshirsagar and Kalamkar, 2014):

- ✓ Decreasing indoor air pollution (IAP)
- ✓ Shorter Time and lower cost of obtaining fuel
- ✓ Lower emissions, and deforestation.

This research is intended to design and develop a rocket stove and evaluate its performance for household use in the rural population of Ethiopia.

1.4. Statement of the problem

The rural areas of Ethiopia have little access to Electric energy and are even more difficult to provide other energy sources and primarily use wood as fuel. The traditional cooking stoves' inadequate design leads to environmental pollution, high fuel consumption, and early death as a result of health problems. The traditional cooking stove has low thermal efficiency as they are open throughout their design and more heat is scattered out without utilizing it for the intended purpose this leads to a high amount of heat energy loss to the surroundings. In those traditional three-stone cooking stoves there is more smoke due to incomplete combustion which results in a health problem. This is the main cause of high wood fuel consumption. Therefore, by employing a rocket stove made from locally accessible materials, the aforementioned issues can be reduced. To avoid those drawbacks, this thesis seeks to construct and assess the rocket stove's parameters.

1.5 Objectives of the study

1.5.1 General objective

Design and development of a rocket stove using materials that are available locally and analyzing the performance.

1.5.2 Specific objectives

- ✓ Design an improved rocket stove with a modified geometry.
- ✓ Develop the rocket cookstove prototype using materials that are readily available locally and run an experimental test.
- ✓ Evaluating the effect of geometric height parameter on the performance of the rocket stove.
- ✓ Evaluating the performance of the system on the principle of water boiling test (WBT) and controlled cooking test (CCT).

1.6 Significance of the study

This study's primary contribution is the development of an improved biomass cookstove that can reduce fuel consumption, flue gas emissions, and heat loss problems for the majority of the population in rural areas who rely on conventional solid biomass cookstoves. The use of traditional stoves can exacerbate health, social, and economic issues, but the outcomes of this study can benefit society by lowering fuel consumption and reducing the number of deaths caused by gas emissions from cooking stoves.

1.7 Scope and limitation

This research project aims to design and experimentally test the performance of a rocket stove made from locally available materials. The study will measure fuel consumption, emissions production, and thermal efficiency to validate the stove's performance. However, the study's scope is limited due to the cost and availability of lightweight insulating materials used to reduce the stove's weight.

1.8 Organization of the study

This thesis comprises six chapters. The first chapter provides an introduction to the study's background, including discussions on biomass cookstoves and improved biomass cookstoves. The second chapter reviews relevant literature and identifies research gaps. The third chapter describes the materials and methods used in designing and developing the rocket stove. Chapter four discusses thermal and experimental analyses. Chapter five presents the study's key findings and their implications. The final chapter concludes the work and offers recommendations for future research.

CHAPTER TWO

2. Literature review

2.1 Introduction

Biomass cookstoves have been the subject of numerous studies and research projects to enhance their effectiveness. Improved biomass cookstoves, which have improved end-users' lifestyles for over thirty years, are one of the most recent design concepts for biomass cookstoves. Through shape optimization and a reduction in heat loss during combustion, the design change intends to improve the efficiency of those cookstoves. A cookstove called the "Improved Cookstove" was created using specific scientific guidelines to aid in better combustion and heat transfer, improve emissions, and perform more efficiently. "Rocket" stoves and Gasifier stoves are the two most well-known ICS subcategories (Kshirsagar and Kalamkar, 2014).

This section presents earlier studies related to the development of biomass cookstoves, including examples of conventional, enhanced, and advanced biomass cookstoves. In-depth presentations of several variables that impact cookstove performance and various kinds of solid fuel were made. The design of stoves, the materials used in their construction, the use of biomass energy, and their effects on the environment were also covered. Finally, the chapter is concluded with an overview of the relevant literature.

2.2 Biomass cookstoves classification

The combustion of biomass occurs in reactors known as combustors, which are created based on the requirements for a regulated environment and the combustion mechanism or process. Based on the requirements, the combustor can be classified into two major categories.

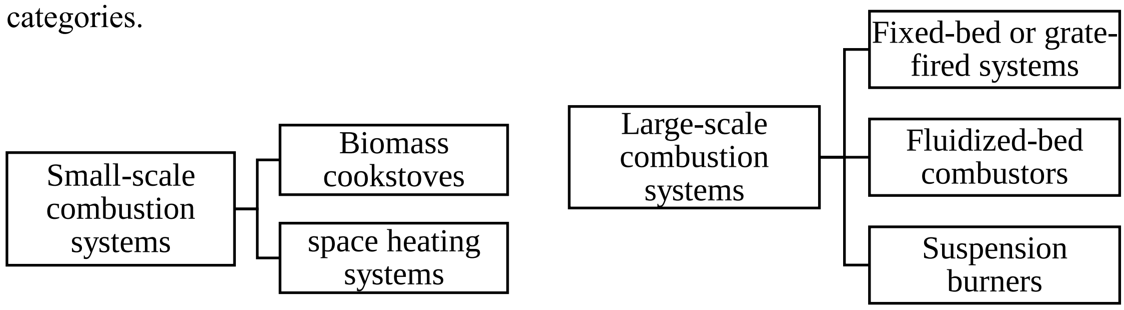


Figure 2.1 Classification of combustor based on requirements (Pal et al., 2016).

Based on the use, requirement, development, materials of construction, and fuel type, biomass cookstoves can be classified as follows.

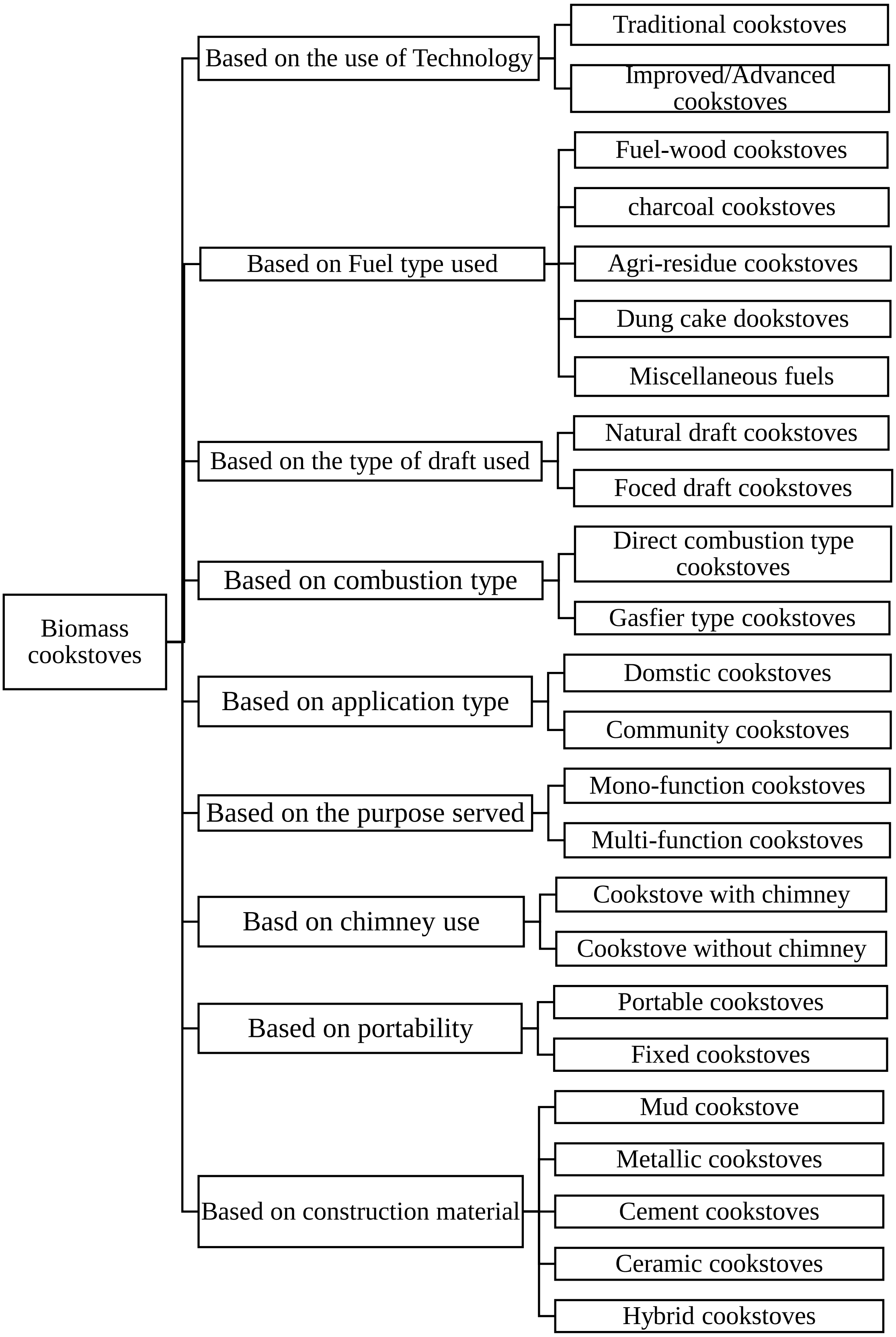


Figure 2.2 Classification of biomass cookstoves (Pal et al., 2016).

The design and development of biomass cookstoves is the topic of active conversation and debate around the world. To simultaneously reduce the need for fuel and emissions, significant research and development are being done on a biomass-burning device that is both effective and clean (Kumar et al., 2013).

2.3 Biomass cookstoves development

Based on their state-of-the-art capabilities, biomass cookstoves can be broadly categorized into classic (open fire), enhanced, and advanced versions.

2.3.1 Traditional (open-fire) biomass cookstoves

Since it was created some 12,000 years ago, the "Arche-typal" stove, also known as the "traditional stove" or "three-stone fire (TSF)," has existed (Westhoff and Germann, 1995). These are the most affordable stoves, and since their users are familiar with how they operate, they are widely used in society. These stoves' lack of shielding causes the fire to escape without reaching the intended target, which leads to significant emissions and poor thermal efficiency. Additionally, these conventional stoves contribute to environmental warming and are one of the factors that lead to human mortality due to their harmful emissions.

Figure 2.3 Traditional three-stone fire (Geleta, 2017)

2.3.2 Improved biomass cookstoves

Improved cookstove is designed by scientific principles for improving heat transfer and lower emission by assisting good combustion, this will lead to improving overall efficiency performance. This is achieved by using materials that are well fit for the purpose. An ICS design aims to address the shortcomings of traditional stoves while maintaining their affordability and usability. Several ICSs can improve fuel efficiency by over 30% and cut emissions by 40-75% (Still et al., 2011), and cut the risk of global warming by 40–60%

(MacCarty et al., 2008). Rocket stoves are one of the most well-known types of improved cookstoves.

Figure 2.4 provides some picture of recently improved cookstoves, developed by various researchers and organizations.

Figure 2.4 Various improved cookstoves developed by researchers (Baqir et al., 2019; Mehetre et al., 2017)

Table 2.1 Comparisons of major cookstove categories

S. No	Type of cookstove	η/%	CO emission/g L^{-1}	PM emission/mg L^{-1}	References
1	Three-stone fire (natural draft)	16	11.1	472.6	Raman et al. (2014)
2	Three-stone fire (natural draft)	10-15	NA	NA	Chagunda et al. (2017)
3	Natural draft open fire (without chimney)	19-24	3.1-10.1	258-858	Raman et al. (2014)
4	Natural draft with chimney (metal stove)	16-36	3.9-9.6	136-1020	Raman et al. (2014)
5	Forced draft cookstove	40-44	1.37	5.4	Raman et al. (2014)

2.3.3 Advanced biomass cookstoves

Modern scientific and product development research has led to the development of advanced biomass stoves (ABS), which are factory-made cookstoves that meet strict specifications for increased durability, lower emissions, and higher efficiency (Venkataraman et al., 2010). The advanced features included in these next-generation cookstoves sometimes include forced or induced airflow for cleaner burning. ABSs currently come in two main categories: improved "Rocket" stoves with one-stage combustion and Gasifier stoves with two stages of combustion. StoveTec from the Aprovecho research center is an illustration of a "Rocket" stove-type ABS. It asserts that compared to Three stone fire (TSF), it uses 40–50% less fuel, cooks meals in about half the time, and emits 50–75% less smoke (Bank, 2011).

2.4 Cookstove performance parameters

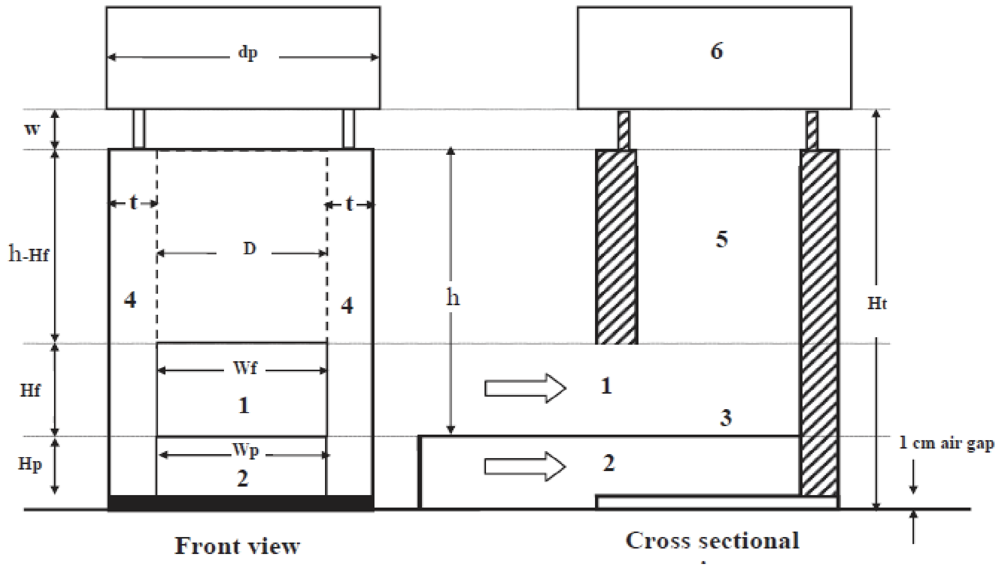
It's vital to ascertain how different operating and geometrical elements affect the cookstove's performance. Scholars have examined cookstove thermal efficiency and other performance metrics primarily utilizing various standards created by agencies in various countries.

2.4.1 Design principles

The Aprovecho research center design principle (Bryden et al., 2005) suggests that maintaining a constant cross-sectional area by keeping the size of the chimney, gap where hot air enters the stove, and opening into the fire the same is crucial. The stove's shape can be modified to maintain heat transfer to the pot, and this should be considered when designing ICS (Bantu et al., 2018). The stove's fire must be kept hot to transfer heat effectively to the pot and maintain good draft. Since air doesn't carry much energy, a lot of air needs to be present in the stove to heat food or water. A family fire typically has a door with a 12cm square opening into the fire, an equal-sized chimney, and tunnels in the stove (Baldwin, 1987; Bryden et al., 2005).

2.4.2 Inlet area ratio

An essential operational parameter known as the "Inlet area ratio" was identified by Kshirsagar and Kalamkar (2015) while creating a validated heat and mass transfer model. The combustion quality and other relevant stove performance characteristics were shown to be significantly impacted by this parameter. In the case of Kshirsagar and Kalamkar (2016) for values of the Inlet area ratio less than 0.7, it was discovered to have a significant impact on the quality of combustion. As a result, only the main air entrance is permitted with a minimum "Inlet area ratio" of 0.7 (main air area factor). Kshirsagar and Kalamkar suggested a modified rocket stove design, as shown in Figure *2.5*, to account for this inlet area ratio aspect.



1 - Inlet area for Fuel +Air (Variable)

2 - Fixed inlet area for primary air (Constant)

3 - Fuel holding mesh

4 - Insulation

5 - Combustion chamber or chimney

6 - Cooking pot

Figure 2.5 The modified rocket stove design (Kshirsagar and Kalamkar, 2016).

2.4.3 Excess air ratio *μ*

Since CO and PM are the pollutants that cause the majority of diseases to people who use biomass cookstoves, a good stove design must use appropriate ways to reduce these pollutants. The percentage of oxygen in the flue gases serves as the definition of the surplus air ratio. (Memon et al., 2020). As excess air ratio rises while the flame temperature falls. The work discovered that the highest fuel firing rate, or power, is reached at $\mu = 1$, but that efficiency will be quite low, and harmful gases would be relatively high (Jain and Sheth, 2019).

Table 2.2 Flame temperature for various excess air ratios (Memon et al., 2020).

Excess air ratio/μ	Flame temperature/°C	References
1.10482	1082.43	Kshirsagar and Kalamkar (2016)
1.9547	940.54	Kshirsagar and Kalamkar (2016)
2.80453	818.92	Kshirsagar and Kalamkar (2016)
4.41926	681.08	Kshirsagar and Kalamkar (2016)
6.96884	587.84	Kshirsagar and Kalamkar (2016)
15.9773	450.00	Kshirsagar and Kalamkar (2016)
29.4901	397.30	Kshirsagar and Kalamkar (2016)
1.9732	534	Parajuli et al. (2019)
2.33	1027	Prapas et al. (2014)

But the limit values for the excess air ratio are 1.95 to 5.8 when taking CO and PM emissions into account (Memon et al., 2020).

2.4.4 Combustion chamber or chimney height

Placing an insulated short chimney right above the fire is one of the design principles stated by Larry Winiarski. And Aprovecho Research Center suggests that about three times as tall as its diameter should be the combustion chamber chimney. (Bryden et al., 2005). A short chimney placed above the fire improves draft and helps in the fire's hot, ferocious burning. Increasing the height of the chimney will result in a better draft for burning (Ayub et al., 2018). Because of the increased view factor and subsequent radiative heat transfer, decreasing chimney height increases the overall efficiency. Additionally, as chimney height is decreased, the overall height of the stove also drops, which is very advantageous from an ergonomic standpoint (Kshirsagar and Kalamkar, 2016). In Figure *2.6*, Kshirsagar and Kalamkar attempt to illustrate how the chimney height affects the stove's overall effectiveness for various fire powers.

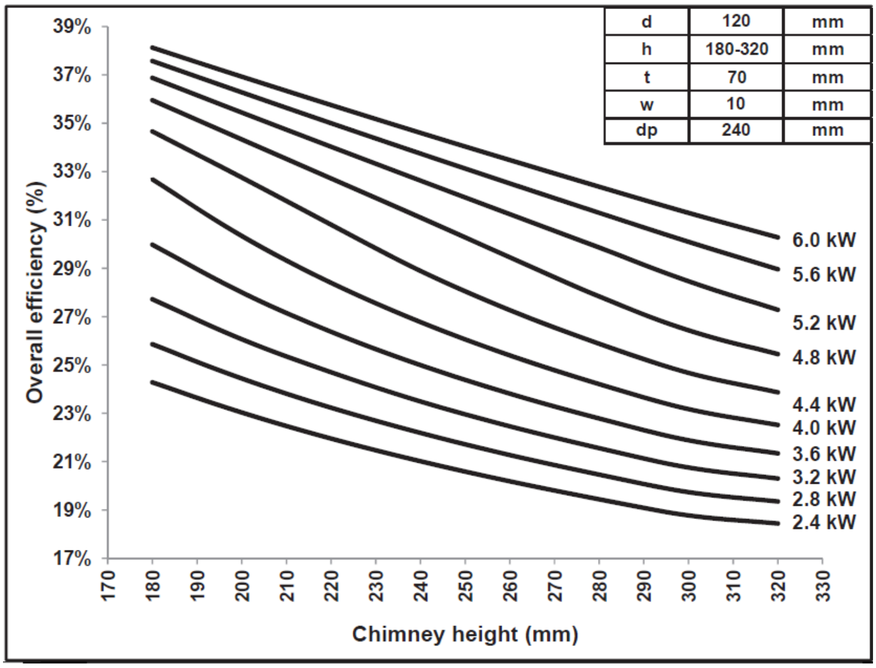


Figure 2.6 Variations of overall efficiency with the chimney height (Kshirsagar and Kalamkar, 2016).

Prapas et al. (2014) intended to comprehend how a chimney influences a stove's ability to burn wood (firepower), the ratio of air to fuel inside the stove, and the amount of carbon monoxide it produces. And according to Prapas et al. (2014), a chimney significantly affects the way biomass burns within a stove by influencing the overall air-to-fuel ratio and, as a result, the amount of carbon monoxide produced.

2.4.5 Insulation and insulation thickness

Cookstove insulation is crucial for improving performance since it decreases heat loss through heated walls and if the combustion chamber is sufficiently insulated, an increase in internal temperature can result in a reduction in emissions. To decrease heat loss and boost draft, Still and Kness (1996). suggested insulating the chimney. An insulated skirt serves as a second wall and lessens the risk of people being burned by the hot stove body. According to Baldwin (1987), efficient outside wall insulation enhanced a cookstove's efficiency by 8% while lowering fuel use by almost 5%. The choice of an insulating material is greatly influenced by the material's conductivity. Cookstove insulation is frequently made of materials like glass wool, ceramic wool, fire bricks, etc. The thermal efficiency, running time, ignition time, and power rating of sawdust, groundnut shell briquettes, cashew nuts, and babul wood were all researched by Panwar (2009) when he was researching the multi-biofuel gasifier cookstoves. He demonstrated that insulating a stove with heat-resistant cement yields roughly 35% thermal efficiency.

A cookstove's building components absorb a significant amount of energy during the cold-start high-power period. Choosing the optimal mixture of materials with low thermal mass and excellent insulation qualities is therefore crucial. Table *2.3* displays the thermal characteristics of a few materials utilized in cookstove construction.

Table 2.3 Thermal properties of selected materials used for the construction of cookstoves (Raman et al., 2014).

Materials	Density, kg/m^3	Specific heat, $J\ kgK^{-1}$	Thermal conductivity, $Wm^{-1}\ K^{-1}$
Ceramic wool	84	1070	0.09
Clay	2400	1381	0.65
Fire bricks	1280	1000	0.3
Metal sheet (mild steel)	7870	447	80.2
Metal sheet (stainless steel)	7900	477	14.9
Vermiculate	90	960	0.06

The effectiveness of a cooking stove when sawdust was used as insulation was examined in a study by Okino et al. (2021). A water boiling test was used to evaluate how well the three biomass fuels performed as a cooking stove. According to computational fluid dynamics, the heat was concentrated on the combustion chamber's inside while temperatures decreased near the stove's wall because of the stove's good sawdust insulation.

Because it lowers heat losses, increasing insulation thickness boosts efficiency in this situation. However, the reduction in heat loss diminishes after a certain insulation thickness, making the installation of more insulation economically unprofitable. The parametric analysis of the potential cookstove should be used to choose the ideal insulation thickness (Memon et al., 2020).

Table 2.4 The efficiency of small-scale cookstoves with different insulation thicknesses (Castaner et al., 2017).

Insulation thickness/mm	η/%
6.35	25.45
12.07	29.54
25.4	33.17
50.0	36.41
76.2	37.65
101.6	38.53

2.4.6 Grate

The grate's improved fuel-air mixing can increase efficiency and reduce pollution. When considering the rate of fuel burning, the grate's size is also crucial (Sedighi and Salarian, 2017). The average efficiency of an open fire is just under 15%, and when a grate is used, the efficiency of an upgraded open fire increases by 7%, according to Ballard-Tremeer and Jawurek (1996).

2.4.7 Effect of the pot gap width

The best way to transfer heat into pots or griddles is through narrow channels. The hot flue gases from the fire are forced through these tiny channels or cracks, scraping the griddle or pot. Obi et al. (2016) claim that efficiency rises when pot gap width decreases. If the gap is too big, the hot flue gases mostly stay in the center of the channel rather than transferring their heat to the intended cooking surface. If the gaps are too small a fire will become cooler, its emissions will increase, and less heat will enter the pot (Bryden et al., 2005). As stated by Baldwin (1987) the pot gap is influenced by the fuel combustion rate. For burning rates larger than 2 kg per hour, a gap of no less than 15 mm is necessary.

2.4.8 Effect of using Skirt

A skirt is a vertical extension or protrusion, typically made of metal, that is attached to the bottom of a pot or pan. Its function is to direct and channel the passage of hot gases from the fire, making sure that they closely circulate and produce even heating on the pot's edges.

For improved thermal efficiency, a skirt is put circumferentially around the pot. It increases heat transfer, reduces fuel combustion, and hence efficiency by directing the flame on the pot (Sedighi and Salarian, 2017). As it maintains the hot gas close to the pot, it is a successful method of enhancing heat transfer.

MacCarty et al. (2010) saw a more than one-fourth reduction in fuel use and CO emissions when pots with skirts were utilized. Use of a pot skirt can reduce fuel consumption and emissions by 25% to 30%. When used in an open fire stove and a model rocket stove, a skirt has a positive effect. In order to illustrate this, Andreatta and Wohlgemuth (2010) employed an open fire, simulated rocket stove, and a Chinese rocket stove. The gap between the skirt and the pan is also the perfect size. Five liters of water takes a long time to boil, according to Andreatta (2007). The Top-lit updraft gasifier (TLUD) with the insulated skirt used less fuel and heated the water more quickly. The TLUD with a pot consumed more fuel and took longer to boil water because no flue could touch its sides.

Wohlgemuth et al. (2009) conducted a computational heat transfer analysis of a basic third-world stove to investigate the impact of various skirt-related parameters on the overall heat transfer characteristics and thermal efficiency. The study revealed that the skirt design, which encloses the hot flue gases, minimizes convective losses from the stove.

To determine the impact of the skirt on the stove's thermal performance in a water boiling test, Ajunwa et al. (2021) developed a wood stove with the primary construction materials of mild steel sheet. The stove consists mostly of two pieces. The stove was put through tests both with and without a skirt, measuring 120 mm in height. The stove tested without a skirt had an average thermal efficiency of 31.33% and an average specific fuel consumption of 0.14 kg/l. However, when tested with a skirt, the stove performed better, with an average thermal efficiency of 38.65% and a specific fuel consumption of 0.09 kg/l. According to Ajunwa et al. (2021) the addition of a skirt in the stove design resulted in an improvement in thermal performance.

2.4.9 Cookstoves construction materials

The effectiveness of the cookstove relies on the material used to construct it. This is because the conductive properties of the material determine the amount of heat lost through its walls. Furthermore, the material's ability to absorb and retain heat also contributes to this loss. Hence, the decision of which material to use for the construction of a cookstove has significant implications on these aspects (Memon et al., 2020). When constructing a cookstove, it is important to keep in mind that the material choice affects the cost of the cookstove (Brady et al., 2017). Alliance (2013) found that a metal cookstove reaches its highest temperature in 17 minutes, whereas a clay stove does so in 36, during the fourth phase of the water boiling test (which involves cooling the material using water to assess the heat acquired by the water).

2.4.10 Biomass fuels

Biomass is regarded as the renewable energy source with the greatest potential to address the energy demands of contemporary society, for both developed and developing countries (Bridgwater, 2006). The selection of fuel is significantly impacted by factors such as the availability, cost-effectiveness, and convenience of the fuel. Additionally, the decision also relies on a household's financial and technological capabilities, as well as cultural and social influences.

2.4.11 Solid biomass fuels

Solid biomass is made up of combustible renewable organic energy sources like animal manure and plant-based materials (McKendry, 2002). Wood biomass fuel is the primary energy source in the globe, mainly for heating and cooking (Jana and Bhattacharya, 2017). Although wood is the preferred and best solid fuel, other biomass fuels can be utilized if the wood is not an option.

According to Arora et al. (2014), the emissions of CO and PM vary depending on the type of fuel used. Mustard stalks were found to result in a 45% and 70% increase in CO and PM emissions, respectively, compared to firewood and kerosene. The researchers also examined the impact of fuel-feeding intervals on CO emissions and discovered that a longer interval of 15 minutes caused the CO concentrations to rise by up to 60% compared to a shorter interval of 7 minutes due to smoldering.

Ptasinski (2008) investigated the energy and exergy efficiency of a variety of biofuels, including grass, vegetable oil, manure, treated and untreated wood, straw, sludge, and coal. While the exergy efficiency was evaluated for chemical exergy and combined chemical and physical exergy, the energy efficiency was determined based on the lower heating value. The energy or exergy of the combustible gases generated was divided by that of the solid fuel in order to calculate the energy or exergy efficiency. According to the study, sludge and manure had much lower efficiencies than coal, treated and untreated wood, vegetable oil, grass, and straw. Additionally, compared to other biofuels, coal and vegetable oil exhibited higher chemical and physical exergies, with coal and vegetable oil's chemical exergy being about 75% and the others' being between 70 and 80% (Ptasinski, 2008).

There exist various forms of solid biomass fuels, each possessing differing energy levels. Table 2.5 presents a comparison of diverse biomass fuels.

Table 2.5 Comparison of various biomass fuels (Memon et al., 2020).

Fuel	PM/g kg^{-1}	CV/MJ kg^{-1}	η/%
Anthracite briquette	0.59	21	39
Anthracite chunk	1.1	21	14
Bituminous briquette	7.1	28	32
Bituminous chunk	12	28	14
Crop straw	5.6	16	16
Crop straw pellet	2.1	14	37
Firewood log	1.8	18	18
Wood pellet	0.85	16	29
Natural gas	0.16	51	57
Wood branches	2.6	17	14
LPG	0.27	49	44

2.5 Recent studies on Rocket Stoves (International and National)

A rocket stove belongs to the category of improved cookstoves that operate through direct combustion, meaning that the fuel is burnt directly to unlock its chemical energy. As per Kshirsagar and Kalamkar (2014) study, it has been identified as one of the most efficient stoves, producing the least amount of emissions.

Rocket stoves rely on the stack effect to create a vacuum that serves as the source of air combustion (Abdurrahman et al., 2018). This occurs when the temperature within the stove exceeds that of the outside, causing a decrease in air density and a resulting lightening of the air. As the lighter air rises, it creates a vacuum inside the stove. Fresh air from outside is then drawn in to fill this vacuum.

MacCarty et al. (2010) investigated the efficiency of fifty different cookstoves by comparing them to the traditional three-stone fire cookstoves in terms of fuel consumption, carbon monoxide (CO) emissions, and particulate matter (PM). Their analysis revealed that the Rocket stove outperformed all other stoves, consuming 33% less fuel and reducing CO and PM emissions by 75% and 46%, respectively. The researchers also found that using a pot skirt resulted in a 25-30% reduction in fuel consumption and CO_2 emissions. Additionally, they emphasized the importance of using a well-designed cookstove with a chimney to effectively remove smoke from the kitchen.

In the research conducted by Khan et al. (2016), the design of the rocket stove was determined based on the amount of water that can be evaporated within a specific time. The cook stove's performance was evaluated through the water boiling test (WBT) and the Gasteq tube method to measure indoor air pollution. The findings indicated that the cook stove's thermal efficiency was 30.52 percent, and the level of indoor pollution was within acceptable limits.

In the study conducted by Ochieng et al. (2013), the effectiveness of the rocket mud stove (RMS) in reducing fuelwood consumption in rural communities in Kenya was assessed. The researchers discovered that the type of stove used had a significant impact on fuel consumption, with rocket stoves using significantly less fuel than traditional three-stone stoves.

The study conducted by Teshome et al. (2020) aimed to address the issues of firewood consumption and carbon monoxide emissions associated with the use of traditional three-stone open fire stoves (TSOFS). To achieve this, they utilized design parameters from the Aprovecho research center to develop an improved rocket stove and incorporated certain modifications to the cookstove. A local substance was added to the rocket stove's combustion chamber's insulating composition in order to limit heat transmission, and the performance was assessed using the controlled cooking test (CCT) method. According to the study, the improved rocket stove used 41% less fuel than TSOFS and reduced the amount of CO in the kitchen by 24.8% when compared to conventional open-fire stoves.

Mekonnen (2020) created the rocket stove per the design philosophy of the Aprovecho Research Center (USA). Red ash and mild steel sheet metal were used to build the stove. The CO and particulate matter ($PM_{2.5}$). Concentrations were measured using the indoor air pollution (IAP meter 5000) monitoring system. The performance of the stove was assessed using the water boiling point test (WBT). Thermal efficiency significantly increased, and emissions were reduced. The average CO and $PM_{2.5}$ levels were 3.1 ppm and 52 g/m^3 correspondingly, and the planned stove had a mean thermal efficiency of 29 percent.

In the study conducted by Hailu (2021), the performance of an institutional rocket stove built by the author was evaluated, as well as the characteristics of the stove's co-product, bio-char, for soil amendment. The experiment yielded a fuel consumption rate of 8.75kg and an overall thermal efficiency of 45.67% using additional pyrolysis for the stove. The bio-char produced was found to be suitable for soil amendment due to its high-temperature burn characteristics.

2.6 Literature summery

From traditional stoves to improved and advanced models, the literature study concentrated on the advancement of biomass cookstoves. While improved biomass cookstoves were shown to have greater cooking efficiency, cleaner operation, and shorter cooking times, the majority of research on traditional biomass cookstoves highlighted their inefficiency, pollution, and detrimental effects on health. Recent advancements in this area include advanced biomass cookstoves, which are made in factories using current technology advancement and product development research. larger efficiency, lower emissions, increased longevity, and improved safety are all features of these stoves. Several studies have identified the parameters that significantly impact the performance of improved biomass cookstoves, such as the stove design, insulation, combustion chamber, and air flow. By incorporating appropriate materials and designs to improve these parameters, the performance of the cookstoves can be enhanced. Many of these studies have recommended the adoption of Rocket stoves, as they have been shown to have superior thermal efficiency and lower emissions compared to traditional wood-burning cookstoves.

In many studies, there is a significant focus on the geometrical design of rocket stoves as it is a crucial parameter for their performance. However, there has been comparatively little effort toward the height of the combustion chamber, insulation design and choice of materials. Furthermore, when it comes to studies on rocket stoves in Ethiopia, there is a lack of research on household or domestic-sized rocket stoves, with most studies focusing on institutional types. This study aims to address this gap by adopting the principles and design of family-sized (household) rocket stoves and analyzing their performance under the conditions present in local rural areas.

CHAPTER THREE

3. Material and methodology

3.1 Introduction

This section gives a thorough explanation of the techniques and approaches used for achieving the study's objectives. It covers the methodologies of study design, different types of data sources, data gathering techniques, required materials, and instruments to facilitate data collection.

3.2 Data source and data collecting method

For this research, both primary and secondary data collection methods were utilized to gather comprehensive inputs.

Primary data were obtained by direct measurement of the ambient temperature, distinct zonal temperature, beginning and final boiling water temperatures, the mass of the wood fuel and fuel moisture contents. A thorough literature study was also conducted while secondary data was collected from a variety of online sources, including books, website documents, local and international journal articles, and publications.

3.3 Methodology

This study aims to develop a version of a rocket stove based on the design principles of the Aprovecho Research Center. It incorporates several geometrical modifications to ensure superior performance and ease of construction. Local, readily available materials are also utilized, including a mix of wood ash and gypsum, which is used as insulation. The designing and drawing of this improved rocket stove are carried out using Solid Works 2023 software, ensuring accurate and seamless execution.

To initiate an understanding of enhancing stove performance, it is imperative to comprehend both the theoretical and current practical limits. Accordingly, the theoretical constraints are analyzed first. Experimental approaches have been used to study the rocket stove performance.

3.4 General work flow chart

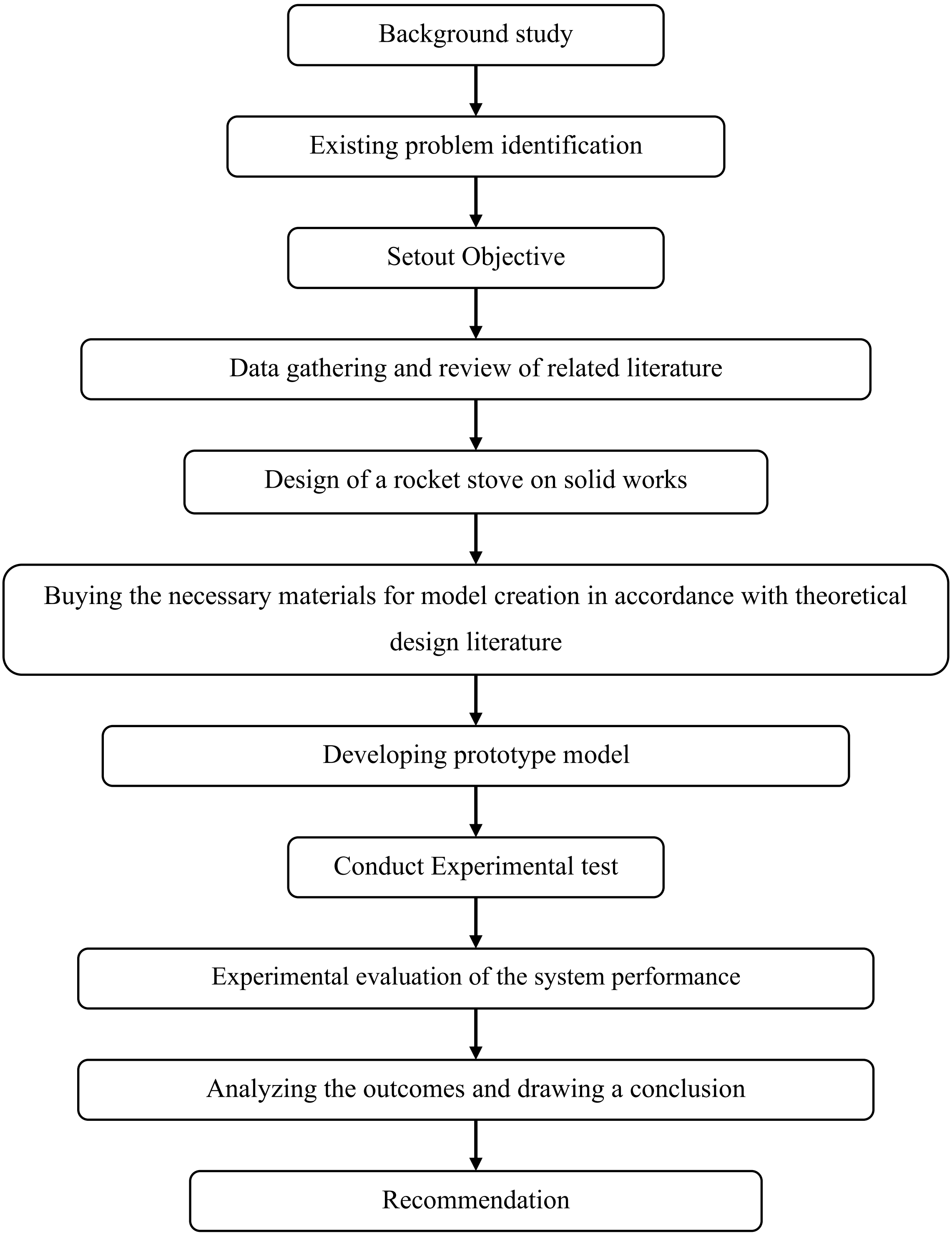


Figure 3.1 General work flow of the research

CHAPTER FOUR

4. Rocket stove design and development

4.1 Design consideration

This rocket stove has been developed by incorporating design parameters from the Aprovecho Research Center. Enhancements in insulation design material selection have been made to the original design. Additionally, locally sourced insulation materials have been included to minimize heat transfer in the combustion chamber. A deep understanding of fundamental physical phenomena, including heat transfer, fluid flow, and combustion, is necessary to develop a production prototype of a new system with high thermal efficiency and low emissions of toxic gases and particulate matter. In the process of designing the rocket stove, careful consideration is given to various factors such as the quantity of water to be vaporized, minimization of heat loss, environmental impact, and cost-effectiveness.

When designing a rocket stove, careful consideration is given to the size and capacity of the pot it will be used with. Additionally, the availability of locally sourced materials is taken into account to minimize production and maintenance costs. The materials selected for constructing the various components of the stove are chosen based on their ability to withstand the weight and forces acting upon them, their expected performance, and the environmental conditions in which they will operate. Finally, wood ash is used as an insulator to optimize the stove's thermal efficiency and achieve the desired operating temperature range.

4.2 Description of the Rocket Cookstove

The rocket stove's operating concept serves as the foundation for the design's configuration. The stove's overall height is 55 cm with its skirt attached and 45 cm without. This biomass cookstove, which is made of 1 mm thick sheet metal, is quite similar to other rocket stoves. The pot holder and the combustion chamber are the two primary components of the stove.

The cookstove consists of two concentric cylinders, with the inner cylinder acting as the combustion chamber for burning wood and the outer cylinder acting as the body of the stove. A rectangular hole that connects the inner and outer cylinders allows air and biomass fuel to enter for burning as well. On the top of the combustion chamber, there is a pot holder and there is a detachable skirt attached to the body of the stove. Table 4.1 gives a detail of the stove design.

The stove's body is 300 mm in diameter and 420 mm in height, while the combustion chamber inside it measures 120 mm in diameter and 360 mm in height. The body serves the dual purpose of hosting the cooking pot and providing support to the combustion chamber. Both the body and combustion chamber are constructed from steel sheet material that has a thickness of 1 mm.

The body of the stove and the combustion chamber are fitted to a bottom plate that measures 300 in diameter. A door opening of 120 mm by 180 mm has been created, which includes a 120 mm by 120 mm opening for wood fuel and secondary air, as well as a 120 mm by 60 mm primary air inlet that is located below the grate. The stove's body also includes a top plate with a diameter of 300 mm, featuring an overlapping flange and six pot supports. Figure 4.1 shows the schematic diagram of the Rocket Stove.

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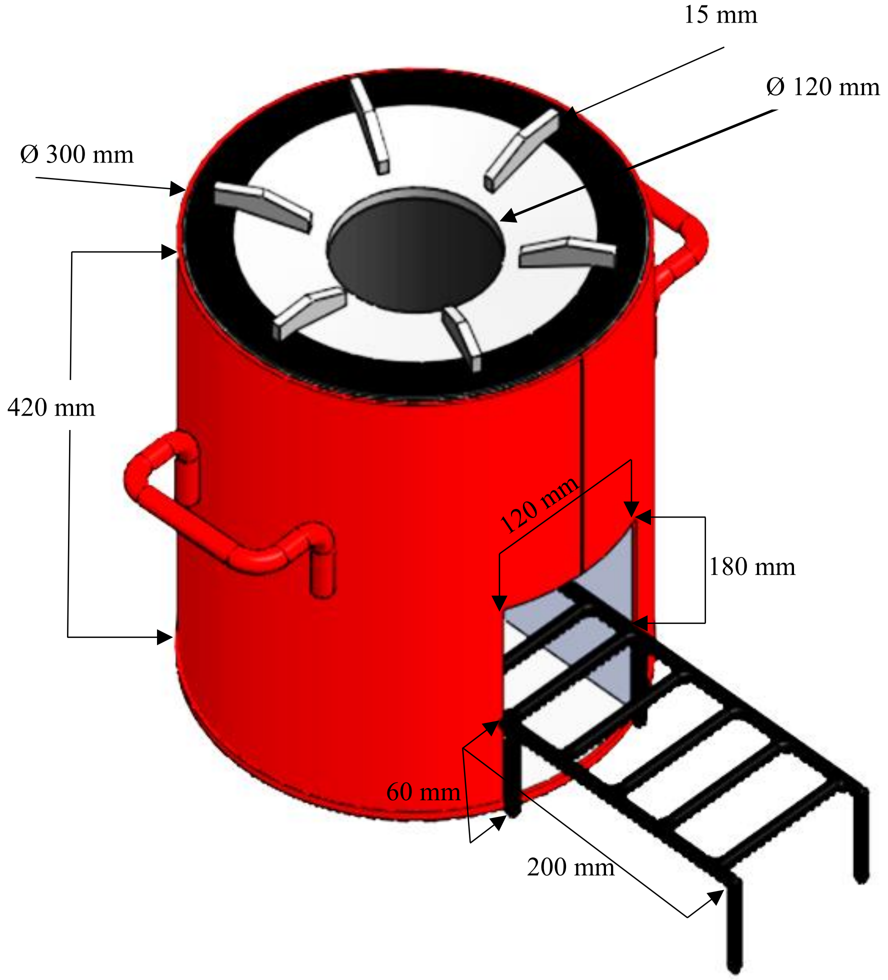

Figure 4.1 Schematic diagram of the designed Rocket Stove

Table 4.1 Design calculation of the rocket stove.

Initial data / Parts	Design equation and Result	Reference
Pot diameter, 260 mm	Pot diameter, $D_p = 260\ mm$ as chosen as a family-size pot and available in the market. Circumference of the pot, $C_P = \pi \times D_p = \pi \times 260\ mm = 817\ mm$	-
Door opening for the wood fuel inlet, 120 mm by 120 mm	Aprovecho Research Center has recommended this cooking stove opening for family size. The area of fuel opening becomes, $A_f = (120\ \times 120) mm^2 = 144\ cm^2$	(Bryden et al., 2005)
Air inlet, 72 cm^2	Baldwin (1987) stated that it is constructed to be half the size of the fuel door. $A_a = \frac{144\ cm^2}{2} = 72\ cm^2$	(Baldwin, 1987)
In the combustion Chamber, the diameter is 120 mm and the height is 360 mm. D_c = 120 mm H_{c1} = 360 mm H_{c2} = 240 mm	The combustion chamber was constructed with a 120 mm diameter, the same size as the chamber entrance (Winiarski, 1997). One combustion chamber height is three times the diameter and the other is two times (Dana, 2009) and two times , $H_{c1} = 3 \times 120mm = 360\ mm$ $H_{c2} = 2 \times 120mm = 240\ mm$ Area of the combustion chamber, $A_c = \frac{\pi}{4} \times {D_c}^2 = \frac{\pi}{4} \times (120\ mm)^2 = 11310\ mm^2$ Circumference of the combustion chamber, $C_c = \pi \times D_c = \pi \times 120\ mm = 377\ mm$	(Baldwin, 1987; Bryden et al., 2005; Dana, 2009; Still and Winiarski, 2001)
The gap between the Combustion Chamber and Pot, and the Gap at the Edge of the Pot.	The gap between the bottom of the pot and the edge of the combustion chamber, $G_c = 3\ cm$ $G_c = \frac{A_c}{C_c} = \frac{11310\ mm^2}{377\ mm} = 30\ mm$ Gap at the edge of the pot and the stove's body, $G_p = 2\ cm$ $G_p = \frac{A_c}{C_p} = \frac{11310\ mm^2}{817\ mm} = 15\ mm$	(Bryden et al., 2005)
Body of the stove, The diameter is 300 mm and the height is 390 mm	Height of the stove's body, $H_{B1} = H_{c1} + G_c = 360\ mm + 30\ mm = 390\ mm$	-

for H_{c1} = 360 mm and 270 mm for H_{c2} =240 mm.	$H_{B2} = H_{c2} + G_c = 240\ mm + 30\ mm = 270\ mm$ Diameter of the stove's body, $D_B = D_p + 2G_p + 10mm\ (skirt\ allowans) = 300mm$	
Base Plate Diameter, 300 mm	The stove's base diameter measures 300 mm, designed to fit snugly into the stove's body. $D_{B,P} = 300\ mm$	-
Top plat	300 mm for the top plate's outer diameter and 120 mm for its inner diameter. made to support the six pot stands that are uniformly positioned over the plate. And has an over-flange for a good draft.	-
Skirt	The skirt diameter is the sum of the pot diameter and twice the gap at the edge of the pot and the stove's body, $D_s = D_p + 2G_p = 290\ mm$	-

4.3 Prototype production of the Rocket Stove

To create the combustion chamber of the rocket stove, a 1 mm sheet of metal measuring 18 cm by 37 cm was rolled to form a cylindrical chimney with a diameter of 12 cm. Another piece of 1 mm sheet metal measuring 18 cm by 47 cm was rolled into a half-circle shape from the center to form the door opening, air inlet, and grate for the combustion chamber. The chimney and lower part were then welded together to create an L-shaped combustion chamber, which was then welded circumferentially to the 30 cm diameter bottom part of the stove.

A cylindrical body for the stove was created by rolling another piece of 1 mm sheet metal measuring 42 cm by 95 cm. An 18 cm by 12 cm section was cut from the body cylinder to serve as the feed door opening, with a 12 cm by 12 cm section for the feed door and a 6 cm by 12 cm section for the air inlet. This section was then welded circumferentially to the bottom of the stove body.

For the pot support, a 30 cm by 30 cm sheet metal was cut to form a circular plate with an outer diameter of 30 cm and an inner diameter of 12 cm (matching the diameter of the combustion chamber). At a radius of 14.5 cm from the center, the plate was made to flange to create a gap space for the pot. Six pot supports, each with a height of 1.5 cm and a width of 1 mm, were welded onto the remaining horizontal surface of the plate.

Figure 4.2 Combustion chamber and body of the rocket stove

Figure 4.3 Pot support of the rocket stove

A detachable skirt was created from 0.7 mm sheet metal measuring 10 cm in height and 30 cm in diameter. It was not welded to the top to enable easy detachment when necessary

Figure 4.4 Pot skirt

Finally, the developed rocket stove is shown in Figure *4.5*.

Figure 4.5 Developed rocket stove.

Utilizing insulating material on the heat transfer region to cut down on energy losses is the most pertinent strategy for creating an effective cookstove. The process of choosing insulation for the stove construction involved considering and analyzing recommended insulations from literature based on several parameters; including durability, heat conductivity, toxicity, weight, availability, and cost-effectiveness. Table 4.2 shows the comparative property of some insulation materials.

Table 4.2 Comparative properties of Pumice Rock, Dry Wood Ash, Vermiculite Clay soil, and Aluminum Foil.

Insulating materials	Availability	Durability	Cost-effectiveness	Weight	Non-toxic	Score/100
Pumice Rock	F	G	P	P	E	55
Dry Wood Ash	E	G	E	F	E	85
Vermiculite	P	E	P	E	G	65
Clay soil	G	G	E	P	E	75
Aluminum Foil	G	G	F	E	E	70

* E=Excellent, G=Good, F=Fair, P=Poor.

From the above simple analysis, dry wood ash would be convenient to implement for insulation.

Based on the available local material, specifically wood ash is free insulation material, And the air is a reliable insulation medium due to its low thermal conductivity of 2.623-6.763E10^{-2} W/m.k between 300 and 900 K (Graczykowski et al., 2017). To create an effective insulator, a proper design must combine air with wood ash. This study includes an examination of the air gap between two walls of insulation, which is designed using a combination of wood ash and gypsum (for its adhesive properties).

To investigate the thermal conductivity of various insulation samples, four distinct ratios of the primary element were employed. Each sample was prepared with a diameter of 30 mm.

(a) (b) (c) (d)

Figure 4.6 Sample for thermal conductivity test of the insulation, (a) 1:1 ratio, (b) 1:2 ratio, (c) 1:3 ratio, and (d) 1:4 ratio.

Figure 4.7 Preparation of the insulation material.

Using G.u.n.t. WL 374 thermal conductivity tester, the produced samples were tested for thermal conductivity. It operates by applying a constant temperature difference across the material and measuring the resulting heat flow. the material being tested is placed between the two heating plates. One plate is heated to a higher temperature than the other, creating a temperature gradient across the material. The temperature sensor measures the temperature difference, while the heat flux sensor measures the heat flow through the material. These measurements are used to calculate the thermal conductivity of the material. The device was calibrated using materials with established thermal conductivity values as a reference to achieve maximum accuracy. After the test was conducted a ratio of 1 gypsum for 2 wood ash by volume having a thermal conductivity of 0.238 W/mK. was used for the insulation material. See APPENDIXES D.

4.4 Thermal analysis of the Rocket stove

This section provides a comprehensive and detailed account of the thermal analysis of the rocket stove, proximate analysis of the fuel, and performance parameters of the stove. To begin comprehending the performance of a stove, both the theoretical limitations, as well as the existing practical limits to stove performance, must be grasped.

4.4.1 Heat transfer analysis of the Rocket stove

Although investigating the thermal analysis of fluid flow in a biomass cookstove may be a difficult process, it is advisable to make some assumptions to make the issue simpler. So, in order to make it easier to estimate the energy analysis in the model, several critical assumptions have been specified. A cookstove's heat transfer method can be characterized as one-dimensional. Under steady-state conditions, where the combustion products are regarded as fluids, this stove performs effectively. The stove zones are treated as fixed, non-deformable control volumes for the analysis. Notably, there is little any pressure loss within the combustion chamber. The flow within the stove is also symmetrical.

4.4.1.1 Heat transfer analysis

The process of energy transfer within a stove occurs through heat transfer, which is driven by temperature differences between two bodies. To model the heat transfer analysis, the primary governing equation used is the mass and energy balance of the first law of thermodynamics. The three modes of heat transfer equations are used to examine different zonal heat transfers and energy losses. This section focuses on discussing the heat and energy transfer in stoves, including convection, conduction, and radiation losses of heat inside a medium.

Conduction is the primary mode of heat transfer that takes place on a stove, which occurs between different walls of the stove. The temperature of a solid, liquid, or gas is determined by how quickly the atoms and molecules inside it move: the faster they move, the hotter the substance. Conductive heat transfer happens in gases and liquids when fast molecules collide with slower molecules unexpectedly, giving away part of their energy. Heat is gradually moved from higher temperature zones to lower temperature regions in this manner.

To calculate the heat transfer by conduction on a cookstove, one can rely on the Fourier law of conduction (Baldwin, 1987). This law outlines how heat transfers through a material based on its thermal conductivity and temperature gradient. To calculate the rate of heat transfer by conduction $\dot{Q}_{cond}$ (measured in W), it is needed to know the area of the cross-sectional surface (A), the thermal conductivity of the materials (k), and the temperature difference between the endpoints of the stove (ΔT). Additionally, it must determine the distance between the two ends or lengths (ΔX) to complete our calculation accurately. These factors play a crucial role in understanding how heat is transferred and how efficiently it can be done through different materials.

$$\dot{Q}_{cond} = -kA \, {}^{\Delta T}/_{\Delta X} \qquad 4\text{-}1$$

However, using only this equation to calculate the heat transfer across a stove wall would yield significantly exaggerated outcomes; the conductivities of the respective surfaces, as well as the conductivity within the object, collectively discern the amount of heat transferred in and out of it. The rate of heat transfer ($\dot{Q}_{cond}$) is directly affected by the insulation part's thickness, as well as the types of materials used for insulation and the temperature difference across the medium (Gogoi and Baruah, 2016). In certain situations, the presence of dirt or oxide layers can hinder the ability of heat transfer through a surface, whilst in others, the presence of air at the surface can indeed impede the heat transfer process. Taking this into consideration results in

$$\dot{Q}_{cond} = \frac{A(\Delta T)}{\frac{1}{h_1} + \frac{s}{K} + \frac{1}{h_2}} \qquad 4\text{-}2$$

Where h_1 and h_2 are the inner and outer surface heat transfer coefficients. Typical h values range from 5 W/m^2°C in still air to more than 15 W/m^2°C in a moderate 3 m/s breeze. The thermal resistances to heat transfer is represented by the inverse values 1/h and s/k. For 1-mm-thick steel, 0.04 m^2°C for 2-cm-thick baked clay, and 0.10 m^2°C/W for a 10-cm-thick concrete wall, the typical values of thermal resistances (s/k) are 0.0000286 m^2°C/W. In comparison, the thermal resistance of the air at the surface of the stove wall (1/h) for still air is 0.2 m^2°C/W and 0.0667 m^2°C/W for a 3 m/s breeze. To account for both the inner and outside surfaces, these values must be doubled.

In the convection mode of heat transfer, heat is transferred from a moving fluid to a solid surface that is stationary. Free convection, where warmer gases stimulate the transfer and the convection velocity is relatively lower than in forced convection, is used by natural draft-based biomass cooking stoves to transfer heat. Examples of surfaces where this sort of heat transfer takes place include the cooking pot's base and the fluid (such as flue gas in motion), as well as the region around the pan's edges and the fluid. To calculate the amount of heat transmitted by convective mode, utilize the convective heat transfer equation.

$$\dot{Q}_{conv} = hA\Delta T \qquad 4\text{-}3$$

Where, $\dot{Q}_{conv}$ is the heat transferred rate by convection (W),

h is the heat transfer coefficient for convection (W/m^2°C).

A is the heat transfer area (m^2), and

There are assumptions to be taken to determine the convective heat transfer coefficient h.

- The heated, flat, one-dimensional surface is facing the vertical cylinder.
- Convective heat transfer's flow field is modeled as a vertical plate.

Then convective heat transfer coefficient h is;

$$h = \frac{k}{L} N_u \qquad 4\text{-}4$$

$$N_u = \frac{hL}{k} = 0.59(G_r \times P_r)^{0.25} \qquad 4\text{-}5$$

Where, P_r is Prandtl number and G_r is Grashof's number

$$P_r = \frac{\mu C_p}{K} \qquad 4\text{-}6$$

$$G_r = \frac{L^3 \rho^2 g \beta (T_{fl} - T_\infty)}{\mu^2} \quad \text{4-7}$$

T_∞ is ambient temperature

$$T_f = \frac{T_{fl} - T_a}{2} \text{ °C} \quad \text{4-8}$$

Radiation is one of three different forms of heat transmission that take place during combustion. This mode is in charge of transferring heat from the char and fire radiation in the combustion chamber to a variety of surfaces, such as the bottom of the pot, the stove wall, and the stove body. Additionally, it is essential for maintaining the temperature in the area around.

The rate of radiation heat transfer is calculated using the Stefan-Boltzmann equation and is given by;

$$\dot{Q}_{rad} = \varepsilon \sigma As T^4 \quad \text{4-9}$$

Where;

- $\dot{Q}_{rad}$ is heat transfer rate by radiation
- ε is emissivity of the emissive body
  ε=exp{(0.848+9.02×10^{-4} × T^4)+(0.9589+4.8×10^{-6}×T) × ln (0.2×L_b)
  L_b is the characteristic length
- σ is Boltzmann constant ($5.67 \times 10^{-8}\ W/_{m^2K^4}$)
- T is the absolute temperature
- A_c is the Area of the combustion chamber

Heat transfer by radiation is influenced by surface geometry (As), the fluid's properties (viscosity, density, specific heat (Cp) as well as, the kind of fluid motion, and fluid velocity (Núñez et al., 2020).

4.4.1.2 Heat balance equation

A rocket stove is comprised of several key components, including a combustion chamber to enclose the fire, insulation to minimize heat losses and control surface temperature, an air supply system to direct the flow of air, a heat transfer zone to facilitate convective and radiative heat transfer to the cooking pot and a cooking pot to hold the food being prepared.

The configuration depicted in Figure *4.8* shows the “Rocket stove" design, featuring a cylindrical combustion chamber that is insulated to protect the fire, and a single pot. This design can be divided into four distinct zones: firstly, the combustion zone - which comprises the air supply port, fuel bed, fuel feeding door, and fire shield or chimney; secondly, the pot bottom zone - where an impinging flue jet strikes against the pot bottom; thirdly, the pot gap zone - which denotes the space between the pot bottom and the stove body; and finally, the pot side zone - in which flames scrape against the pot sides.

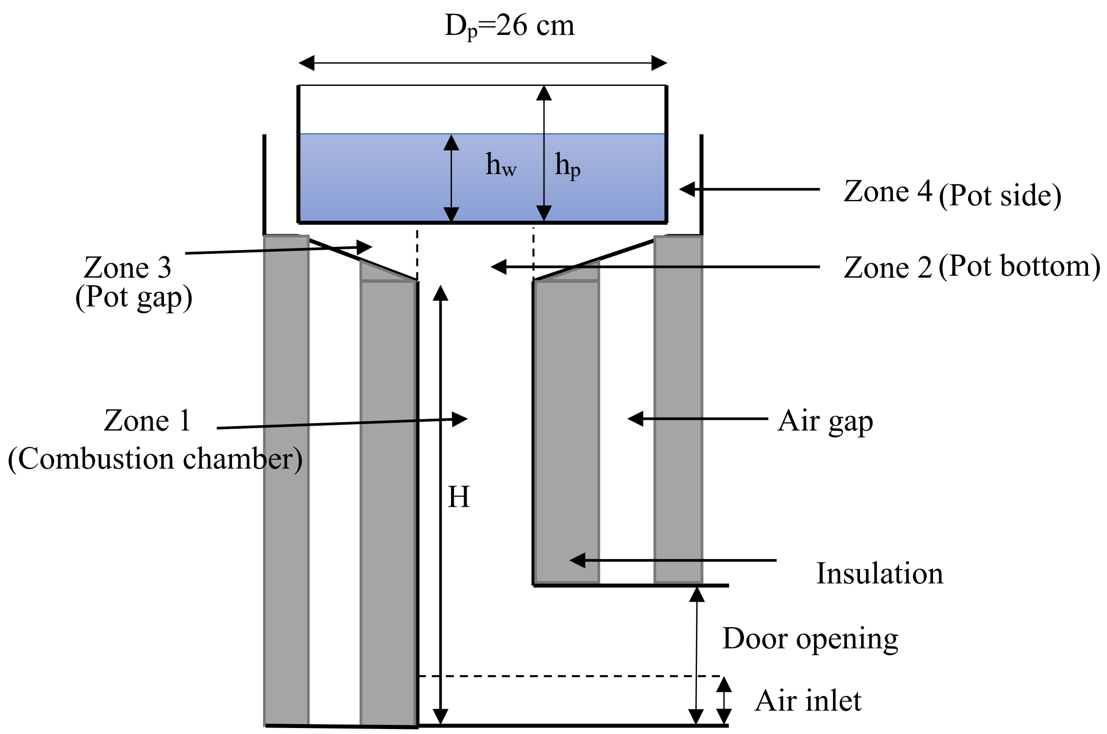

Figure 4.8 Model geometry of the Rocket stove

Combustion, heat transmission, and fluid flow are the three fundamental phenomena that make up a cookstove's operation. These phenomena include several sub-phenomena, such as impinging jet heat transfer, char combustion, volatile combustion, drying, turbulence, pyrolysis, pressure drops between sections, and conductive, convective, and radiative heat transfers. And to predict the performance of a rocket stove, certain simplified assumptions are made. However, these assumptions do not neglect any important aspects of the stove's operations.

Figure 4.9 Shows schematic and heat transfer resistance diagram of the Rocket stove.

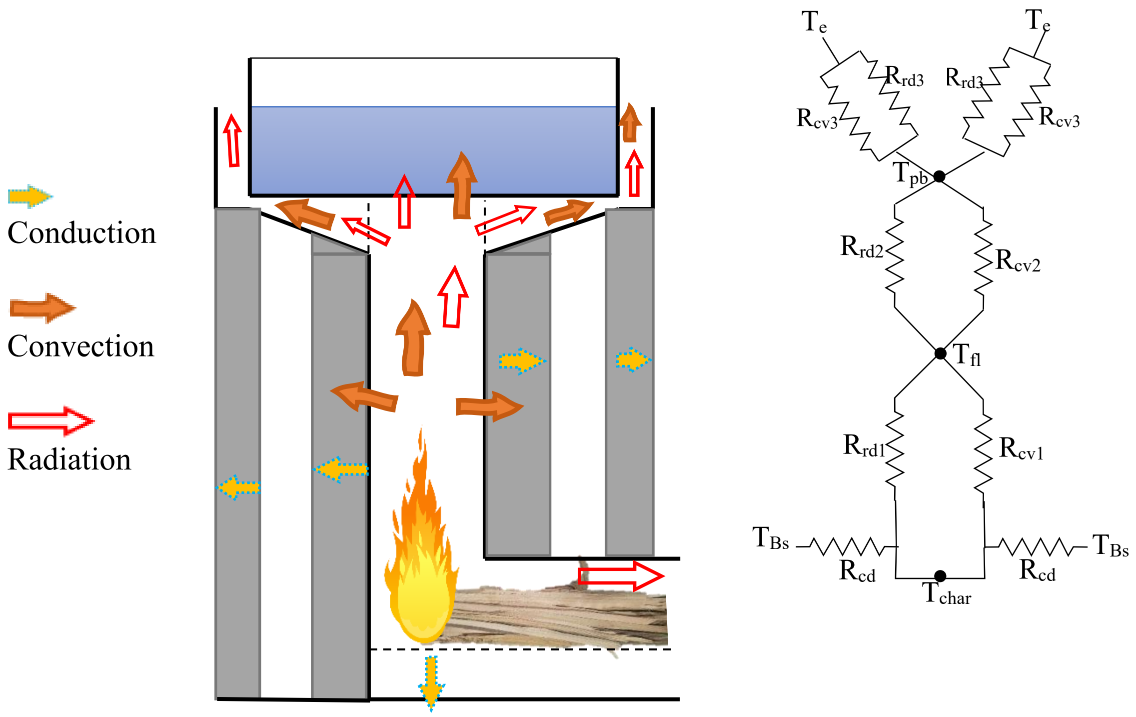

Figure 4.9 Schematic and heat transfer resistance diagram of the Rocket stove.

For the objective of operating a cookstove, the bare minimum assumptions listed below are made:

- The stove runs under steady-state conditions.
- The flow within the stove is axisymmetric and one-dimensional.
- The whole grate's surface is covered by the fuel bed.
- Burning char has a surface temperature of 1100 K and an emissivity of 0.85. (Dasappa and Paul, 2001; Urbas and Parker, 1993; Varunkumar et al., 2012)).
- Assuming they are black bodies, the outside surface of the pot and the inner surface of the stove have an emissivity of 1.
- Assuming high conductivity aluminum pots, the cooking pot's conductive resistance is insignificant.
- The cooking pot's average temperature is 373 K, or the point at which water begins to boil.
- The flue gas exhibits perfect gas behavior, and when measured at atmospheric pressure, its thermodynamic characteristics are identical to those of air. Different air

characteristics show correlations for the temperature range of 300-1500 K at 1 atm (Holman, 1986).

$$\mu = 0.0447 \times 10^{-5} \times T^{0.7775} \qquad 4\text{-}10$$

$$K = 0.00031847 \times T^{0.7775} \qquad 4\text{-}11$$

$$C_p = 0.9362 + 0.0002 \times T \qquad 4\text{-}12$$

$$v = (0.0000644 \times T^2 + 0.0631 \times T - 9.54) \times 10^{-6} \qquad 4\text{-}13$$

$$\rho = {}^{353}/_{T} \qquad 4\text{-}14$$

$$P_r = 0.685(constant) \qquad 4\text{-}15$$

$$h = 9.314 \times 10^{-5} \times T^2 + 0.94576 \times T + 7.0445 \qquad 4\text{-}16$$

This enthalpy value of air is correlated from Cengel et al. (2011).

Combustion chamber (Zone 1)

The combustion chamber primarily accounted for the combustion of fuel, including volatiles and char, as well as the transfer of radiant heat to the pot from the flame and char. Additionally, heat loss from the stove walls and the open door to the surroundings was also taken into consideration.

The airflow in naturally aspirated wood-burning stoves is driven by the chimney effect caused by buoyancy force, which pushes the air against various flow resistances. This airflow plays a crucial role in determining the wood burning rate, as well as the overall heat transfer and combustion performance of the stove. The chimney effect, which refers to the upward flow of air through a chimney, is influenced by various factors, including the total amount of heat added at the base of the chimney and the constant temperature and density of the flue gas given as;

$$\Delta P_{chimney} = H \times (\rho_a - \rho_g) \times g = {}^{1}/_{2}\, \rho_g V_{th}^2 \qquad 4\text{-}17$$

And the density of the flue gases inside the chimney is

$$\rho_g = {}^{353}/_{T_g} \qquad 4\text{-}18$$

Rearranging Eqs. (4-17) and (4-18) give the theoretical velocity of flue gases inside a chimney:

$$V_{th} = \sqrt{2 \times g \times H \times \left({T_g}/{T_a} - 1\right)} \tag{4-19}$$

From continuity equation theoretical mass flow rate of flue gases:

$$\dot{m}_{th} = \frac{353}{T_g} \times A \times \sqrt{2 \times g \times H \times \left({T_g}/{T_a} - 1\right)} \tag{4-20}$$

Taking into consideration the pressure drop caused by various factors throughout the stove, the actual mass flow rate is:

$$\dot{m}_{act} = C_d \times \frac{353}{T_g} \times A \times \sqrt{2 \times g \times H \times \left({T_g}/{T_a} - 1\right)} \tag{4-21}$$

The discharge coefficient C_d is utilized to account for losses caused by viscous effects within the stove as well as scattered heat addition from the combustion process. C_d values are normally less than one and range from 0.35 to 0.42 for various types of chimneys (Agenbroad et al., 2011a, 2011b; Ong and Chow, 2003; Sakonidou et al., 2008).

APPENDIX C provides equations for various loss coefficients, density ratios, and area ratios.

Applying mass balance:

$$\dot{m}_{act} = m_{flue} \times \dot{m}_f \tag{4-22}$$

$$m_{flue} = \left(m_a + 1 + \frac{M}{100 - M}\right) \tag{4-23}$$

As indicated in equation (23), the firepower and net calorific values of the fuel can be used to determine the fuel mass flow rate ($\dot{m}_f$).

$$\dot{m}_f = \frac{F_P}{NCV} \tag{4-24}$$

The heat supplied by the fuel in the combustion chamber, or the heat addition, is equal to the firepower (F_P) of the cooking process.

Rearranging Eqs. (*4-23*) and (*4-24*) give

$$m_{flue} = C_d \times \frac{353}{T_g} \times \frac{1}{\dot{m}_f} A \times \sqrt{2 \times g \times H \times \left({T_g}/{T_a} - 1\right)} \tag{4-25}$$

When applying a heat balance to the combustion chamber:

$$\mathrm{Q_{supplied\ by\ the\ fuel\ combustion}} = \mathrm{Q_{gain\ by\ the\ flue}} + \mathrm{Q_{char\ radiation}} + \mathrm{Q_{flame\ radiation}} + \mathrm{Q_{heat\ loss}} + \mathrm{Q_{door\ loss}} + \mathrm{Q_{H2\ moisture}} + \mathrm{Q_{fuel\ moisture}} \quad \text{4-26}$$

$$\mathrm{LHV} \times \eta_c = \mathrm{m_{flue}} \times (\mathrm{h_g} - \mathrm{h_a}) + \mathrm{Q_{char\ radiation}} + \mathrm{Q_{flame\ radiation}} + Q_{heat\ loss} + Q_{door\ loss} + Q_{H2\ moisture} + Q_{fuel\ moisture} \quad \text{4-27}$$

Rearranging gives:

$$m_{flue} = \frac{LHV \times \eta_c - \begin{pmatrix} Q_{char\ radiation} + Q_{flame\ radiation} + \\ Q_{heat\ loss} + Q_{door\ loss} + Q_{H2\ moisture} \\ +Q_{fuel\ moisture} \end{pmatrix}}{(h_g - h_a)} \quad \text{4-28}$$

The individual heat transfers in Equation (27) are expressed through mathematical definitions that are derived by rearranging the expressions for radiative heat transfer from the work of J. P. Holman (Holman, 1986) and applying the radiation network method.

The radiative heat transfer from char ($Q_{char\ radiation}$) and flame ($Q_{flame\ radiation}$) to the pot bottom in the combustion chamber of the rocket stove can be computed as follows: Kshirsagar and Kalamkar (2015) gives the equation as.

$$Q_{char\ radiation} = \frac{\sigma \times A \times (T_{char}^4 - T_p^4)}{\frac{(1-\varepsilon_c)}{\varepsilon_c} + \frac{2}{(1 + F_{char-pot})}} \quad \text{4-29}$$

And

$$Q_{flame\ radiation} = \sigma \times A \times (\varepsilon_g T_g^4 - \alpha_g T_p^4) \quad \text{4-30}$$

A generic equation from Shah and Date Shah and Date (2011) was used to evaluate the flue gas emissivity across the zone.

$$\varepsilon_g = e^{\{A+B\times ln(0.2\times L_b)\}} \quad \text{4-31}$$

Where A= 0.848+9.02*10^{-4}*T and B=0.9589+4.8*10^{-6}*T

L_b is the characteristic length and is given;

$$L_b = 3.6 \times \frac{V(volum)}{A(area)} \quad \text{4-32}$$

The flue gas's absorptivity α_g is also given by Bejan and Kraus (Bejan and Kraus, 2003);

$$\alpha_g = \varepsilon_g \times \sqrt{T/T_s} \quad 4\text{-}33$$

Another loss is due to the opening of the feed door, heat is lost from the fuel bed to the feed door opening and is given as; expressions are from Holman (1986).

$$Q_{door\ loss} = F_{char-door} \times \sigma \times A \times (T_{char}^4 - T_a^4) \quad 4\text{-}34$$

In the field of thermal radiation, the view factor is a dimensionless coefficient that describes the fraction of radiant energy leaving one surface that is received by another surface. It is used to calculate radiative heat transfer between surfaces in a system.

The view factor between the char bed and the feed door was determined by approximating the situation as a 'Rectangle to perpendicular circular segment', which is a common approach for estimating view factors in engineering and physics applications. The value of 0.2 for the view factor was obtained from the 'Catalog of radiation heat transfer configuration factors' by Howell (2010), which provides a compilation of view factors for various geometric configurations.

The heat transfer process via a plane wall, which combines conduction, convection, and radiation modes, is used to study the heat loss from the combustion chamber through a wall of the stove body from Kshirsagar and Kalamkar (2015).

$$Q_{heat\ loss} = \frac{(T_g - T_a)}{\frac{1}{(h_{ci}+h_{rfl}+h_{rch})A_i} + \frac{ln\left(D_o/D_i\right)}{2\pi \times H \times k_i} + \frac{1}{(h_{co}+h_{ro})A_o}} \quad 4\text{-}35$$

In equation *4-35*, the heat transfer coefficients are taken from Cengel et al. (2011).

$$h_{ci} = \frac{k}{D} \times 0.023 \times Re_D^{0.8} \times Pr^{0.3} \quad 4\text{-}36$$

$$h_{co} = \frac{k}{H} \times 0.59 \times Re_D^{0.8} \times (Gr_H \times Pr)^{0.25} \quad 4\text{-}37$$

$$h_{rfl} = \frac{\sigma \times (\varepsilon_g T_g^4 - \alpha_g T_{wi}^4)}{(T_g - T_{wi})} \quad 4\text{-}38$$

$$h_{ro} = \sigma \times \varepsilon_o \times (T_{wo}^2 + T_a^2) \times (T_{wo} + T_a) \quad 4\text{-}39$$

$$h_{rch} = \frac{\sigma \times (T_{char}^2 - T_{wi}^2) \times (T_{char} - T_{wi})}{\frac{(1-\varepsilon_c)}{\varepsilon_c} + \frac{F_{char-wall} + F_{char-pot}}{F_{char-wall} \times \left(F_{char-wall} + 2 \times F_{char-pot}\right)}} \quad 4\text{-}40$$

Were, $F_{char-wall} = 1 - F_{char-pot} - F_{char-door}$

The loss of heat due to the presence of moisture in fuel can be attributed to two distinct mechanisms: the sensible heating of hydrogen molecules associated with moisture and the heat of vaporization resulting from the evaporation of fuel moisture. Both of these mechanisms contribute to the overall heat loss associated with moisture in fuel, and their magnitudes depend on various factors such as the moisture content, temperature, and heating conditions of the fuel.

$$Q_{H2\,moisture} = (h_s - 2547) \times 0.09 \times H \quad 4\text{-}41$$

$$Q_{fuel\,moisture} = \{h_s - 4.187 \times (T_a - 273)\} \times \frac{M}{100 - M} \quad 4\text{-}42$$

The equation from Cengel et al. (2011) was used to correlate the enthalpy of superheated steam.

$$h_s = 0.00032273 \times T^2 + 1.64833661388 \times T + 2021.531847 \quad 4\text{-}43$$

According to Pande et al. (2019), the application of heat balance to the heat transfer process from the flame to the surroundings reveals that the heat lost from the inner wall of the combustion chamber ($Q_{flame-inner\,wall}$) is equivalent to the heat lost from the inner wall to the outer wall ($Q_{inner\,wall-outer\,wall}$), which is also equivalent to the heat lost from the outer wall to the surroundings ($Q_{outer\,wall-surroundings}$).

$$\dot{Q}_{heat\,loss} = \dot{Q}_{flame-inner\,wall} = \dot{Q}_{inner\,wall-outer\,wall} = \dot{Q}_{outer\,wall-surroundings} \quad 4\text{-}44$$

$$\dot{Q}_{flame-inner\,wall} = \frac{(T_g - T_{wi})}{(h_{ci} + h_{rfl} + h_{rch})A_i} \quad 4\text{-}45$$

$$\dot{Q}_{outer\,wall-surroundings} = \frac{(T_{wo} - T_a)}{(h_{co} + h_{ro})A_o} \quad 4\text{-}46$$

Pot bottom (Zone 2)

The main mechanism taken into account in this zone was the impinging jet heat transfer that transferred heat from the zone to the pot. which results;

$$\dot{Q}_{lost\,by\,flue\,gas} = \dot{Q}_{transfer\,to\,the\,pot} \quad 4\text{-}47$$

Zuckerman and Lior (2006) provided the equation for the average heat transfer of an impinging jet.

$$\dot{Q}_{conv2} = h_{bottom} \times A_p \times \left\{\left(\frac{T_g + T_e}{2}\right) - T_p\right\} \quad 4\text{-}48$$

$$h_{bottom} = h_{conv2} + h_{rad2} \quad 4\text{-}49$$

From Kshirsagar and Kalamkar (2015) correlation for $h_{bottom}$is given as;

$$h_{bottom} = \frac{K_{bottom}}{D} \times 0.424 \times Re_D^{0.57} \times \left(\frac{w_i}{D}\right)^{-0.33} \quad 4\text{-}50$$

Pot gap (Zone 3)

In this zone, the main mechanisms taken into account were heat transfer from an impinging jet and radiative heat transfer from the flame to the bottom of the pot, with the assumption of no heat loss.

$$\dot{Q}_{supplied\ by\ flue\ gas} = \dot{Q}_{transfer\ to\ the\ pot} \quad 4\text{-}51$$

$$\dot{Q}_{rad3} = \sigma \times A_{pg} \times \left\{\varepsilon_3 \left(\frac{T_c+T_e}{2}\right)^4 - \alpha_3 T_p{}^4\right\} \quad 4\text{-}52$$

$$\dot{Q}_{conv3} = h_{pot\ gap} \times A_{pg} \times \left\{\left(\frac{T_c+T_e}{2}\right) - T_p\right\} \quad 4\text{-}53$$

And heat balance equation for this zone;

$$\dot{m}_{act} \times (h_e - h_c) \times 1000 = \sigma \times A_{pg} \times \left\{\varepsilon_3 \left(\frac{T_c + T_e}{2}\right)^4 - \alpha T_p{}^4\right\} + h_{pot\ gap} \times A_{pg} \times \left\{\left(\frac{T_c + T_e}{2}\right) - T_p\right\} \quad 4\text{-}54$$

Pot side (Zone 4)

The three main mechanisms taken into consideration in this zone were convective heat transfer (laminar fully formed flow), radiative heat transfer from the flame to the pot side, and heat loss from the pot side to the surroundings.

$$\dot{Q}_{supplied\ by\ flue\ gas} = \dot{Q}_{transfer\ to\ the\ pot} + \dot{Q}_{side\ heat\ loss} \quad 4\text{-}55$$

$$\dot{Q}_{conv4} = h_{pot\ side} \times A_{pot\ side} \times \left\{\left(\frac{T_c+T_o}{2}\right) - T_p\right\} \quad 4\text{-}56$$

$$\dot{Q}_{rad4} = \sigma \times A_{pot\ side} \times \left\{\varepsilon_3 \left(\frac{T_c+T_o}{2}\right)^4 - \alpha_4 T_p{}^4\right\} \quad 4\text{-}57$$

The heat balance equation for this zone;

$$\dot{m}_{act} \times (h_c - h_o) \times 1000 = h_{pot\ side} \times A_{pot\ side} \times \left\{\left(\frac{T_c + T_o}{2}\right) - T_p\right\} + \sigma \times A_{pot\ side} \times \left\{\varepsilon_3 \left(\frac{T_c + T_o}{2}\right)^4 - \alpha_4 {T_p}^4\right\} + \dot{Q}_{side\ heat\ loss} \quad 4\text{-}58$$

Suppose the heat transfer coefficient for convection and radiation is 10 w/m^2 K, $\dot{Q}_{side\ heat\ loss}$ is given as;

$$\dot{Q}_{side\ heat\ loss} = 10 \times A_{side} \times \left(\left(\frac{T_c + T_o}{2}\right) - T_a\right) \quad 4\text{-}59$$

Referring to the equation for the average Nusselt number, as presented in Cengel and Heat (2003), for laminar flow over a flat vertical plate.

$$h_{side} = \frac{K_{side}}{h_w} \times 0.664 \times Re_h^{0.57} \times pr^{1/3} \quad 4\text{-}60$$

Finally, the overall efficiency of a stove is given as;

$$\eta_o = \frac{\dot{Q}_{char\ radiation} + \dot{Q}_{flam\ radiation} + \dot{Q}_{conv2} + \dot{Q}_{conv3} + \dot{Q}_{rad3} + \dot{Q}_{conv4} + \dot{Q}_{rad4}}{P} \times 100 \quad 4\text{-}61$$

4.5 Proximate analysis of the fuel

Proximate analysis is a method used to determine the chemical composition of wood. It involves breaking down the wood sample into its various components and analyzing them separately. The analysis typically measures the percentage of moisture, ash, volatile matter, and fixed carbon in the wood. Proximate analysis of wood is an important tool for understanding the properties of wood and for determining its potential uses in different applications (Telmo et al., 2010).

4.5.1 Moisture content

The moisture content of wood fuel can have a significant impact on its combustion behavior and overall heating value. The moisture content of wood fuel is typically expressed as a percentage of the weight of the wood that is made up of water. As a general rule, lower moisture content will result in more efficient combustion and higher heat output. By obtaining a sample of a pre-weighed eucalyptus wood log feedstock and using the equation, Sukarta et al. (2018) the moisture content of the fuel was determined.

$$Moisture\ content\ \% = \frac{M_i - M_f}{M_i} \times 100\% \quad 4\text{-}62$$

Where, M_i is the pre-weight mass of the wood and M_f is the mass of the wood after heating (105°C). See APPENDIXES B.

4.5.2 Ash content

Ash content is another important parameter that is commonly measured in wood fuel. Ash content refers to the amount of inorganic material that remains after the wood has been burned. This inorganic material includes minerals such as calcium, potassium, and magnesium, as well as other metals and non-metallic elements. Ash content is typically expressed as a percentage of the dry weight of the wood. The ash content of wood fuel can have a significant impact on its combustion behavior, as the inorganic material can interfere with the combustion process and contribute to the formation of pollutants. Calculating ash content is also one technique to identify the non-combustible and wasteful material in fuel that lowers the feedstock's calorific value (CV). And it is determined by the equation;

$$Ash\ content\ \% = \frac{M_{ash}}{M_i} \times 100\% \qquad 4\text{-}63$$

Where, M_{ash} is the mass of the ash after the wood is burned.

4.5.3 Volatile Matter

Volatile matter refers to the organic material that evaporates when the wood is heated. This organic material includes a variety of compounds such as water, methane, carbon dioxide, and various hydrocarbons. The volatile matter content of wood fuel is typically expressed as a percentage of the dry weight of the wood. The volatile matter content of wood can have a significant impact on its combustion behavior, as it contributes to the formation of flames and provides a significant portion of the heat released during combustion. Lower volatile matter content can result in slower burning and less efficient combustion. The weight loss in the wood is equivalent to the quantity of volatile matters [v] in percent, which is computed as; where M_e is the mass of the residue after heating.

$$Volatile\ matter\ \% = \frac{M_i - M_e}{M_i} \times 100\% \qquad 4\text{-}64$$

4.5.4 Fixed carbon

Fixed carbon is another important parameter that is commonly measured in wood fuel. Fixed carbon refers to the non-volatile organic material that remains after the volatile matter has been driven off during heating. The fixed carbon content of wood fuel is typically expressed as a percentage of the dry weight of the wood. Fixed carbon content is an important parameter for understanding the combustion behavior of wood fuel, as it determines the amount of carbon that will be available for combustion. Higher fixed carbon content can result in more complete combustion and higher heat output. Therefore, to calculate the quantity of fixed carbon, also known as by difference, the mass of volatile matter (VC), moisture content, and ash content are subtracted from the initial mass of a wood fuel sample.

$$Fixed\ carbon\ \% = 100\% - M\% - Ash\% - VM\% \qquad 4\text{-}65$$

4.5.5 Calorific Value

The calorific value of a fuel is a measure of the energy content that can be obtained from the complete combustion of the fuel. It is typically expressed in units of energy per unit of mass, such as joules per gram or kilocalories per kilogram. The calorific value depends on the fuel's chemical composition and can be determined through controlled combustion experiments. This parameter is critical for evaluating the energy potential of different fuels and comparing the energy efficiency of various combustion processes.

Two types of calorific values are commonly used: Gross Calorific Value (GCV), also known as Higher Heating Value (HHV), which is the total heat released when a unit of fuel is burned completely and the products of combustion are cooled to the initial temperature. GCV includes the latent heat of vaporization of any water produced during combustion, making it a more conservative estimate of the fuel's energy content. The second type is Net Calorific Value (NCV), also known as Lower Heating Value (LHV), which is the heat released when a unit of fuel is burned completely and the products of combustion are allowed to escape without being condensed or cooled. NCV does not include the heat of vaporization of any water produced during combustion. The lower calorific value of the fuel can be assessed using the following relationships. (Bryden et al., 2022).

$$LHV = HHV - \left\{\left(9 \times \frac{H}{16}\right) - \left(M \times (2.5 + 0.015H)\right)\right\} \qquad 4\text{-}66$$

Where H is the mass fraction of Hydrogen and M is the mass fraction of moisture in the fuel.

4.6 Performance parameters of the Rocket Stove

4.6.1 Firepower

The firepower of a stove is a measure of the rate at which it can produce heat, typically expressed in units of power such as watts. Firepower is closely related to heat output, which is a measure of the total amount of heat produced by the stove over a given time. And it can be determined by the equation;

$$F_p = \dot{m}_f \times NCV \quad \text{4-67}$$

Where, $\dot{m}_f$ is the fuel burn rate and NCV is the net calorific value.

The burn rate is the rate at which fuel is consumed while the water is being boiled. It is computed by dividing the equivalent dry fuel burned by the test's duration.

4.6.2 Specific Fuel Consumption

Specific fuel consumption (SFC) is a measure of the amount of fuel consumed by a stove to boil a certain amount of water. It is typically expressed in units of mass of fuel per unit of water boiled, such as kilograms of fuel per litter of water boiled.

$$SFC = {}^{Fuel\ consumed}\!/_{water\ boiled} \quad \text{4-68}$$

4.6.3 Wood fuel consumed

The amount of fuel consumed during combustion depends on several factors, including the heating value of the fuel, the efficiency of the combustion process, and the conditions of combustion such as the temperature, pressure, and air-fuel ratio. It can frequently be calculated by subtracting the fuel mass before and after the test, respectively.

$$Fuel\ consumed = m_{fi} - m_{ff} \quad \text{4-69}$$

Where, m_{fi} and m_{ff} are the mass of the fuel initially and the mass of fuel after respectively.

4.6.4 Boiling time

To determine the total time required to boil or cook a given sample, the starting time of the test is subtracted from the time at which the water is boiled. This boiling time can be easily calculated using a simple equation.

$$Time\ to\ boil = t_f - t_i \quad \text{4-70}$$

4.6.5 Thermal efficiency of the stove

The ratio of heat gained by the water inside the pot and the water evaporated to the energy of the fuel used for heating can be used to determine the thermal efficiency (Adem and Ambie, 2017). This can be calculated using the following equation:

$$\eta_{th} = \frac{m_w \times C_p \times (T_f - T_i) + m_{ew} \times h_{fgw}}{m_f \times NCV_f} \quad 4\text{-}71$$

Where, m_w, m_{ew} and m_f are the initial mass of water, the mass of water evaporated, and the mass of the fuel in kg respectively, C_p is the specific heat capacity of water (kJ/kg. K), T_f and T_i are the initial and final(boiling) temperature of the water in °C, h_{fgw} is Latent heat of evaporation of water (kJ/Kg), NCV_f is the heating value of the fuel (kJ/Kg).

4.7 Experimental analysis of the Rocket Stove

4.7.1 Experimental setup

The experiment was conducted at Adama Science and Technology University (ASTU), sheet metal shop lab. located at 8.5625⁰ N 39.2891⁰ E at an elevation of 1712 meters above sea level.

To evaluate the performance of the rocket stove, a water boiling test and control cooking test was conducted, which involved measuring the thermal efficiency and recording temperatures from multiple locations and exhaust gas readings.

4.7.2 Measuring devices

Various laboratory equipment was utilized to conduct an experimental test aimed at measuring the thermal efficiency of the newly developed stove. Before, during, and after the experiment, different measurements were taken using state-of-the-art tools. such as the for determining CO, and CO_2 levels *Infralyt* smart gas analyzer was used. Meanwhile, thermocouples (K-type), thermometers were employed for temperature measurements of the stove's ambient, surface, water samples, flame, and wall. The experimental test also required the use of an electronic balance with a 2000 g capacity and a precision of five grams to weigh the necessary materials.

The equipment used in the water boiling test is

- Al pot
- Infralyt gas analyzer

- Stopwatch
- Digital thermometer (300-1300 K)
- Thermocouples (K-type)
- Weight balance (0.1-2000 g)
- Tape measure
- Biomass fuel (Eucalyptus globules)
- Water

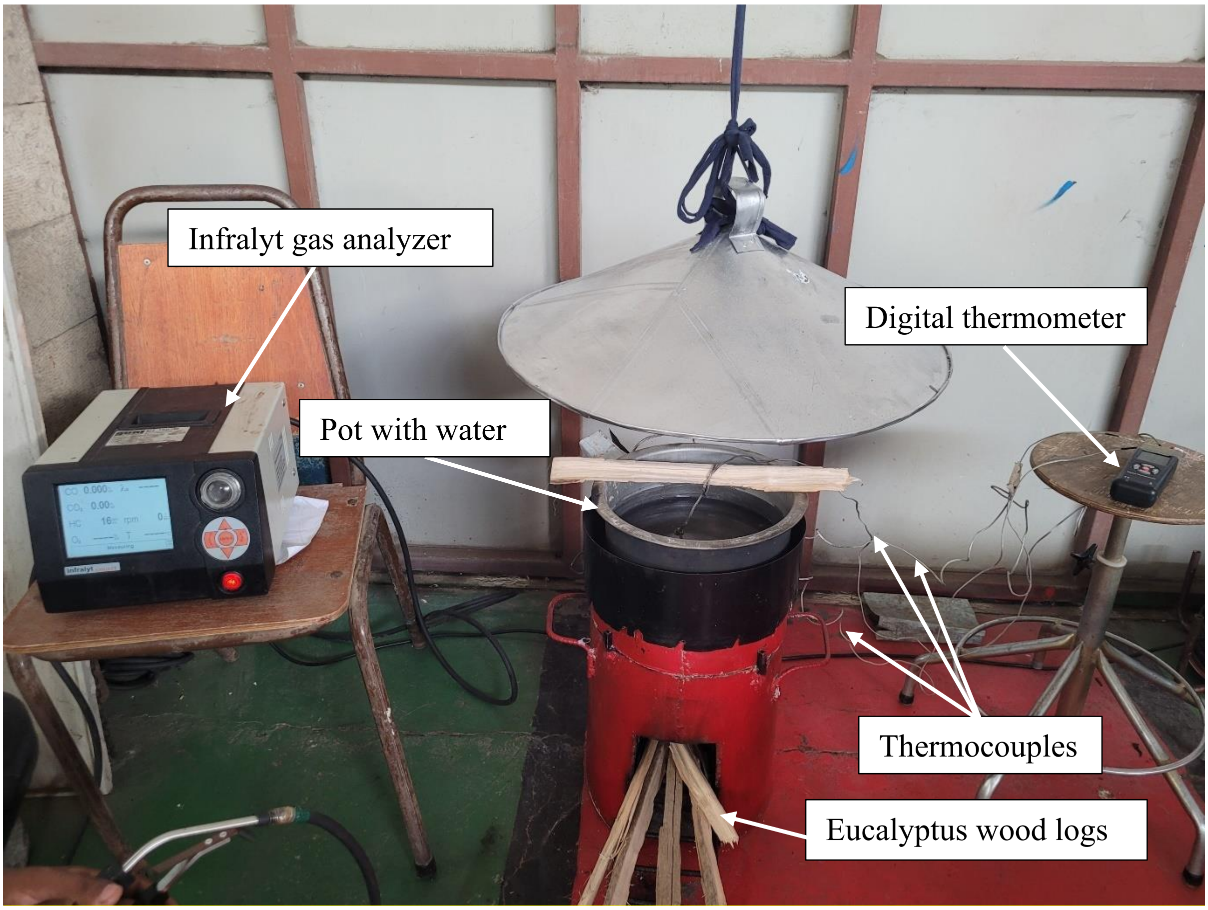

Figure 4.10 Expermental setup.

4.7.3 Experimental Procedure

In a controlled laboratory setting with no significant effect of the wind, the experiment was conducted once per day after allowing sufficient time for background concentration levels to decrease and the rocket stove to cool down before the next cold-start test. The test involved measuring and recording various parameters, including fuel consumption, temperature readings from different zones, flame, external body of the stove, exhaust emissions, and the time needed to boil 2.5 kg of water. For the emission measurement setup it is referred from MacCarty et al. (2010), see in APPENDIX H for the procedure.

4.7.3.1 Water boiling test (WBT)

The Water Boiling Test (Version 4.2.3), commonly referred to as WBT, is the predominant method used in laboratory settings to evaluate the performance of cookstoves (Alliance, 2013; Arora et al., 2014). The test is designed to determine the amount of fuel used by the stove and the emissions produced in relation to the quantity of water boiled and it is a simplified simulation of the cooking process that aims to assess the efficiency of a stove in heating water in a cooking pot (Alliance, 2013). The testing protocol consists of three sets of experiments to evaluate the stove's performance under different conditions. The test is divided into three sets: the "cold start (High power)" set, This begins with the stove at room temperature and requires using a pre-weighed bundle of wood to boil a certain amount of water in a standard pot; the "hot start (High power)" set, which involves replacing the boiling water with cold water and measuring the stove's performance when boiling water on a hot stove; and the "simmering (Low power)" set, which involves boiling a specific amount of water and then simmering it just below boiling point for a set time of 45 minutes, using a pre-weighed bundle of wood (Alliance, 2013; Kole et al., 2022). Several measurements and computations are necessary for each phase.

Table 4.3 Variables that are constant throughout all three phases are;

HHV	Gross calorific value (dry wood) (kJ/kg)
LHV	Net calorific value (dry wood) (kJ/kg)
M_C	Wood moisture content (% - wet basis)
EHV	Effective calorific value (accounting for moisture content of wood)
LHV_{char}	Net calorific value of char (kJ/kg)
P1	Dry mass of empty pot (grams)
K	Weight of empty container for char (grams)
T_a	Ambient Temperature (°C)
T_b	Local boiling point of water (°C)
fuelFracC	Fuel carbon fraction (%)
charFracC	Char carbon fraction (%)

4.7.3.2 Controlled cooking test (CCT)

The purpose of the controlled cooking test (CCT) is to evaluate how well the improved stove performs in comparison to the traditional stoves it is meant to replace. The test involves a standard cooking task that closely resembles the everyday cooking practices of the local population. The conditions are carefully designed to eliminate the impact of extraneous factors and ensure reproducibility.

CHAPTER FIVE

5. Results and discussion

5.1 Introduction

Experimental results relevant to the performance of rocket stoves are presented and discussed in detail in this chapter. The thermal efficiency, and other zonal heat transfers were calculated using the experimental output temperatures, and all of these topics are thoroughly discussed here.

5.2 Experimental result of the Rocket Stove

To evaluate the performance of the cookstove, a series of three water boiling tests were conducted. The boiling point of water was determined to be 94.506°C at an elevation of 1712 meters above sea level at Adama Science and Technology University. The Rocket stove's performance was assessed by measuring several output metrics during the three water boiling tests and calculating the average values. Specific fuel consumption, firepower, boiling-over time, thermal efficiency, output temperatures, and exhaust emissions were among the output parameters measured during the experimental tests.

For the experimental tests the Rocket stove was fueled using a eucalyptus globules wood log with a moisture content of 10.53 % and having a NCV of 18,840 kJ/kg (Alliance, 2013) for all the tests.

5.2.1 Effect of height of combustion chamber on the performance of the Rocket Stove

The experiment studied two heights of combustion chamber variables one with a height of three times the diameter of the combustion chamber (36 cm) and the second one, two times the diameter of the combustion chamber (24 cm). The variation in the height of the combustion chamber is studied from the experiment. And the flame temperature that reached the bottom of the pot was examined.

Table 5.1 Water boiling test result of 36 cm height combustion chamber.

High power test (cold start)	Units	Average
Time to boil the water (2.5 kg)	min	12
Fuel consumed	g	277
Burning rate	g/min	18
Thermal efficiency	%	30.36
Specific fuel consumption	g/liter	93

Firepower	watts	5726.72
CO_2	%Vol.	4.14
CO	%Vol.	0.082
High power test (hot start)	Units	Average
Time to boil the water (2.5 kg)	min	7.67
Fuel consumed	g	212
Burning rate	g/min	20.97
Thermal efficiency	%	30.09
Specific fuel consumption	g/liter	65.00
Firepower	watts	6586.08
CO_2	%Vol.	5.21
CO	%Vol.	0.077
Low power test (simmering)	Units	Average
Fuel consumption	g	743
Thermal efficiency	%	29.86
Firepower	watts	4380

Table 5.2 Water boiling test result of 24 cm height combustion chamber.

High power test (cold start)	Units	Average
Time to boil the water (2.5 kg)	min	12.67
Fuel consumed	g	296
Burning rate	g/min	15
Thermal efficiency	%	28.75
Specific fuel consumption	g/liter	79
Firepower	watts	4758.73
CO_2	%Vol.	4.07
CO	%Vol.	0.104
High power test (hot start)	Units	Average
Time to boil the water (2.5 kg)	min	10.17
Fuel consumed	g	242
Burning rate	g/min	19.50
Thermal efficiency	%	28.27
Specific fuel consumption	g/liter	79.76
Firepower	watts	6122.24
CO_2	%Vol.	5.3
CO	%Vol.	0.093
Low power test (simmering)	Units	Average
Fuel consumption	g	821
Thermal efficiency	%	27.96
Firepower	watts	4271.57

The experimental results indicate that the rocket stove with a combustion chamber height of 36 cm exhibited higher thermal efficiency compared to the stove with a 24 cm combustion chamber height.

The increased height of the combustion chamber allowed for a longer duration of fuel combustion and heat generation, resulting in a more efficient combustion process and reduced emissions of smoke.

Additionally, the taller combustion chamber facilitated a stronger draft and greater oxygen supply, leading to a more efficient burn and a cleaner flame.

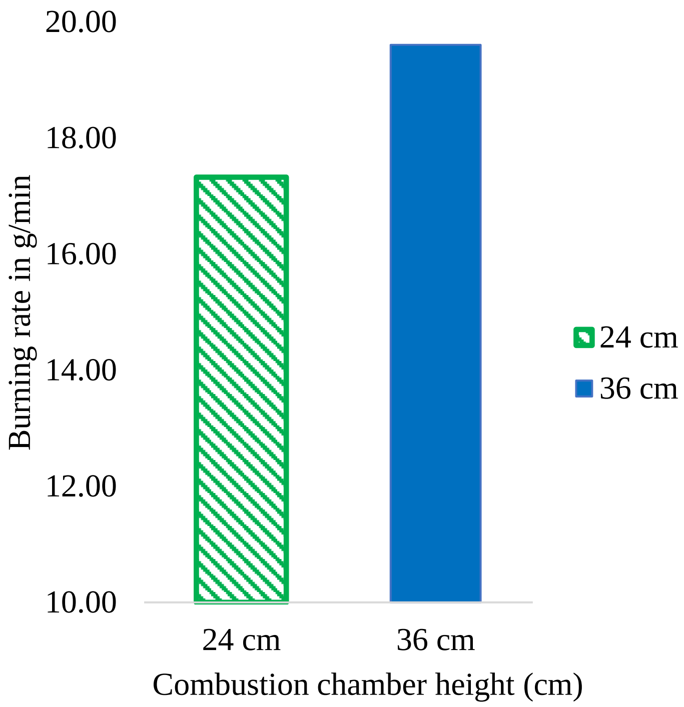

Figure 5.1 Average burning rate

In contrast, the shorter combustion chamber produced more soot, which comprises fine black particles primarily composed of carbon that results from incomplete fuel combustion than the taller combustion chamber. Moreover, the height of the combustion chamber influenced the fuel consumption of the stove, with the taller chamber providing a longer burn time for the same amount of fuel. This characteristic can be advantageous in situations where fuel is scarce.

5.2.2 Zonal temperature variations

During the experiment, a thermocouple (K-type) was put into an essential part of the stove to measure the stove's zonal temperatures. To measure the temperature of the flame, Exhaust flue gas, and the outside walls of the stove, thermocouples were inserted at various points inside each zone. In Figure 5.2 and Figure 5.3Figure *5.3*, the experimental findings for temperatures at various zones of the stove at high power cold start and high-power hot start are displayed versus time.

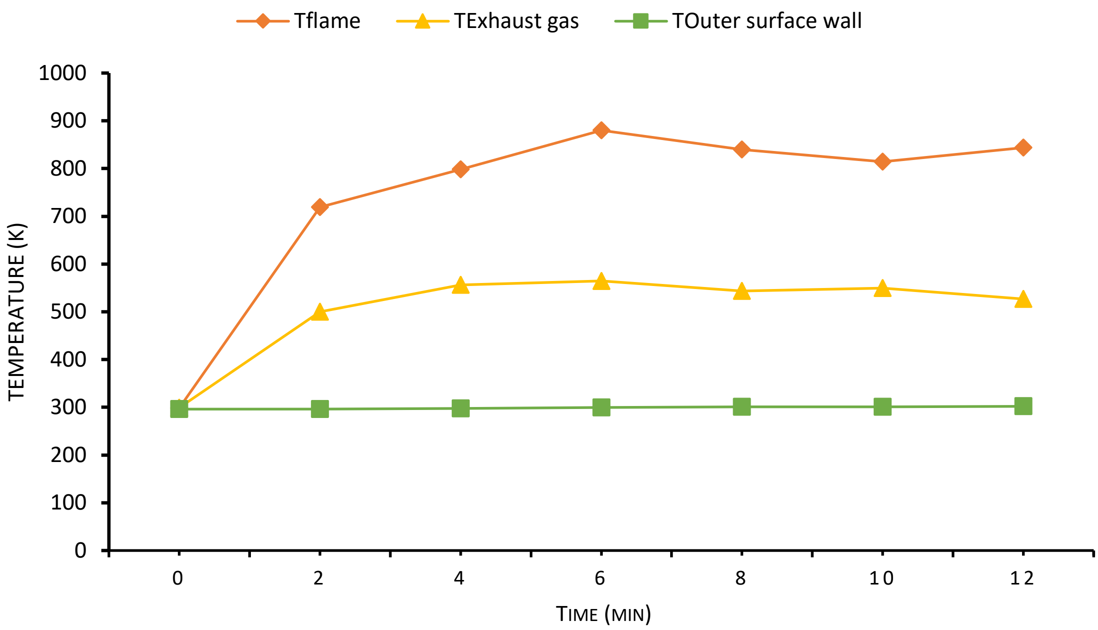

Figure 5.2 Experimental output temperatures versus time for high power cold start test.

Figure 5.2 and Figure 5.3 illustrate the temperature distribution at various sections of the rocket stove during WBT cold and hot starts. The output temperatures in various parts of the stove rise as the boiling time increases for both 36 cm and 24 cm combustion chamber heights.

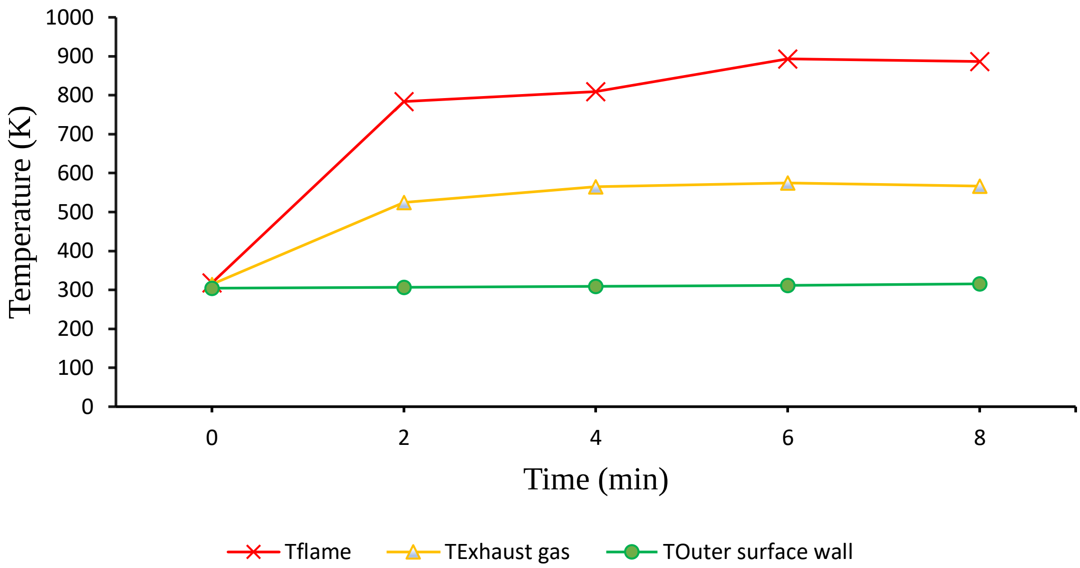

Figure 5.3 Experimental output temperatures versus time for high power hot start test.

The conducted experiment demonstrated that the flame temperature exhibits a positive correlation with time during both cold and hot start tests. The increase in flame temperature can be attributed to the enhanced completeness of the combustion process, which is facilitated by an increase in the amount of fuel consumed by the stove. A higher amount of fuel consumption optimizes the oxygen supply to the combustion process, leading to more complete combustion and a consequent increase in the flame temperature.

5.2.3 Exhaust gases

During the experiment, the exhaust gases exiting the Rocket stove were measured using an Infralyt gas analyzer. The experimental test revealed that incomplete combustion caused an average CO emission of 0.0795% volume for the 36 cm combustion chamber height and 0.0985% volume for the 24 cm combustion chamber height. The experimental results show that the concentration of carbon monoxide (CO) in the combustion chamber falls proportionately to temperature, which is related to the increased completeness of the combustion process as the temperature rises.

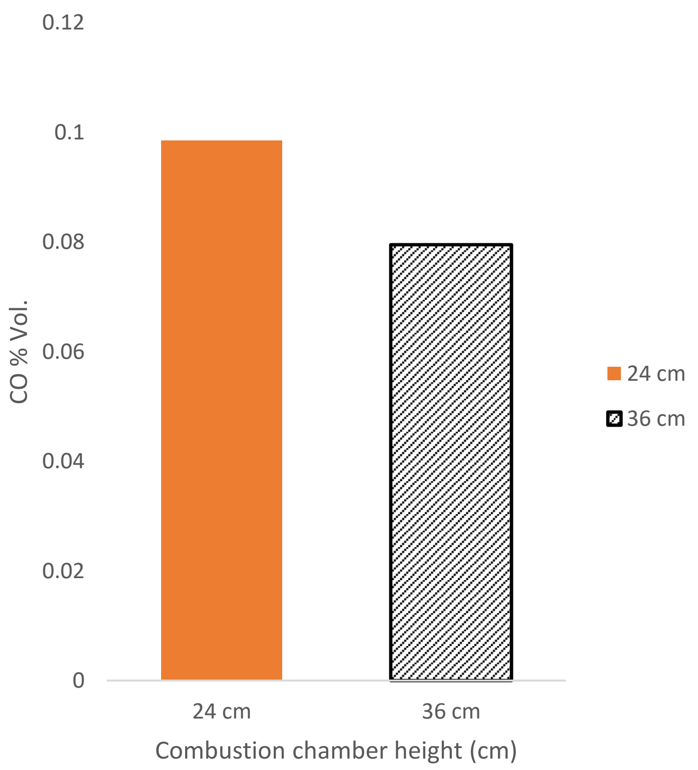

Figure 5.4 Average emission of CO in %Vol.

The rise in temperature results in facilitating complete burning and lowering CO concentrations in the combustion chamber. Figure 5.5 shows the variation of CO emissions with a flame temperature for 36 cm combustion chamber height.

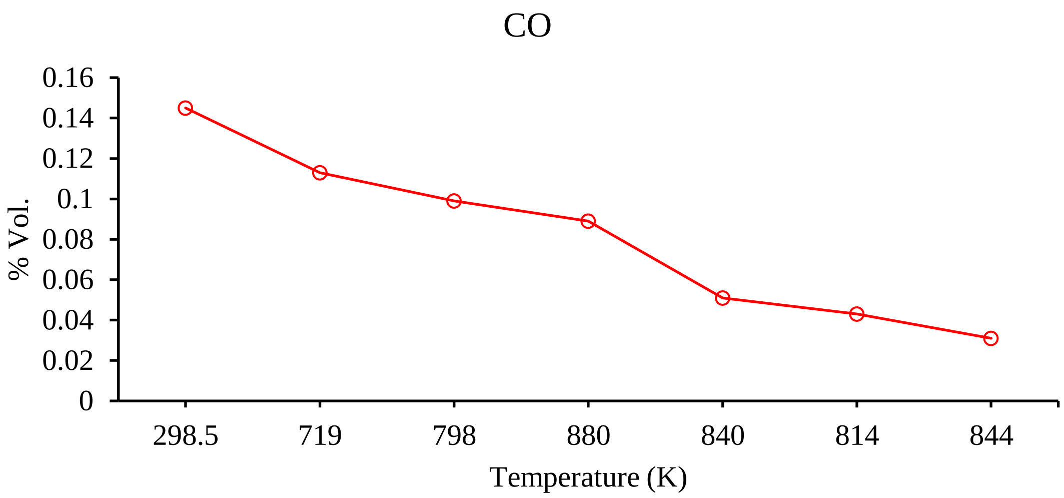

Figure 5.5 Emission of CO with a flame temperature

The relationship between the change in carbon dioxide content and output temperatures is closely related. The experimental results demonstrate that the concentration of CO_2 increases as the temperature in the combustion chamber rises, which is attributed to an increase in the conversion of feedstock to CO_2. This result makes sense given that, when the burning process is optimal a brighter flame is produced from the feedstock and the conversion of carbon in the fuel rises, indicating that the air-to-fuel ratio in the combustion chamber is balanced.

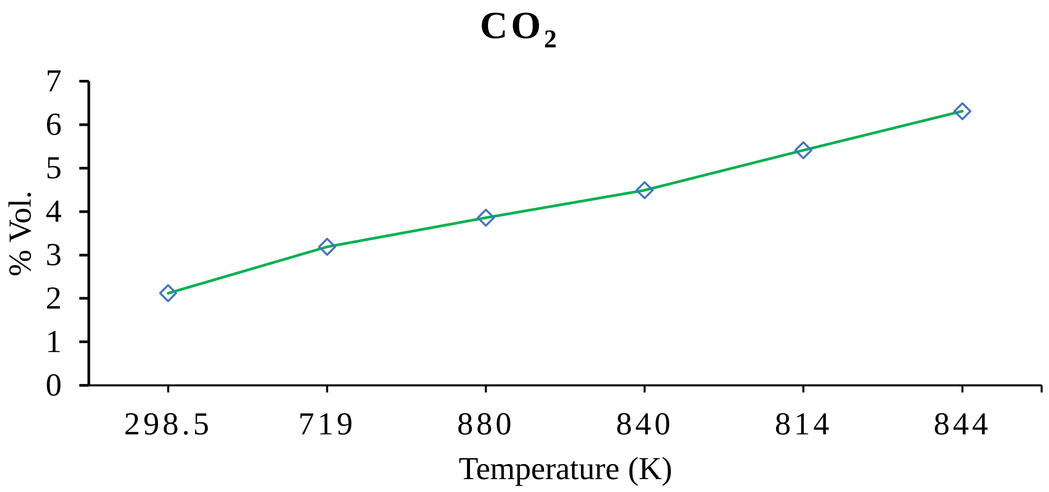

Figure 5.6 Variations of CO_2 versus flame temperature.

The experimental test yielded an average volume of 4.675 %Vol. of CO_2 gas emitted from the stove. On the other hand, the volume of CO emissions from the stove ranged between 0.031 to 0.145%. The outcome was that the stove's CO emissions met WHO guidelines.

According to the data presented in Figure 5.7, there exists an inverse correlation between the average output concentrations of carbon monoxide (CO) and carbon dioxide (CO_2) emissions. This correlation is indicative of an optimized combustion process that is designed to minimize the production of CO while maximizing the production of CO_2. This optimization is based on the principle that CO is a byproduct of incomplete combustion, while CO_2 is a product of complete combustion. Therefore, the inverse relationship between CO and CO_2 concentrations in the emissions demonstrates the effectiveness of the combustion process in achieving a more complete combustion of the fuel, resulting in lower CO emissions and higher CO_2 emissions.

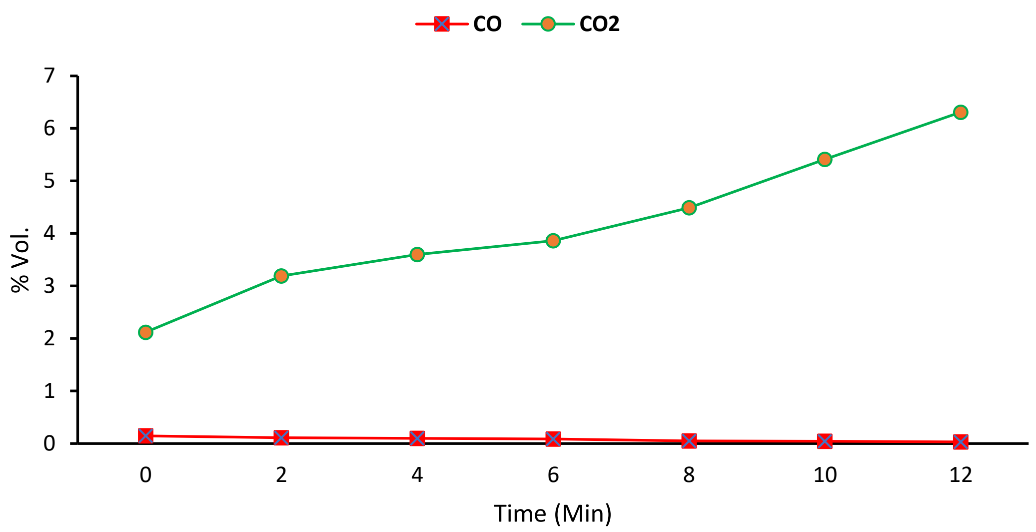

Figure 5.7 Variations of exhaust emissions Vs Time.

5.2.4 Time to boil

Based on the experiment, it was observed that the taller combustion chamber design resulted in a shorter boiling time compared to the shorter combustion chamber design. The boiling time for the taller combustion chamber was 12 minutes for high power cold start and 7.67 minutes for high power hot start, while the shorter combustion chamber recorded 12.67 minutes and 10.17 minutes for high power cold and hot start, respectively. This difference in boiling time can be attributed to the fact that the tall and narrow combustion chamber in a rocket stove creates a stronger draft, which increases the airflow to the fire and improves combustion, resulting in higher temperatures and faster heating rates. In addition, the insulation around the combustion chamber helps to retain heat and reduce heat loss, thereby reducing the time required to boil water.

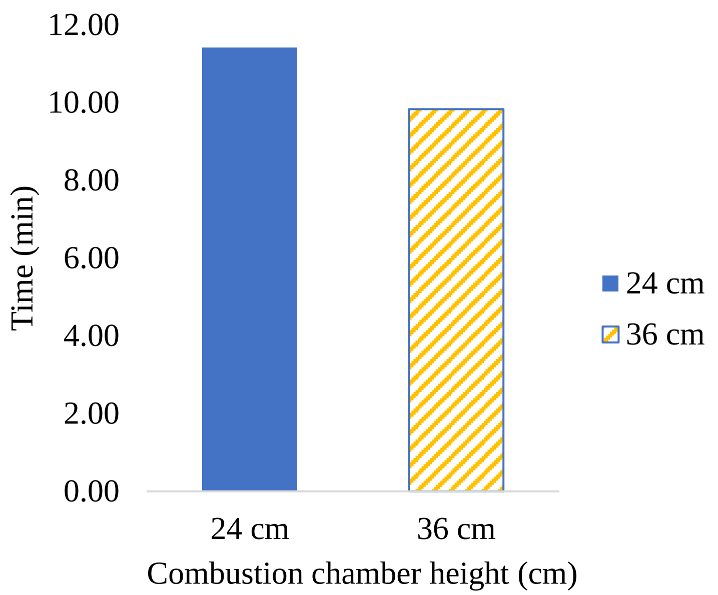

Figure 5.8 Average time to boil 2.5 kg of water in high power.

5.2.5 Specific Fuel Consumption

The specific fuel consumption (SFC) was utilized as a parameter to evaluate the stove's performance, measuring the amount of fuel required to boil water completely. Averagely, 79 g/litter of water was used to boil 2.5 kg of water in the case of 36 cm and 24 cm combustion chamber height, there was no significant difference in this case between these two heights. The primary fuel input for the rocket stove was a local log of Eucalyptus globulus woody biomass. However, the inclusion of alternative feedstocks may have an impact on both indoor air quality and thermal efficiency. This result indicates that the designed rocket stove has reduced fuel consumption than the traditional three-stone stove.

5.2.6 Firepower

The burning rate of fuel and rising temperatures are both factors that have been observed to increase the firepower of a stove. However, incomplete combustion resulting from inadequate air supply or a poor fuel-to-air ratio in the combustion chamber can reduce the output firepower. This effect is particularly evident in stoves with taller combustion chambers, which have been found to achieve higher firepower levels. For example, the taller combustion chamber design produced a firepower of 5726.72 watts for cold start and

6586.08 watts for hot start WBT, which is higher than the shorter combustion chamber design that produced a firepower of 4758.732015 watts for cold start and 6122.24 watts for hot start WBT.

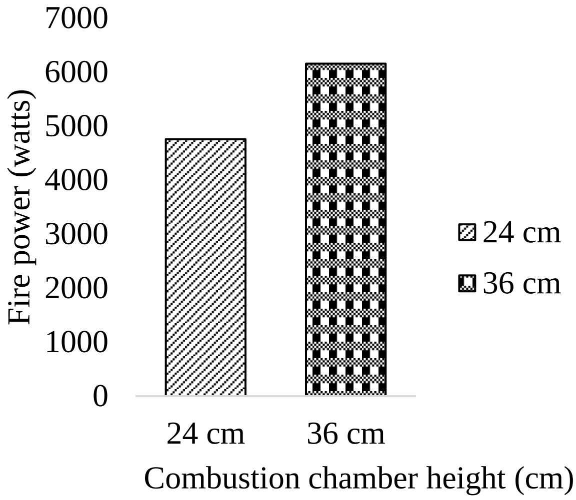

Figure 5.9 Average fire power in watts

Based on the experimental results, the energy balance within the combustion chamber was determined by using the high-power cold-start firepower for the 36 cm combustion chamber height, which was found to have a higher average firepower than the 24 cm height combustion chamber. The energy balance of the stove in the combustion chamber is resented in Table 5.3.

Table 5.3 Energy balance in the combustion chamber (zone 1).

Heat Transfer	Symbol	Value (Watts)	Percentage %
Heat gain by a flue	$Q_{gain\ by\ the\ flue}$	4911.6030251	85.7664252
Radiation from the char to the pot	$Q_{char\ radiation}$	462.5806766	8.077585
Door opening loss in the feeding zone	$Q_{door\ loss}$	187.7818326	3.2790469
Radiation from a flame to the pot	$Q_{flame\ radiation}$	21.74294135	0.3796753
Loss through combustion wall	$Q_{heat\ loss}$	78.26182586	1.3666082
heat loss caused by the fuel's hydrogen content	$Q_{H2\ moisture}$	27.93058823	0.487724
Moisture loss	$Q_{fuel\ moisture}$	36.81911023	0.6429354
Total (Firepower)	FP	5726.72	100%

Table 4.3 shows that the heat loss through the combustion chamber wall was calculated to be 78.26 Watts, which is only 1.37% of the overall firepower. These data indicate that the rocket stove's insulating material and design were efficient in decreasing thermal

conductivity, resulting in significantly reduced heat loss through the combustion chamber wall.

5.2.7 Thermal efficiency

The thermal efficiency (η_{th}) parameter, which is a key performance indicator for rocket stoves, was evaluated using the experimental water boiling test. The thermal efficiency was calculated for both the 36 cm and 24 cm combustion chamber heights, and the results showed a thermal efficiency of 30.23% and 28.51%, respectively. Therefore, it can be concluded that the taller combustion chamber design has a higher thermal efficiency than the shorter combustion chamber design.

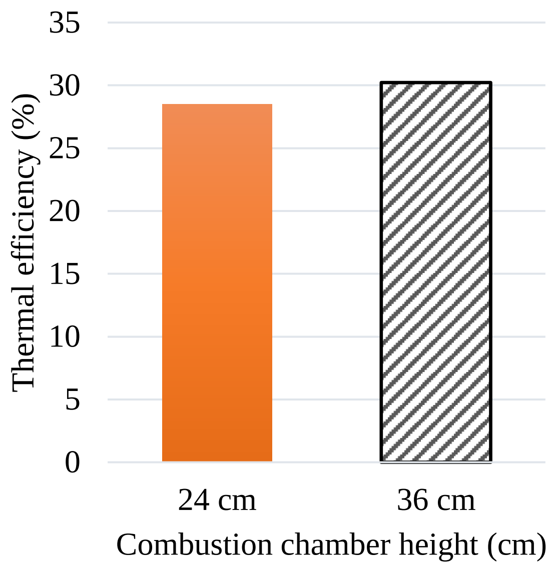

Figure 5.10 Thermal efficiency (%)

A comparison with existing stoves in the area was done to evaluate the thermal performance of the designed stove. Previous Ethiopian studies reported thermal efficiencies of 7-8% for three-stone stoves (Accenture, 2012), whereas other comparative studies reported higher thermal efficiencies ranging from 14% to 18% for the same type of stove (Grieshop et al., 2011; Jetter et al., 2012). Wassie and Adaramola (2021), on the other hand, reported a thermal efficiency of about 28 percent for a portable domestic cook stove built of galvanized sheet metal with a ceramic liner rocket stove (Tikikil stove). A Rocket stove was developed by Mekonnen (2020) with a thermal efficiency of 29 %. The designed prototype stove has a thermal efficiency of 30.23%, which places it in tier 2 of the International Workshop Agreement (IWA) tiers of performance (Alliance, 2013). This represents a substantial improvement over the baseline traditional 3-stone stove.

5.2.8 Controlled cooking test results

The test involved a standardized cooking task which is cooking a Rice that is representative of the typical cooking practices of the local population. The cooked Rice was 265 g in weight and was cooked until it reaches a state where it is edible (checked by hand and observation). The thermal efficiency of the cook stove is calculated as equation 4-71 and the results are tabulated in table 5.4.

Table 5.4 Control cooking test results

Parameters	Unit	Value
Initial mass of Rice	g	265
Mass of water add for cooking	g	1010
Time taken for cooking	min	21
Mass of water absorbed by the Rice	g	555.64
Mass of water evaporated	g	454.36
Mass of fuel consumed for cooking	g	691.22
Firepower	Watts	6,519.24
Burn rate	g/min	20.7
Thermal efficiency	%	21.3
Specific fuel consumption	Kg of fuel per Kg of rice cooked	2.65

Figure 5.11 Control cooking test result of the cooked Rice

CHAPTER SIX

6. Conclusions and recommendations

6.1 Conclusions

The present thesis investigates the experimental performance of a rocket stove that has been built with a variable combustion chamber height. The produced rocket stove was built utilizing the Aprovecho research center's (USA) design principle, which is constructed using locally accessible materials and cost-effective wood ash for insulation for everyday cooking requirements in rural Ethiopia. The experimental investigation was carried out using two combustion height parameters, one with a height of 36 cm and the other with a height of 24 cm. The experimental investigation was performed to assess the performance of the rocket stove when the height of the combustion chamber was varied. Data from water boiling tests, including time to boil, fuel usage, temperature readings, and exhaust gases, were collected. Finally, the outcomes of the experiments were interpreted. The following conclusions were reached from the rocket stove's experimental investigation.

- ✓ The average time to boil 2.5 kg of water in the 36 cm combustion chamber was 12 minutes in the cold start and 7.6 minutes in the hot start, which is quicker than the 24 cm combustion chamber height.
- ✓ The study found that the taller combustion chamber was more effective in achieving complete combustion, resulting in lower CO emissions that were within the WHO standards. In general, the developed rocket stove emission was found to be much lower than currently used traditional stoves in rural areas.
- ✓ The thermal efficiency of the designed rocket stove was significantly better than that of locally accessible traditional stoves and considerably greater than that of recently developed and accepted stoves. The combustion chamber's height and the anticipated insulation also helped improve thermal efficiency.
- ✓ The developed rocket stove's specific fuel consumption of 79 g/litter was rather low when compared to traditional cooking stoves and reasonably lower than recently developed improved cookstoves in Ethiopia.

6.2 Recommendations

The present study involved the design, development, and experimental investigation of a rocket stove with variable geometrical parameters, and the key results have been detailed in section 5.1. However, there remain several opportunities for further research to enhance the performance of the rocket stove. Some of the recommended areas for further study include:

- Investigating the effect of the gap height between the stove and the pot, as this study primarily focused on the combustion chamber height.
- Exploring the insulation material to further reduce the overall weight of the rocket stove while maintaining its insulating properties.
- Enhancing the stove's performance through the addition of a chimney for cleaner burning.
- Analyzing the experimental results and focusing on simulating the stove's performance using computational fluid dynamics (CFD) in future research.

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APPENDIXES

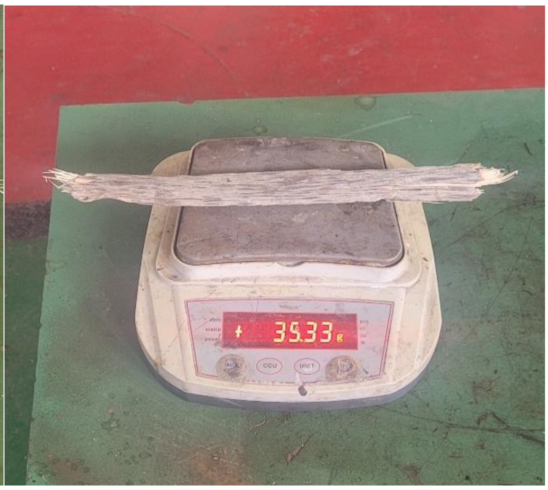
APPENDIX A: Measuring Instrument Calibration

Thermocouples are temperature sensors that convert temperature into an electrical voltage. They are made of two dissimilar metals or metal alloys joined together at one end, called the junction, and connected to a voltage measuring device at the other end. When the junction of a thermocouple is exposed to a temperature gradient, a small voltage is generated in proportion to the temperature difference between the junction and the other end of the thermocouple. This is known as the Seebeck effect. The voltage generated by the thermocouple can be measured using a voltage measuring device, such as a voltmeter or data acquisition system, and converted into a temperature reading using a calibration equation or lookup table. Calibration of the measuring instrument is necessary before taking any measurements when testing the experiments. In the current study, the boiling water (100°C) was used to calibrate the thermocouple. Numeric labels were assigned to the thermocouples for the purpose of facilitating their identification.

Thermocouples	Reading out of Boiled water (100°C)	Uncertainty (%) $\frac{100 - measured}{100} \times 100\%$
Digital thermometer	99.7	0.3
Thermocouple 1	99.4	0.6
Thermocouple 2	99.7	0.3
Thermocouple 3	99.6	0.7
Thermocouple 4	99.2	0.8
Thermocouple 5	99.5	0.5

So, the average uncertainty is obtained as 0.533.

APPENDIX B: Moisture content calculation



$$Moisture\ content\ \% = \frac{M_i - M_f}{M_i} \times 100\%$$

$$Moisture\ content\ \% = \frac{39.49\ g - 35.33\ g}{39.49\ g} \times 100\%$$

$$MC\ \% = 10.53\ \%$$

APPENDIX C: Loss coefficients, density ratios and area ratios.

S. N.	Type of loss	K_l	ρ/ρ_l	A/A_l
1	Sudden contraction at inlet	$=0.5$	T_a/T_g	$1/A_r$
2	Friction loss in elbow length 	$=\frac{f_e*L_e}{D_h},\ f_e=\frac{64}{R_{ee}},\ D_h=\frac{4*A_r*A}{d*[\pi-\theta+\mathrm{Sin}\theta]}$ $\theta=(-2.289503842*A_r^2+1.23599729*A_r+1.522230692)$ Correlated from the results obtained from expression: $A_r*A=\frac{D^2}{4}\left(\pi-\theta\frac{\mathrm{Sin}2\theta}{2}\right)$	$\frac{T_g+T_a}{2*T_g}$	$1/A_r$
3	Expansion to chimney	$=[1/(A_r-0.5)-1]^2$	1	1
4	Fuel bed resistance (Viscous and Inertial)	$=\frac{3.5*H}{d_p}*\frac{(1-\varepsilon)}{\varepsilon^3}*\frac{\rho_b}{\rho_g}+\frac{300*H*\mu}{d_p^2*\rho_g*V}*\frac{(1-\varepsilon)^2}{\varepsilon^3}$ ε=bed voidage $=0.69$ $H=D/4$	1	1
5	Friction loss in chimney	$=f*h/D$, $f=(0.79*l_n Re_D-1.64)^{-2}$, for $Re_D>900$ $f=64/Re_D$, for $Re_D<900$	1	1
6	Loss due to bend at pot bottom	1	1	1
7	Loss due to friction in the pot gap zone	$=\frac{4f(d_p-d)}{D_h},\ f=\frac{24}{R_e},\ D_h=W_1+W_2$	$\frac{T_c+T_g}{2*T_g}$	$\frac{d^2}{(d+d_p)*(W_1+W_2)}$
8	Loss at the outlet	1	1	1

APPENDIX D: Insulation in the combustion chamber

The G.U.N.T WL 374 is a Conduction in Solids Tester designed and manufactured by G.U.N.T. Gerätebau GmbH, a German company. The device consists of a test rod made of different materials, such as copper, aluminum, and steel, which can be heated by an electric current. The temperature distribution in the test rod is then measured using temperature sensors, which are connected to a digital display unit.

The key specifications of the G.U.N.T WL 374 Conduction in Solids Tester are as follows:

- Test rod length: 30 mm
- Test rod diameter: 40 mm
- Test rod material: Copper and steel
- Heating power rating: 400 W
- Temperature measurement range: -10 to 50°C

From thermal conductivity test conducted using this instrument the results are tabled as follow.

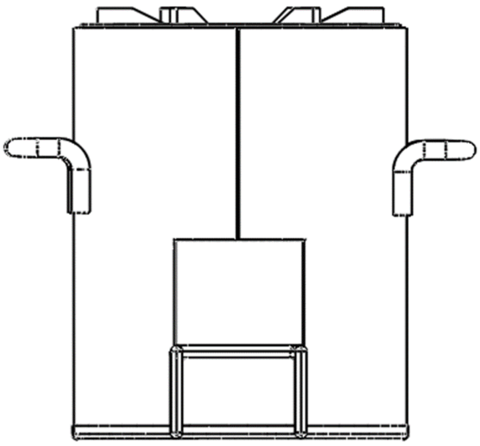
Ratio of gypsum to wood ash	Thermal conductivity W/mK.	Remark
1:1	0.261	x
1:2	0.238	✓
1:3	0.217	x
1:4	0.184	x

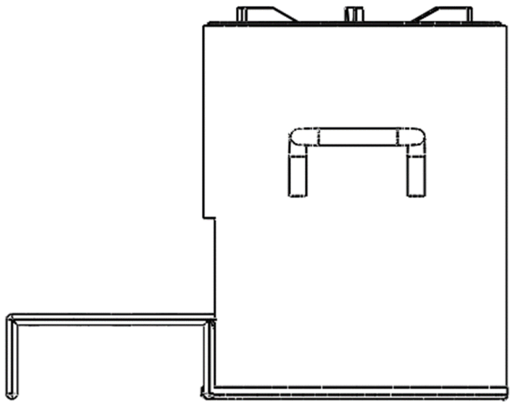
Reference material

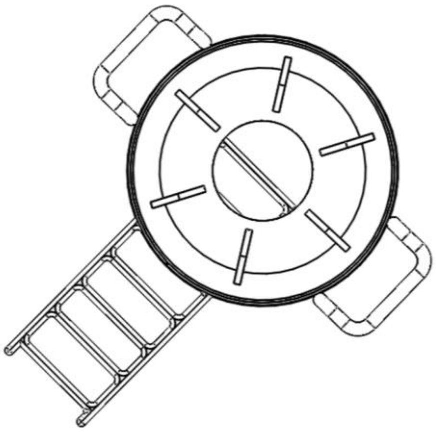
The 1:2 ratio was chosen for its adhesive properties, despite having a higher thermal conductivity compared to the 1:3 and 1:4 ratios, which exhibited a tendency to fragment.

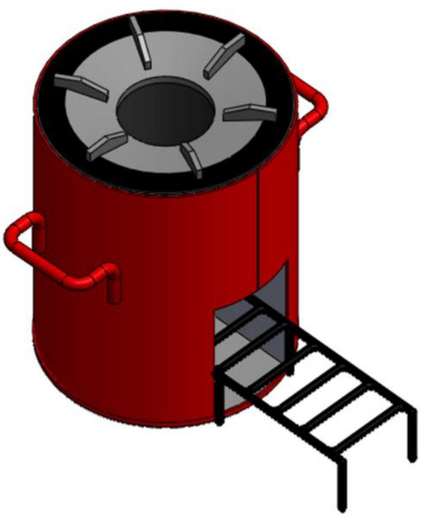
Insulation material pouring into the shapes

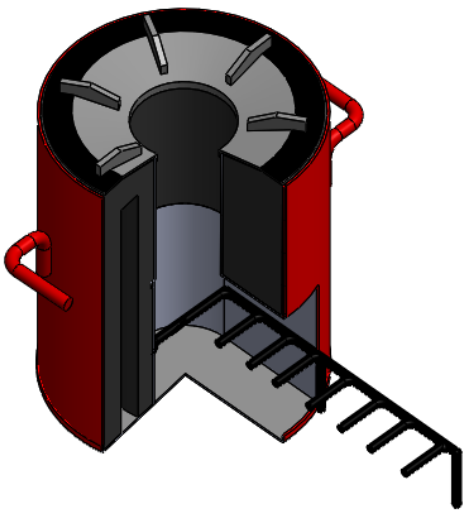
APPENDIX E: Solid works drawing of designed Rocket Stove











APPENDIX F: Proximate analysis result.

GEOLOGICAL INSTITUTE OF ETHIOPIA	Doc. Number: GLD/F5.10.2	Version No: 1
Geochemical Laboratory Desk		Page 1of 1
Document Title:- Hydrocarbon Analysis Report	Effective date:	Nov. 2022

Customer Name:- Frew Gebretsadik Gebremariam

Sample type: -Eucalyptus Wood

Sample Preparation:- 60 Mesh

Date Submitted:-06/06/2023

Issue Date:- 23/06/2023

Request No:-GLD/RN/1378/23

Report No:- GLD/TR/1967/23

Number of Sample: -One (01)

Elements to be determined:-(Moisture,Volatile matter, Fixed carbon and Ash).

Method of analysis:- Proximate Analysis.

Collectors' Code	Moisture %	Volatile Matter %	Fixed carbon %	Ash %
Sample-101	8.81	73.02	10.79	7.38

Note: - This result represent only for the sample submitted to the laboratory.

Analysts

Bethelhem Tefera

Shashe Haile

Approved By

Alemnesh Abate

Quality Control

Negash Worku

Geochemical Laboratory Desk Pag

APPENDIX G: Conducting the water boiling test in picture.

APPENDIX H: Emissions measurement procedure.