PERFORMANCE TEST OF CHARCOAL COOK STOVES EXPERMENTALLY AND USING ANSYS CFD FOR IMPROVEMENT

TEMESGEN WOLDEYOHANIS DUTEBO

A THESIS SUBMITTED TO

THE DEPARTMENT OF MECHANICAL ENGINEERING

SCHOOL OF MECHANICAL, CHEMICAL AND MATERIALS ENGINEERING

PRESENTED IN PARTIAL FULFILLMENT OF THE DEGREE OF MASTER OF SCIENCE IN THERMAL ENGINEERING

OFFICE OF GRADUATE STUDIES

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APPROVAL PAGE

We, the advisors of the thesis entitled "Performance Test of Charcoal Cook Stoves Experimentally and Using Ansys CFD for Improvement and developed by Temesgen Woldeyohanis; hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Major Advisor	Signature	Date
Co-advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by Temesgen Woldeyohanis have read and evaluated the thesis entitled "Performance Test of Charcoal Cook Stoves Experimentally and Using Ansys CFD for Improvement**",** and examined the candidate during the open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Thermal Engineering

Chairperson	Signature	Date
Internal Examiner	Signature	Date
Samson Mekbib Atnaw (PhD)		June, 2022
External Examiner	Signature	Date

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

Department Head	Signature	Date
School Dean	Signature	Date
Office of Postgraduate Studies, Dean	Signature	Date

DECLARATION

I hereby declare that this Master Thesis entitled "Performance test of charcoal cook stoves experimentally and using Ansys CFD for improvement." 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.

_________________________________	__________________	___________________
Name of the student	Signature	Date

RECOMMENDATION

We, the advisors of this thesis, hereby certify that we have read the revised version of the thesis entitled "Performance test of charcoal cook stoves experimentally and using Ansys CFD for improvement." prepared under our guidance by Temesgen Woldeyohanis submitted in partial fulfillment of the requirements for the degree of Masters of Science in Thermal Engineering. Therefore, we recommend the submission of the revised version of the thesis to the department following the applicable procedures.

______________________________	_________________	__________________
Major advisor	Signature	Date
______________________________	_________________	__________________
Co-advisor	Signature	Date

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ABSTRACT

Due to poor thermal performance of the conventional bare metal stove, plenty of improved cooking stove development projects have been introduced all over the world over the last 14 years in order to improve energy consumption . All improved stoves saved fuel on average when compared with the conventional bare metal stove, and the majority also lowered total emissions released. The conventional stove, on the other hand, may be difficult to replace because it had the shortest time to boil, which is an important aspect for end users. Using the emission and performance test protocol (EPTP protocol), there were also noticeable differences in stove performance between all stoves. In this work, ANSYS 2012 design modular is used to model six conventional locally available cooking stoves (Turumbe, Ethio, Obama, Hexagon, Bandira and bare metal) and the new design stove geometries and a computational fluid dynamics (CFD) analysis has also been carried out for these different geometries of stove to analyse the flow behaviour of gas, heat transfer behaviour, oxygen mass fraction, volatile mass fraction and CO_2 *mass fraction during the cooking period using Autodesk Simulation CFD 2012. For all stoves the computational results were compared and validated with the experimental data. The experimental data were handled by using WBT excel spread sheet for all cooking stoves and the analytical analyses were done only for the new design modified stove (MS).From experimental data thermal efficiency result was found to be 27.8, 22.6, 22.6,23, 25.47, 16 and 28 % for Turumbe, Ethio, Obama, Hexagon, Bandira, bare metal and new design modified stove, respectively. The analytical result of the new design modified stove was found to be 27%. For all stoves the emission (CO and CO2) results were compared and the bare metal showed large CO by % volume.*

Keywords: *Thermal performance, charcoal stove, Emissions, CFD*

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LIST OF ACRONYMS AND ABBREVIATIONS

WBT	Water boiling test
EPTP	Emission and performance test protocol
TTB	Time to Boil
ICS	Improved Cook stove
ABS	Advanced Biomass Stoves
PM	Particulate Matter
ESC	Existing Stove Insulating Clay
IHEA	Industrial Heating Equipment Association
TSF	Three Stone Fire
IAP	Indoor Air Pollution
MS	Modified Stove

NOMENCLUTURE

A	Area (m^2)
Cp	Specific Heat ($\frac{J}{g\ {}^{o}C}$)
D	Diameter (m)
m	Mass (kg)
E	Energy (J)
P	Static Pressure (kPa)
f	Friction Factor ($\frac{kg}{m^2 s^2}$)
h	Heat Transfer Coefficient ($\frac{W}{m^2 {}^{o}C}$)
h_{fg}	Enthalpy of Vaporization of Water ($\frac{J}{mole}$)
HHV	Higher Heating Value of Char ($\frac{J}{g}$)
k	Thermal Conductivity ($\frac{W}{m.k}$)
LHV	Lower Heating Value of Wood ($\frac{J}{g}$)
Q	Heat Transfer (W)
Nu	Nusselt Number
Pr	Prandtl Number
G	Gap between pot and stove (m)
R	Resistance ($\frac{{}^{0}C}{W}$)
Re	Reynolds Number

S	View Factor
T	Temperature (K)
T_{amb}	Ambient Fluid (air) Temperature (K)
ε	Emissivity
μ	Viscosity ($\frac{N.s}{m^2}$)

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CHAPTER ONE

1. INTRODUCTION

1.1. Background of the study

Energy has an important role in socio-economic growth by changing the standard of living and the quality of life of society in a country; therefore, providing reliable and sustainable energy is a requirement for the prosperity of that country. Approaches to research and forecasting future energy needs emphasize local, renewable and sustainable sources of energy. In the total primary energy supply, fossil fuels account for 81 %, nuclear energy represents 5 % and renewable energy sources 14 % (of which the contribution of biomass is about 70 %) (Raturi et al., 2019).

In general, the provision of modern, reliable, and efficient energy services is believed to be an important and indeed indispensable driving force for economic development. Many people living in developing countries of the world do not have access to modern energy services for economic and social development as showed in Table 1.1. However, due to the insufficient supply of modern energy services, most African countries face great challenges in their efforts to meet their social and development obligations. A large proportion of households do not have access to the electricity grid. Globally, biomass is the main contributor to renewable energy. According to a recent bio-energy report from the International Energy Agency, renewable energy accounted for 13% of total energy consumption in 2006 (Bioenergy, 2009).

Biomass fuels such as wood are potential sources of renewable and carbon-neutral energy. About 10% of the world's energy demand comes from wood and more than 3 billion people burn some type of biomass fuel to obtain energy every day. However, biomass combustion is often inefficient and incomplete, leading to the release of toxic gases and particulate matter (PM). There are significant disparities in how biomass is used around the world. Biomass contributes for about 20% of the energy mix in developing nations, primarily woody biomass and dung, which are utilized for traditional residential heating, and cooking mostly in simple, inefficient stoves. Bio-energy accounts for about 3% of the mix in industrialized countries, although it is used for electricity, heating, and transportation (Fritsche et al., 2009).

Many African countries continue to meet a large portion of their national energy needs with traditional biomass, which frequently has negative environmental and health consequences. Furthermore, its current energy system is unsustainable. Those who rely on electricity for cooking, on the other hand, face intermittent power supply (Lemaire et al., 2008). Currently; approximately 2.6 billion people do not have access to clean cooking facilities. and if predictions are believed, approximately same number will still be so in 2030 (Jestin-Fleury et al., 1994). The frequent use of stoves developed by improper combustion designs may result in indoor air pollution, which can have a negative impact on the health of household members, especially women and children. Every year, approximately 1.6 million people die prematurely as a result of indoor air pollution caused by solid-fuel cooking, accounting for more than 2% of all global diseases (4 percent in the poorest nations) (Smith et al., 2003).

Table 1.1: Access to Electricity and Clean Cooking. Source (World Bank, 2017)

Region	**Access to Electricity (% of Population)**							**Access to Clean Fuels and Technologies for Cooking (% of Population)**			
	Total					Urban	Rural	Total			
	1990	2000	2010	2012	2014	2014	2014	2000	2010	2012	2014
World	73	78	84	85	85	93	73	50	56	56	57
Africa	38	38	43	45	47	76	27	25	25	25	25
North Africa	75	81	85	86	88	95	80	75	83	84	85
Rest of Africa	23	26	32	35	37	70	17	11	12	12	12

According to the WHO (Organization, 2006) and World Bank (Kapur et al.,2011) reports, house air pollution caused by the combustion of solid biomass fuels such as wood, animal dung, and crop residue in traditional earthen cook stoves is directly responsible for the premature death of approximately 2 million people worldwide.

Human exposure to by-products of biomass combustion has been linked to negative effects on the respiratory, cardiovascular, immune, and nervous systems. Chronic exposure to biomass combustion particulate matter has been linked to an increased risk of respiratory illness and infection, lung cancer, and permanent decreases in lung function (Khalequzzaman et al., 2007) and increased risk of myocardial infarction, irregular heart rate, and increased blood viscosity are all cardiovascular effects (Wallace et al., 2003). Cooking with solid bio-fuels has a large global impact on greenhouse gas and black carbon emissions, accounting for 1–3 percent of all human-caused global warming (Smith et al., 2013). Concluded that, the solid bio-fuel combustion is the dominant source of global black carbon emissions (Venkataraman et al., 2005). The heavy dependence on biomass resources and there in efficient utilization can be a significant source of deforestation and resulting climate change.

Biomass accounts for 10% of global energy production, with two-thirds of that used for cooking and heating in developing countries. People rely on solid fuels such as biomass and coal for their energy needs, burning millions of tons of biomass each day, which has implications for the environment and human health. Biomass is extremely difficult to completely burn in the most common household-sized stoves (Bantu et al., 2018). More than 700 million Africans (82%) use solid fuels for primary cooking, such as wood, charcoal, dung, crop waste, and coal, a figure that is expected to rise to 850–900 million by the end of the decade (Energy, 2014). However, its increased use by inefficient technologies has raised concerns about long-term forest degradation, including the loss of environmental services and biodiversity.

Ethiopia's energy sector is highly dependent on biomass, such as wood fuel, charcoal, crop residues and animal dung as showed in Table 1.2. The country has a huge biomass energy potential with estimates putting the national woody biomass stock at 1,149 million tons with annual yields of 50 million tons in the year 2000. Biomass energy accounted for 89 per cent of total national energy consumption in 2010 (AFRICA, 2014).

Table 1.2: Fuel Used for Cooking and Access to Modern Fuel in Ethiopia (% of National Population), 2006. Source (AFRICA, 2014)

Population (%)	Fuel used for cooking									Access to modern fuels
	Electrical	**Gas**	**Kerosene**	**Charcoal**	**Wood**	**Biomass**	**Dung**	**Coal**	**Other**	
All	0.2	0.1	3.9	2.8	85	92	7.4	-	0.6	4.2
Rural	0	0	0.2	0.2	91.1	91.5	8.3	-	0.2	0.2
Urban	1	1.2	25.9	18.1	48.7	94.9	2.1	-	3	28.1

In Ethiopia, nearly 70% of the population cooks food using different biomass fuels and live without electricity. The forest cover has been reduced from an initial estimate of 40% a century ago to less 3%. This brings environmental degradation, natural resource depletion and air pollution as well as associated health risks become serious issues as a result of cutting trees to serve as fuel wood. Concerning regional distribution of biomass consumption, annually about 88% of total biomass fuel is consumed mainly in three regions: Amhara (34%), Oromia (32%), and SNNP region (22%) (Geremew et al., 2014). According to Ethiopian environmental protection, approximately 95 percent of the total population relies on biomass fuels as their primary source of energy.

These biomass energy sources account for more than 90% of total domestic energy demand (Mangoyana et al., 2009). The biomass burning devices used for cooking are known in the literature by various names such as cook stoves, wood-burning cook stoves or biomass cook stoves. The traditional versions of cook stoves are highly inefficient and have high emissions leading to respiratory and other health problems. "Biomass cook stove" is a physical structure that contains air-fuel combustion for heat release, and subsequently, directs the heat of combustion towards a cooking target (pot or pan).

Besides cooking, stoves provide useful energy for space/water heating, in house lighting, fish/meat smoking, and grain/flour roasting. People in developing countries value the savings in fuel and time. They frequently spend 25% of their household income, or approximately 5 hours per day, purchasing or gathering fuel for cooking, water purification, and heating. Lower emissions and fuel consumption can be beneficial to the user's health, security, economic situation, and the environment at large. To improve energy security in developing countries, particularly in rural areas, efforts are being made to promote more efficient and sustainable use of traditional biomass, as well as to encourage people to switch to modern cooking fuels and stove technologies. Improved Cooking Stoves (ICSs) that are energy and emission efficient can help to solve these global issues.

ICSs can reduce:

- Diseases by decreasing indoor air pollution (IAP).
- Time and cost of obtaining fuel.
- Risk of violence against women and child gathering fuel in conflict areas.
- Climate change, lower emission, and deforestation.

Presently, different types of ICSs are being developed and disseminated for societies living in rural and urban city in Ethiopia by governmental and NGOs. For instance, in Ethiopia, for heating and cooking, charcoal stoves such as the Mirchaye stove (ICS), Lakech stove (ICS), Metal stove, and Tickle stove (ICS) are used which are shown in Figure 1.1. These conventional and the so-called improved cooking stoves are used almost everywhere in Ethiopia for domestic & hotels uses, and micro and small-scale restaurants uses. In addition, these cooking stoves are boosting the Ethiopian economy through providing employment opportunities in the form of cottage level coffee outlets which is very widespread nowadays in every street corner in Ethiopia.

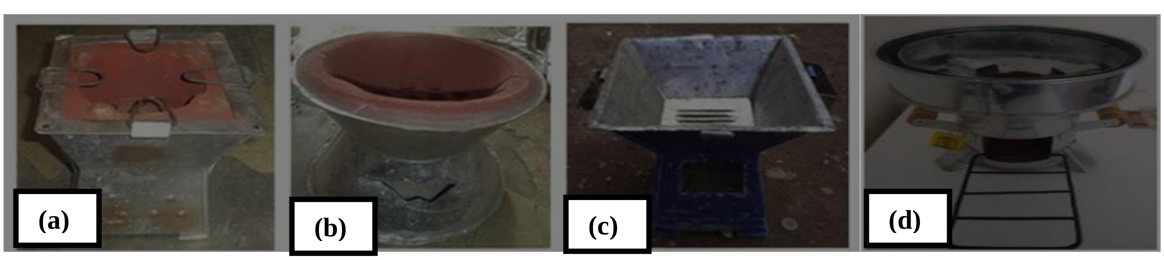


Figure 1.1: Charcoal stoves in Ethiopia (a) Mirchaye stove, (b) Lakech stove, (c) Metal stove, (d) Tikikil stove

1.2. Statement of the Problem

Diversely designed conventional and improved charcoal fired cooking stoves are in use in every day almost in every household, hotels, and restaurants in Ethiopia for cooking food, making tea & coffee, etc. They are serving the Ethiopian community very well. In the contrary, these cooking stoves are also responsible in creating localized pollution in every household and are sometimes causes of premature death due to inhalation of carbon monoxide CO and contribute to environmental pollution. The heat energy lost to surrounding from these cooking stoves is also high due to the improper selection of insulating clay material and the design of combustion chamber. This research work is intended to improve the efficiency of cooking stove through proper selection of the construction materials of the stove such as the clay liner with effective insulation & heat barrier property and improving design of the cooking stove geometry particularly the combustion chamber and studying the heat transfer and fluid flow characteristics using modeling & ANSYS 2012 simulation software and experimentation.

1.3. Objectives of the Study

1.3.1. General Objectives

The general objective of this research is the development of an improved and efficient charcoal modified stove from locally available materials and tests its performance using Ansys 2012 for the geometry design and CFD simulation for the performance.

1.3.2. Specific Objectives

- ❖ To test locally available stoves performance and efficiency using standard testing protocols
- ❖ To develop new stove model and conduct heat transfer analysis of the model.
- ❖ To prepare insulating material for modified stove development (low thermal conductive material from raw clay and waste silica).
- ❖ Numerically analyze the performance of the existing charcoal stoves and the modified one using ANSYS CFD.

- To compare the performance of charcoal stoves available in the market with the newly developed modified.
- Experimentally test the performance of the modified charcoal cook stove.

1.4. Significance of the study

The efficiency and performance of any coking stove which are available in Ethiopia market is not known. The benefit of knowing the performance of the coking stove is allowing the user to select the stoves base on specific requirements. The main significance of this study is to determine the performance of locally available cooking stove and then to develop a modified stove to reduce the fuel consumption, emission of flue gases and heat loss, which are challenge of the society on health, social and economic suffer due to utilization of biomass stoves, based on the data obtained from tested stoves. The result of research will profit the society in reduction in cost for fuel and from premature death caused by emission of gasses from cooking stoves and reduces frequent fuel demand.

1.5. Scope of the study

This study focuses on the experimental and computational analysis of the performance of selected locally cooking stoves available in the local market and newly designed modified cook stove.

1.6. Organization of the Thesis

The thesis remaining sections are organized as follows:

Chapter 2 presents literature reviews about Characteristics of Biomass, Biomass energy, Biomass cook stoves, Heat Transfer modes in Biomass Cook stoves**,** Performance testing of biomass cook stoves, Insulation materials for cooking stove and gap for the literature review.

Chapter 3 discusses the materials and methods section for the research work.

Chapter 4 explains the conventional cooking stoves and their performance evaluation analysis**.**

Chapter 5 discusses the design and analytical performance of the new modified stove.

Chapter 6 discuss about Computational Fluid Dynamics results on the cooking stoves performance.

Chapter 7 explains the result and findings obtained from experimental test and discuss the Performance evaluation of the cookstoves.

Chapter 8 presents conclusions of the study and recommendation for further study.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Biomass

Biomass is organic material that comes from plants and animals, and it is a renewable source of energy. It contains stored energy from the sun. Plants absorb the sun's energy in a process called photosynthesis. This is the primary cooking fuel for the majority of rural households, is usually available for free in rural areas.

2.2. Characteristics of Biomass

The term biomass is referred to crop residues and firewood. Biomass can be used directly as energy through combustion, or it can be converted into liquid and solid gaseous fuels that are more convenient and more efficient through thermo chemical (combustion, gasification and pyrolysis) and biochemical (anaerobic digestion and fermentation) conversion processes (Jain et al., 2013). The characteristics of the fuel that is important for the design and analysis of the biomass conversion process are: physical characteristics, that is, density, angle of repose and moisture content; thermal characteristics, that is, calorific value and approximate analysis, and chemical characteristics, elemental analysis and chemical composition. Physical characteristics vary greatly depending on the environment and processing procedures, while the rest are inherent characteristics.

2.2.1. Physical Properties of Biomass

The important physical characteristics of biomass are density, moisture content and angle of repose.

Density

True density is the weight per unit volume of a single piece of biomass. It depends on the humidity of the biomass and has a constant value based on the dry weight. Volume is the weight of the bulk biomass material divided by the volume occupied. The weight of biomass depends on the size, shape and level of its compaction or densification(Shojaeiarani et al., 2019). Table 2.1 shows the true and bulk density of different fuel materials.

Angle of Repose

The angle of repose is the angle made by the biomass from the horizontal to the sides of pile under free falling conditions. It is expressed in degrees. It is a flow property of the material. Angle of repose is useful in the determination of the angle of fuel hopper, fuel transportation lines to the furnaces or gasifier. During the thermo chemical conversion process the angle of repose changes due to change in shape and size of the fuel particle (Schott et al., 2011).

Table 2.1: Bulk Density and True Density of Certain Fuel Materials. **(**Kaupp & Goss, 1981)

Fuel	**Density** $\frac{\mathbf{kg}}{\mathbf{m^3}}$
Coal anthracite	830-900
Coal bituminous	770-930
Wood hard 20-40 mm^3	330
Wood soft 20-40 mm^3	250
Charcoal	130-150
Saw dust	175
Paddy husk	105
Straws	50-80
Bagasse	70

Moisture Content

Most of the biomass are hygroscopic in nature and absorb moisture from the atmosphere. Moisture in biomass is fundamentally subdivided into inherent, surface and decomposition moisture. Inherent moisture is the moisture a fuel can hold in the capillary openings of the biomass when in equilibrium with the atmosphere. Surface moisture occurs on the surface of the biomass and is in excess of inherent moisture (Wu et al., 2011).

2.2.2. Thermal Characteristics

The important thermal characteristics of biomass are calorific value and proximate analysis.

Heating Value

Heating value or calorific value is the heat released by the fuel under ideal combustion conditions. It is usually classified as higher heating value (HHV) and lower heating value (LHV).

Higher Heating Value

It is the amount of heat liberated when a known quantity of biomass is burned under ideal combustion condition at constant volume and the decomposition moisture is condensed.

Lower Heating Value

Knowing the elemental analysis and higher heating value of the biomass, the lower heating value can be determined. It is usually 10 to 15% lower as compared to the higher heating value. The lower heating value can be linked with the higher heating value by the following expression. λ and W_f are the latent heat of vaporization of water and weight fraction of water formed during combustion process. HHV is calculated by equation 2.1 (Pathak et al., 1985)**.**

$$HHV = LHV + \lambda W_f + \text{expansion work} \tag{2.1}$$

Where: HHV- High heating value

LHV- Lower heating value

W_f - Weight fraction of water

λ- Latent heat of vaporization of water

Proximate Analysis

Proximate analysis provides information on the combustion characteristics of biomass. It is a measure of fixed carbon (FC), volatile matter (VM), Ash (A) and Moisture (M) in the biomass material and expressed as percent. The biomass is placed in a muffle furnace at $915^{o}C$ for 7 minutes in a covered platinum crucible. The moisture and VM and are driven off and the residue left after 7 minutes is the fixed carbon and ash. The percent ash content can be determined using the following equation 2.2 (Wu et al., 2011) .

$$\text{Ash} = \left[\frac{\text{weight of ash}}{\text{weight of wet biomass}}\right] \text{x}100 \tag{2.2}$$

Table 2.2: Ultimate Analysis of Selected Fuels (Pathak et al., 1985)

Fuel Material	**Calorific Value**	
	HHV	**LHV**
Carbon	32.7	-
Anthracite	30.9	-
Bituminous	25.1	-
Charcoal	24.7	-
Lignite	23.9	-
Eucalyptus	19.4	18
Bagasse	20	18.6
Wheat straw	17.2	16
Cotton stick	17.4	16.3

2.2.3. Chemical Analysis

Chemical analysis gives information about the chemical composition (cellulose, hemi-cellulose, and pentosan lignin and alcohol benzene extractives) and elemental analysis (carbon, hydrogen, nitrogen, oxygen, sulfur, silica, sodium, potassium etc.) of biomass.

Ultimate Analysis

Ultimate analysis gives information regarding the elemental composition of carbon, hydrogen, oxygen and nitrogen content of a biomass fuel (Pathak et al., 1985).

Table 2.3: Ultimate Analysis of Selected Fuels (Pathak et al., 1985)**.**

Fuel material	**C**	**H**	**O**
Carbon	100	0	0
Anthracite	95	1.5	3.5
Bituminous	87	5	13
Charcoal	75	5	15
Lignite	71	5	24
Eucalyptus	50.3	6.26	43.44
Ba0gasse	48.2	6.1	0.2

Wheat straw	47.8	5.89	46.3
Cotton stick	52.7	5.07	42.23

2.3. Biomass Energy

The range of fuel used for cooking depends on availability, affordability, convenience, and applicability. Fuels can be divided into several categories according to their physical state (solid, liquid, gas). Before fossil fuels became widespread in the 20thcentury, biomass was the main source of energy and remained the main source of energy for billions of the poorest people. Therefore, it is important to understand the common sources of cooking energy that people in rural areas use and the challenges they face in making fuel sources economically viable, socially acceptable, and ecologically sustainable.

Without adequate access to affordable cooking fuels, it will be difficult to eradicate poverty and achieve food and nutrition security in a sustainable environment. In sub-Saharan Africa (SSA), more than 90% of the population depends on fuel wood and charcoal (firewood, collectively) as the main source of household energy. The sustainability of wood fuel is challenged by unsustainable logging and inefficient methods of converting wood into energy (Njenga et al., 2019).

Burning wood or biomass directly is very inefficient and only provides about 10% of useful energy. It is a polluting and inconvenient fuel due to the massive formation of smog. Therefore, the best way to obtain high thermal efficiency is to convert wood or biomass into charcoal. Because of its efficiency and ease of transportation, wood fuel in the form of charcoal is usually the fuel of choice. An increase in the supply of charcoal in rural areas can make an important contribution to the overall quality of life. Biomass fuel types used in different stove are discussed in Table 2.4.

Table 2.4: Biomass Fuels Used For Different Cook Stoves.

Fuel type	Description	Reference
Wood	• The gasifier is filled to within 2 cm of the top. It is desirable to have the fire spread rapidly laterally across the surface to provide gas over the whole area, so an easily combustible material, • 12 V, 3 W blower for supply of gasification and combustion air. The superficial velocity in the range of 1.7–6.2 cm/s. satisfactory operation of stove for fuels with moisture content up to 30%.	(Reed et al., 2000)
Rise hask	• Rice-husk conversion to energy • Rice husk combustion in a circulating fluidized bed • Downdraft: 13 W fan for gasification air supply. maximum fuel consumption rate: 2 kg/h.	(Beagle et al. , 1978)
Charcoal	• Combustion of wood charcoal • Dynamics of wood charcoal combustion are examined both experimentally and theoretically • Performance of three charcoal stoves	(Bhagat et al., 1980)

2.3.1. Wood

Wood is considered to be the first energy source for mankind. Today, it is still the single most important source of renewable energy, accounting for about 6% of the world's total primary energy supply(Sreevani et al., 2018). Wood fuel, such as firewood, charcoal, chips, sheets, pellets, and sawdust. (Lauri et al., 2014) stated that the world's energy wood supply is estimated to be 0-23 G m^3/year. By 2050, woody biomass will account for 2-18% of global primary energy consumption. If virgin forests are excluded from the timber supply, the potential will be reduced by as much as 25%. The specific form used depends on factors such as source, quantity, quality and application. Today, burning wood is the largest use of solid fuel biomass energy. In the case of burning wood, the potential energy (in the form of chemical energy) stored in the trunk is released due to the heating of other excited atoms. Saw dust particles and other agglomerated energy products are manufactured from dry sawdust, wood chips or flour, and the raw materials are compressed under high pressure. Bergman et al.,(2008) showed that wood fuel has many environmental benefits compared with fossil fuels. Wood can be reloaded continuously to obtain a sustainable and reliable supply. However, proper forest management must be implemented to ensure that the growth conditions do not degrade during the biomass production process. Pellets and agglomerates are currently the most economical way to convert biomass into fuel and are a fast-growing energy source.

2.3.2. Charcoal

It is a solid biomass fuel that is obtained by carbonization (also called pyrolysis) of wood. Its average energy content is 30 MJ / kg (Rosillo-Calle et al., 2000). Taking in to account only the energy content of firewood and charcoal, it could be concluded that charcoal is a more preferable cooking fuel.

Rosillo-Calle et al., 2000 Stated that during the carbonization process, high temperature will cause heat absorption, leading to the complete decomposition of wood and separation into volatile gases, steam and solid carbon. At 400°C, wood is almost completely converted to charcoal. However, at this stage, charcoal still contains a considerable amount of tar, about 30%. To reach a final carbon content of approximately 75%, which is ideal for a good commercial grade, additional heating is required to remove tar and increase the fixed carbon content. Converting 1 kg of wood can only produce 0.1-0.3 kg of charcoal. Therefore, replacing firewood with charcoal will lose 2 to 6 times the total energy contained in the original wood. To convert wood into charcoal, a "smelting furnace" must be used. The energy efficiency of the carbonization process as well as the quality of the charcoal is dependent on many factors, such as:

- The type of kiln (open pits, earthen kilns or steel cylinders – also called retorts)
- Moisture content
- Wood species and wood stacking
- Production skills of the producer

Advantage of using Charcoal

In many developing countries, charcoal is the primary cooking fuel for urban households. Switching from firewood to charcoal in urban areas can have the following advantages for end-users:

- ❖ The accessibility of charcoal in urban environments is usually higher than in rural environments, because charcoal has monetary value and urban households can pay for charcoal. In addition, due to its lightweight physical properties, charcoal is easy to transport and store.
- ❖ Affordability remains the deciding factor in household fuel decisions. Considering that in most cities, charcoal is cheaper than kerosene, liquefied petroleum gas (LPG) or electricity, which is why many households prefer it. An analysis by ECO Consult and GIZ in 2013 showed that households that use firewood sometimes even use more energy per unit than households that use coal (Sepp et al., 2014).
- ❖ Compared with cooking with wood, another advantage of using charcoal is convenience. Users do not need to be alert to fire when using charcoal and less harmful smoke is produced when burning. Therefore, the cooking pot can be kept clean for a longer time.

Charcoal Combustion

Combustion is the conversion of a substance called a fuel into chemical compounds known as products of combustion by combination with an oxidizer. The combustion process is an exothermic chemical reaction, i.e., a reaction that releases energy as it occurs. Thus combustion may be represented symbolically by:

$$\text{Fuel} + \text{Oxidizer} \longrightarrow \text{Products of combustion} + \text{Energy}$$

Here the fuel and the oxidizer are reactants, i.e., the substances present before the reaction takes place. This relation indicates that the reactants produce combustion products and energy. Either the chemical energy released is transferred to the surroundings as it is produced, or it remains in the combustion products in the form of elevated internal energy (temperature), or some combination thereof. Fuels are evaluated, in part, based on the amount of energy or heat that they release per unit mass or per mole during combustion of the fuel. Such a quantity is known as the fuel's heat of reaction or heating value. Charcoal particles can be fully merged into oxidation conditions sufficiently at high temperatures.

The reaction between charcoal and oxygen is a gas-solid heterogeneous reaction. The gaseous oxygen is absorbed and reacts in the pores of the particles. This heterogeneous process often requires more than a few seconds or more because it is much slower than the devolatilization process. The speed of this process depends on the type of charcoal (biomass source), temperature, pressure, characteristics of the charcoal (size, the area of the surface, etc.) and the concentration of oxidant. Other reactants, including steam, CO_2 and H_2, can also react with char, but the rates with these reactants are considerably slower than with oxygen. The primary reactions of charcoal combustion and the heat of the reactions are listed in Table 2.5.

Table 2.5: Primary Reactions Taking Place during Coal Combustion (Shen, 2009)

Reaction	Heat of reaction (KJ)
$C + O_2 \rightarrow CO_2$	-392.9
$C + \frac{1}{2}O_2 \rightarrow CO$	-111.2
$CO + \frac{1}{2}O_2 \rightarrow CO_2$	-281.7
$C + CO_2 \rightarrow 2CO$	+170.5

Han et al., (2016) studied the combustion patterns, characteristics, and kinetics by thermo-gravimetric analysis for raw maize straw, cotton stalk, and chars obtained from segmented heating carbonization at 300–800°C.With increasing carbonization temperature, the combustion patterns from biomass to chars transform from the sequential reaction steps corresponding to pyrolysis and heterogeneous oxidation of volatiles and char to the in situ heterogeneous oxidation of fixed carbon and volatiles, the ignition temperature of biomass chars gradually increases, the ignition index does not monotonically increase, and the burnout index and combustion characteristic index decrease to different degrees.

2.4. Biomass cook stoves

Cook stoves are as old as the human history (Nyahoro et al., 2008) stated that the three-stone fire is the simplest and the most common cook stove throughout history (Nyahoro et al., 2008). The traditional cooking method is in a three-stone stove or clay stove. Over time, they have evolved into a variety of shapes and sizes, composed of different materials, and adapted to different cultures and cuisines (Kshirsagar et al., 2014). There is evidence that biomass fuel was used in the caves 500,000 years ago (Pandey et al., 2014).

2.4.1. Classification of Biomass Cook Stoves

Cooking stoves are classified using various parameters such as age of use, durability, working principle, and so on and showed in Table 2.6. Some of stove types are discussed as follows:

Traditional cook stoves: According to local culture and eating habits, traditional stoves have been developed for thousands of years. There are two types of traditional stoves. The first is the "Three Stone Fire" (TSF), a fire that is built directly under ground with three stones and a cooking target is placed on the top. Since ancient times, with the continuous development of cooking styles and methods, the "modified" stove, which is today's" traditional stove" or "Three Stone Fire (TSF)", was formed in a way of approximately 12,000 years. Until the 18th century, "Modified" stoves were still prevalent all over the world, and to this day, they are still prevalent in rural areas of many developing countries.

Three-stone fire is the cheapest stove, because it only requires three suitable stones of the same height, and a pot can be balanced on the fire. However, this cooking method also has problems, such as exhausting smoke into the home instead of outdoors, causing health problems; fuel is wasted because heat is released to the open air. This requires the user to gather more fuel and may result in increased deforestation if wood is used for fuel (Preble et al., 2014). The main disadvantage of TSF is low efficiency, but compared to some newly designed stoves, its performance is better. The second type of traditional stove is "built-in stove" or "clay stove", which is an improved version of TSF. "Built-in furnace" is a semi-permanent clay structure that encloses the fire from at least three directions different from the ground(Still et al., 2011).

Improved cook stoves: The “Improved Cook stove” ICS is a cook stove designed using certain scientific principles, to better combustion and heat transfer to improve emissions and efficiency performance. The goal of an ICS design is to improve upon the short comings of the traditional stoves, while still ensuring lower cost and ease of use (MacCarty et al., 2008).

Advanced cook stoves: Advanced Biomass Stoves (ABS) are newly developed, factory-manufactured stoves based on modern research and technology and product development standards, including higher efficiency, lower emissions, better safety and longer durability.

Currently, there are two main types of ABS available, a two-stage combustion gasifier and an improved single-stage "rocket" combustion furnace(Venkataraman et al., 2010).

Natural draft: Almost all previous household stoves (traditional and improved) use free convection operation. Due to the low cost and ease of manufacture, freestanding convection heaters are now even inevitable (MacCarty et al., 2008).

Forced draft cook stoves: A stove equipped with a fan produces a high-speed air jet that mixes fuel, air, and flame. Stoves with a fan can not only reduce emissions by improving combustion, but also improve heat transfer to the cooking vessel. Compared with natural ventilation stoves, forced ventilation stoves consume an average of 37% less fuel, 80% less carbon dioxide emissions, and negligible PM emissions(Jetter et al., 2009; Still et al., 2011).

Direct combustion type: Direct fire stove combustion is the process by which fuel is burned with air to release the chemical energy stored in it. Most stoves are direct-burning stoves, where solid fuels are burned directly (Soini et al., 2014).

Gasifier type cook stoves: In the gasifier, combustion occurs in two stages. In the first stage, the fuel is burned to release gas. In the second stage at the top of the furnace, the air mixes and burns these gases.(Fontaine et al., 1993).

Mono-function cook stoves: Single-function stoves have a single purpose, such as cooking, heating water or space, smoking fish or meat, baking, stewing milk, roasting grains or flour, etc. Most stoves are single-function(Xiangjum et al., 1993).

Multi-function cook stoves: In addition to cooking, multi-functional or multi-purpose stoves can also be used for other purposes, such as heating water, heating space, boiling milk, smoking fish or meat, grilling, and generating light or bio-char (Champier et al., 2011).

Domestic cook stoves: Household kitchen stoves can meet the cooking needs of a family (about five or six people).

Institutional type cook stoves: Institutional or community stoves are suitable for large-scale cooking in restaurants, hotels, schools, religious places, etc. Today, most community stoves are low-efficiency three-stone stoves.

Chimney stoves: The chimney is used to remove smoke from the furnace combustion chamber and away from the user. Attaching this vertical structure to the furnace generally ensures that the air passing through the furnace flows quickly, thus promoting better combustion (Shastri et al., 2002).

Fixed cook stoves: Improved metal and ceramic stoves suitable for indoor or outdoor movement are inherently portable. In hot developing countries, cook on the terrace in summer to reduce the extra heat from the stove; in winter, in the house, heat the space.

Portable cook stoves: Most clay stoves, multi-function stoves and fireplace stoves are usually heavy to move and stationary (Gujral et al., 1992).

Table 2.6: The Classification of Cook Stove.

Parameter	**Classification**	
	Traditional cook stoves, Improved cook stoves	
Technology and evolution	Advanced cook stoves	
Fuel type	Wood, Charcoal, Agro-residue, Dung cake	
Fuel feeding	Batch feeding, Continuous feeding	
Design typed	Draft	Natural, forced
	Combustion	Direct combustion, gasifier-based
	Chimney	With chimney, without chimney
	Material	Metallic, non-metallic, hybrid
	Number of pots	Single pot, double pot
Customer’s choice	Demography	Domestic size, community size
	Function	Single function, multiple function
	Portability	Fixed, portable

2.4.2. Improved cook stoves (ICS)

If a stove is more efficient, has lower emissions, or is safer than a traditional stove or three-stone stove, it is often referred to as an "improved" stove. Improved stoves are stoves that use biomass (charcoal, wood, paper, or plant matter) to maximize thermal and fuel efficiency, operate safely, and minimize emissions that are harmful to human health. The term generally refers to stoves that burn wood, charcoal, agricultural residues, or manure. The design of the "improved stove" adopts certain scientific principles to help better combustion and heat transfer, improve emissions and efficiency performance; you can also use modern building materials to achieve this goal.

The goal of ICS design is to improve the shortcomings of traditional stoves while ensuring lower costs and ease of use. Basic performance indicators used to evaluate stoves include boiling time (TTB), fuel use, thermal efficiency, and emissions in the form of CO and PM. The goal of the stove is to improve the shortcomings of the three-stone stove and the traditional built-in stove, while maintaining user affordability. There exists a number of ICSs able to reduce emissions by 40–75% (Grabow et al., 2013), increase fuel efficiency by almost 30% and reduce global warming potential up to 40–60 % (Baldinger et al., 2010). The most famous categories of ICS are “Rocket” stoves and gasifier stoves.

One of the main motivations to improve the promotion of stoves is to reduce fuel use, which affects the rate of deforestation. Energy efficiency describes the relationship between the heat transferred to the pot and the total energy produced by the oven in a defined task. Higher efficiency can be obtained in the following ways (MacCarty et al., 2010) :

- By providing an insulated combustion chamber around and under the fire, the fuel can burn better, so that the gas, flame and air can be better mixed.
- Maximize the transfer of combustion heat from the flame and hot air to the cooking pot.
- Minimal heat loss to the environment.

The Clean Stove Alliance report shows that in 2014, the partners of the Global Clean Stove Alliance distributed 3 million stoves, including liquefied petroleum gas stoves and biogas stoves. Nearly one-third of them are in Africa, more than 60% are in Asia, and 6% are in Latin America. Two-thirds of the stoves distributed are portable. In 2014, 20 million stoves were reported, of which 12 million were classified as clean and/or efficient (Global Allinace, 2013). Emissions from traditional cooking utensils are a major health issue. Emissions lower than that of a reference stove or open flame is an additional feature of improved stoves. Emissions are by-products emitted into the air when the fuel is burned incompletely. They can be very harmful to human health and the environment. If smoke can escape from the fuel inlet or otherwise leak into

the room, the level of harmful emissions will increase (MacCarty et al., 2010).
Safety is another aspect of improving stoves. This means that there is no open flame coming out of the stove, the stove is not easy to tip over, and the part of the stove that needs to be touched during the cooking process will not be too hot and cause burns (Gallagher et al., 2016).

Table 2.7: Selected Cook Stove Technologies

Improved Cook Stoves	Country/Institute	Special Feature	Reference
Lakech	Ethiopia	• Smaller both in height and in volume • reduced emissions of CO, CO_2, and PM by 15, 8, and 13%	(Mamuye et al., 2018)
Ugastoves	Uganda	• Fuel efficiency of up to36% • The stoves have an estimated working life of 3–10 years • Has a metal "pot skirt"	(Adkins et al., 2010)
Envirofit	Colorado State University	• 80% less smoke • 40% reduction in cooking cycle time • 60% less biomass fuel compared with TSF	(Envirofit, 2013)
Centrafricain	Chad and Cameroon	• burns raw wood • The stove reduce fuel expenditure by 25%	(Vitali et al., 2011)
BCSIR 1	Bangladesh	• burning fuel wood, branches, cow-dung cake, briquettes • reduce fuel use by 50%	(Vitali et al., 2011)

Improved Charcoal Stoves

In Ethiopia, families that switched from the traditional three-stone open flame to the improved model saved 20 to 56% of their firewood (Duguma et al., 2014)**.**The total charcoal production of the African continent in 2015 was 31.8 million tons showed in Table 2.8. Nigeria and Ethiopia are the biggest producers of charcoal in Africa, producing 4.4 million and 4.3 million tons, respectively in 2016. Other top-ten charcoal producers in Africa include the DRC, Ghana, Tanzania, Madagascar, Egypt and Somalia, producing between 2.4 and 1.2 million tons each.

Smith et al., (1994) suggested that the widespread deployment of stove technology to improve fuel and energy efficiency can help reduce adverse effects on human health, energy, and the environment Smith et al., (1994). Most charcoal stoves are lightweight and easy to transport, usually with one fire for each pot. They are added in batches, which means that all the required fuel is filled into a container and ignited at the beginning of the cooking process. The heat from charcoal is transferred mainly through radiation. This requires the cooking pot to be close to the surface of the fuel, which makes the combustion chamber quite shallow.

Table 2.8: Regional Wood Charcoal Production, Import, Export And Consumption (Tons), Source (Abdi et al., 2016)

Region	**Production**	**Import**	**Export**	**Consumption**
East Africa	13,724,533	2,087.03	52,612.1	13,674,007.93
Middle Africa	3,939,346	153	537	3,938,962
Northern Africa	3,169,414	2,323	80,567	3,091,170
Southern Africa	448,494	89,133	127,290	410,337
Western Africa	10,471,547	2,797.25	192,445	10,281,899.25
Total Africa	31,753,334	96,493.29	453,451.1	31,396,376.19
World	50,873,234	2,513,752.26	2,387,889.1	50,999,097.19

Smith et al., (1994)suggested that the widespread deployment of stove technology to improve fuel and energy efficiency can help reduce adverse effects on human health, energy, and the environment Smith et al., (1994). Most charcoal stoves are lightweight and easy to transport, usually with one fire for each pot. They are added in batches, which means that all the required fuel is filled into a container and ignited at the beginning of the cooking process. The heat from

charcoal is transferred mainly through radiation. This requires the cooking pot to be close to the surface of the fuel, which makes the combustion chamber quite shallow.

Most traditional charcoal stoves are made from scrap metal, which cannot regulate the burning rate of the fuel, and there is usually no ceramic, so the pot is placed directly on the charcoal. This can lead to potentially deadly high carbon monoxide emissions and waste a lot of fuel, because carbon monoxide is an unburned fuel with a high energy value. Due to these design features, and based on proper use and maintenance, compared to traditional charcoal stoves, this stove can save 30-50 % charcoal and reduce toxic emissions.

2.4.3. Utilization of improved cook stoves

In the early 1970s due to the oil crisis, fuel wood energy security and deforestation became a big concern for the world. Institutions such as the World Bank and the UN Food and Agriculture Organization claimed that food and fuel needs of the rapidly growing populations had resulted in deforestation (Manibog et al., 1984; Marcoux et al., 2000). Cook stove program has been promoted in developing countries as a way to significantly improve rural well-being. The Cook Stove project has grown into a global company. Various non-governmental organizations and international development projects have sprung up in Asia, Africa, and South America. The scheme started by the Chinese government in 1982 and ended in 1992 has resurfaced and so far more than 200,000 stoves have been successfully distributed (Bank, 2011)**.**

Improved cook stoves worldwide

Many cooks stove programs have been implemented in many countries in the world. The goal of these plans is to reduce fuel use by reducing environmental emissions, thereby reducing deforestation and improving the health of users. Other goals include improving the social lives of people in developing countries and reducing global climate change. According to reports, the success of the improved cook stove program has been mixed. Although some plans have achieved their desired goals, many of them have failed.

One of the oldest cook stove projects in Africa is the ‘Tso Tso’ kiln project in Zimbabwe, which was established in the early 1980s. "Tso Tso" means "branch" in Shona. The fire grate is made of mild steel and has a removable bottom grill made of wire showed on Figure 2.1(a) (Engineering., 2012). In Asia the biggest project is China’s Stove Improvement Program, which successfully distributed 129 million stoves from 1982 to 1992 (Gifford et al., 2010). India's national plan is probably the second largest ICS plan after China's. The India Biomass Stove Program was initiated by the government of India in 2009 to expand the use of clean energy to all the estimated 160 million households that use inefficient biomass for cooking (Kumar et al., 2021). The first Indian improved cook stove is chulla which is showed on Figure 2.1(b).

In Central American, a country has a history of cook stove programs is Haiti.improved stoves initiatives in that country started in1983, when a collaborative project with the Centre de Recherchéen Development International (CRDI), Haitian Government, and World Bank developed the "Recho Mirak" improved charcoal stove. And from 2007 to 2009 World Bank project produced and sold at a subsidized price over 30,000 "Mirak" stoves which is showed on Figure 2.1(c) (UNEP, 2010).

Figure 2.1: Cook stoves developed by different programs (a) Mirak stove (lask et al., 2015) (b) chulla stove (ullikashi et al., 2015) (c) Mirak stove (kuhnhenn et al., 2003).

Urmee et al., (2014) discussed that envirofit international rocket stove series of this environment is made of metal with ceramic or metal chambers. The design of the furnace is based on advanced computational fluid dynamics (CFD) and heat transfer models. They are designed to burn biomass (wood) and other biomass-derived materials such as charcoal. Colorado State University's Engines and Energy Conversion Lab (EECL) provides Envirofit with state-of-the-art research and development, engineering and rigorous emissions and durability testing (Jackson et al., 2013). Envirofit has the world's most fuel-efficient stove, producing smoke and harmful gas emissions reduced by 80%, biomass fuel (wood, crop residues, etc.) consumption reduced by 60%, cooking cycle time reduced by up to 40%, compared with traditional three stone fire (TSF) (Simons et al., 2017).

The ONIL Stove, which was developed for the program, is a fixed ICS. It was developed by DonO'Neal from Texas, USA, a Project Manager for HELPS International, for Central American households. The top of the stove measures about 400mm across and 900mm long, which provides adequate space for two pots. The stove is normally mounted on concrete blocks, to raise it to a convenient and safe height for cooking(Baden-Powell et al., 2006; Schultz et al., 2017).

Improved cook stoves in Africa

In Africa, the most widespread example of an improved charcoal stove is the Kenyan Ceramic Jiko (KCJ) showed on Figure 2.2a. This stove type has a ceramic liner in a metal cladding. The ceramic liner protects the outer metal structure from deterioration by the fire. It also provides improved insulation, leading to a hotter flame and thus to a better efficiency. It has pot-rests creating a small gap between the charcoal and the pot, to allow some of the produced carbon-monoxide to burn off. In Kenya, improved charcoal stoves are found in about 47% of all households, in Nairobi and Mombasa penetration rate is around 80% (2004 estimate). As charcoal is usually purchased, users see the monetary benefit of saving fuel, which has made this stove model an economic success (Kammen et al., 1995).

Uga stoves are manufactured in a factory in Uganda. There are two major types; improved charcoal stove and a rocket wood stove for house hold use. They have a ceramic liner encased in a sheet of metal showed on Figure 2.2b. Uga stoves have different sizes and shapes. The rocket-type wood-burning stove has a metal "pot skirt" permanently fixed to the outer edge of the top of the stove. Fuel efficiency of up to 36% has been reported for charcoal stoves and 58% for the wood rocket types (Adkins et al., 2010; Urmee et al., 2014).

The Centrafricain is a portable improved stove that can be found in Africa, in Chad and Cameroon. The stove is made of metal and has a ceramic chamber as showed. The combination of metal and clay allows a longer operational life span in comparison with other simple ceramic models. The clay ring increases the stability, resistance, and efficiency of the stove. Moreover, the Centrafricain stove was designed to accommodate the local round bottom pots, making it possible to cook according to local traditional practices. The addition of two handles ensures the portability of the stove(project, 2013; Urmee et al., 2014).

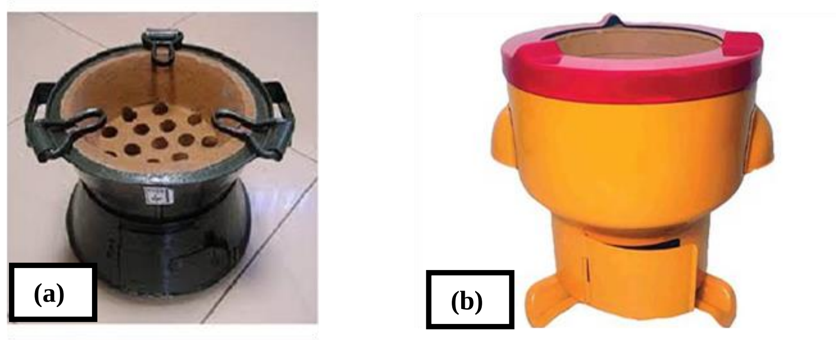


Figure 2. 2: Improved Cook Stove in Africa (a) Jiko (b) Ugastoves

Jackson et al.,(2013) discussed that, made comparison between four ICSs (Upesi, Envirofit, Save80 and Mwoto as showed on Figure 2.3 with traditional 3-Stone fire cooking stove for CO and PM Emissions , the CO emissions for the 3-Stone fire, Upesi, Envirofit, Save80 and Mwoto stoves were 66, 48, 33, 32 and 29 g , respectively, whereas the PM emissions for the 3 Stone fire, Upesi, Envirofit, Save80 and Mwoto stoves were 443 , 331, 220, 224 and 162 mg, respectively. The CO emissions reduction for Upesi, Envirofit, Save 80 and Mwoto were 28, 49, 51 and 56 %, respectively, whereas the PM emissions reduction for Upesi, Envirofit, Save 80 and Mwoto were 30, 49, 50 and 63 %, respectively. The differences in emissions between 3-Stone fire and all improved woodstoves were significant thus; improved wood stoves, if adopted, have a capacity to reduce CO emissions by 28 to 56 % and PM emissions by 30 to 63 % depending on the type of stove.

Figure 2.3: Improved cookstoves in Africa and traditional stove comparison (a) 3-Stone fire (b) Upesi (c) EnvirofitG3300 (d)Mwoto (e) Save 80 (Anderson, 2013; Foote et al., 2013; Simons et al., 2017)**.**

Improved Cook Stoves in Ethiopia

Many rural households in Ethiopia use traditional three-stone stove which has low energy efficiency and incurs indoor air pollution. Despite the fact that improved cook stoves design variability was seen between producers appears, they have received little or no promotion work to improvements over open fire stoves. Charcoal fuel is one of the biomass fuels widely used in urban and semi-urban areas of Ethiopia. At this time there are two improved charcoal stoves and other traditional metal stoves. The improved stoves are called Merchaye and Lakech as showed on Figure 2.4. Merchaye charcoal stove reduced emissions of carbon monoxide (CO), carbon dioxide (CO_2), and particulate matter by 28, 22 and 27 %, respectively in comparison to traditional stoves. Lakech charcoal stove reduced emissions of CO, CO_2, and PM by 15, 8, and 13 % (Mamuye et al., 2018).The study showed that Lakech Ethiopian stove has low performance.

Whereas, the Lakech stove reduced emission of CO, CO_2 and PM by 15, 8 and 13%, respectively. In non-sustainable fuel wood harvest circumstances, the annual emission reduction potential for individual Merchaye stoves was 0.33 to CO_2 and Lakech stoves 0.14 to CO_2/yr. The SFC of Merchaye and Lakech were reduced by 222 and 164 g/d, respectively. The two ICS also reduced the time required for cooking. Regarding the status of adoption of ICS, 43.7% the sample households were adopters of Merchaye stoves and 31.3% Lakech, stoves (Mamuye et al., 2018).

2.5. Heat Transfer Modes in Biomass Cookstoves

The modes of heat transfer that play a role in stove performance. All convection, conduction and radiation are involved in the biomass cooking activity. The first law of thermodynamics provides a tool that allows a thorough energy balance to be performed on the cookstove.

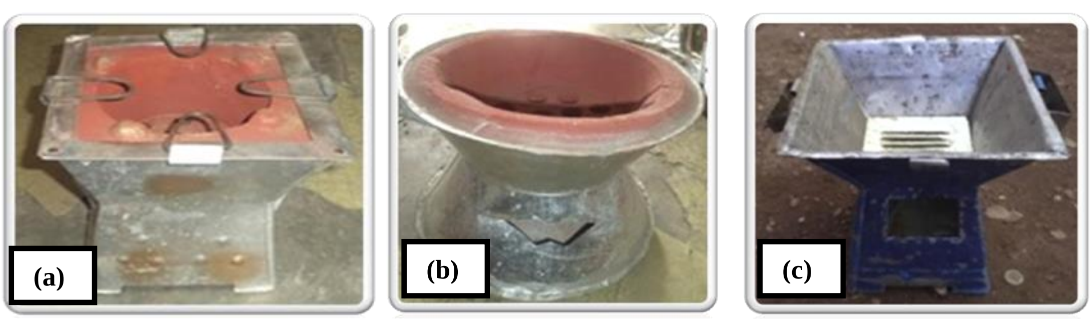


Figure 2.4: Improved cookstoves in Ethiopia (a) Mirchaye, (b) Lakech and (c) traditional stove (Mamuye et al., 2018)

Deriving an accurate energy balance is vital in determining the most effective way to improve heat transfer efficiency. A cook stove represents an open system since it is characterized by fluid flowing across the boundary of a fixed volume, referred to as a control volume. The control volume in this case is bounded by the walls of the combustion chamber with the mouth of the stove acting as the inlet and the annulus formed by the pot and stove interface acting as the outlet. A control volume establishes a finite system boundary to analyses the balance of energy transferred between heat, work, and mass flow.

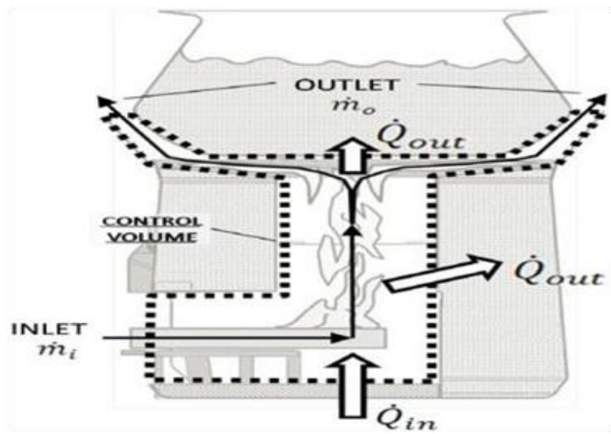


Figure 2.5: Heat flow in and out from Cook stoves (Ravi et al., 2002)

2.5.1. Conduction

Conductive heat transfer occurs through the body of the stove to the surroundings and through the thickness of the pot. There is zero energy gains associated with conduction heat transfer to the pot. The rate of steady state conduction heat transfer is defined by equation,

$$Q_{conduction} = \frac{k \text{ x} A \text{ x } \Delta T}{L} \quad (2.3)$$

Where k = thermal conductivity, A = cross sectional area of object, ΔT = temperature difference, L = object thickness. Conduction resistance through the metal pot is neglected due to high thermal conductivities and small wall thickness.

2.5.2. Convection

Hot combustion gases interact with two separate surfaces:

- ✓ The inner surface of the stove(losses) and

- ✓ The outer surface of the pot (gains).

The magnitude of convective heat transfer is influenced by the velocity of the gases flowing through the stove, the exposed surface are a contacting the gases, and the temperature difference between the gases and the exposed surface. The rate of steady state convection heat transfer is defined by equation 2.4, where h = convection coefficient (W/m^2K), A = exposed surface area, ΔT = temperature difference.

$$Q_{convection} = h x A x \Delta T \quad (2.4)$$

In general, there are three ways to improve convective heat transfer:

- ✓ The flue gases scraping the heated surface should be as hot as possible.
- ✓ The heat exchanger's surface area should be as large as possible.
- ✓ The velocity of the hot flue gases should be increased to the greatest extent possible. A faster flow over the pot's exterior disturbs the stagnant boundary layer of air that slows the flow.

2.5.3. Radiation

Radiant energy from the biomass bed or flames is transferred to the stove body, pot, or surrounding environment. The magnitude of radiation emitted as a loss or gain depends heavily on the temperature difference between the two objects, the area of the emitting surfaces, the emissivity of both surfaces, and the associated view factor. The rate of blackbody radiation heat transfer between two surfaces is described by equation 2.5, where T_2 and T_1 are the respective temperatures of each surface.

$$Q_{Radiation} = A x \sigma x (T_2 - T_1) \quad (2.5)$$

2.6. Performance Testing of Biomass Cook Stoves

Evaluating the performance of a cook stove is an integral part of the process of developing improved designs. Methodology of evaluation of cook stove has always been a very argumentative matter due to a large number of factors affecting the behavior of a cook stove. The performance of a biomass cook stove can be characterized in two categories, thermal performance and emission performance. Thermal performance is measured in terms of fire power or input power of the cook stove, specific fuel consumption, and efficiency and turndown ratio, while emission performance is measured mainly in terms of emission ratios or emission factors of pollutants. Performance of biomass stoves shows a strong dependence on operation parameters like characteristics of the fuel used, sizes and types of pots used, the type of cooking process, the ambient conditions, the ventilation levels, etc.

2.6.1. Thermal Performance Parameters

Some of the commonly used thermal performance parameters are

Power: The term fire power is to indicate the average rate of energy release during the entire burn period (Baldwin et al., 1987). Bussman et al., 1988 experimentally found that for open fires, the design power was about 70% of the maximum power. Mentioned that a cook stove should be operated near design power for safe and durable operation.

Turn-down ratio: Bussman et al., (1988), introduced Turndown ratio which is defined as the ratio between maximum and minimum power of the cookstove.

Thermal efficiency: The thermal efficiency, a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot (Cookstoves, 2014).

Specific fuel consumption: Measures the amount of fuel required to boil (or simmer) 1 litter of water (Baldwin et al., 1987).

2.6.2. Parameters Characterizing Emission Performance

Smith et al., (2013) showed that biomass combustion in cook stoves generally results in emission of several pollutants, which include carbon monoxide (CO), methane (CH_4), non-methane hydrocarbons (NMHCs), nitrous oxide(N_2O), oxides of nitrogen (NO_x), particulate matter (PM), black or elemental carbon(EC), organic carbon(OC)and organic matter (OM).

2.6.3. Cooking Stove Testing Protocols

Sutar et al., (2015) review work on cooking stoves testing protocol discussed all currently used and modified old version testing protocols in depth. Testing of cook stoves in the laboratory has primarily involved water boiling tests (WBT). Most of the time used cooking protocols are VITA protocol (1985), Indian standard on solid biomass Chulha-specification (IS 13152 (Part1):1991). The water boiling test (WBT) (2003–2007):

VITA protocol (1985): For the first time, VITA standards suggested three stages of testing for each cookstove: water boiling test (WBT), controlled cooking test (CCT), and kitchen performance test (KPT) (Bailis et al., 2007).

- The water boiling test (WBT): It is used to take into account different cook stoves by simulating common cooking procedures. It calculates the amount of fuel required for a specific set of tasks that involve the boiling process. This protocol proposed testing at both high and low power levels. During the high power phase, a standard amount of water is rapidly heated from room temperature to boiling. During the low power phase, the water is kept at a temperature of 5^0C below boiling point for 30 minutes at the lowest possible power.
- The controlled cooking test (CCT): Estimates the amount of fuel consumed by a particular cook stove while evaluating a particular cooking task. The procedure for carrying out this test is determined by the food to be cooked, the design of the cook stove, and the operation of the cook stove. CCT is carried out in laboratories or in field demonstration centers by operators who have been trained in food preparation. This test can be used to test different cooking techniques on the same cook stove or to start comparing the performance of a new cook stove.
- The kitchen performance test (KPT): is used to investigate the performance of a new cook stove in a real-world household, as well as the impact of its use on overall energy consumption. This entails measuring the amount of fuel consumed by a new cook stove during a full cooking cycle in the field.

Indian Standard on Solid Biomass Chula-Specification (IS13152(Part1):1991)

A preliminary test is used to determine a cook stove's maximum burning capacity. Based on this, a specific amount of oven dried fuel is selected to last the duration of the one-hour test. This quantity of fuel is divided into four equal parts and fed at 15-minute intervals. A fixed amount of water is heated in a pot of a specific size with a lid until it reaches 50 degrees Celsius below the boiling point.

The Water Boiling Test (WBT) (2003–2007)

It is a reworked version of the VITA protocol (1985). During 2003–2007, the University of California-Berkeley and Aprovecho Research Center revised it (Sutar et al., 2015).

- WBT 3.0.: The protocol involves operating the cook stove in three stages namely, high power cold start, high power hot start and low power simmering. During first two stages, the fuel consumed to boil a certain amount of water is determined whereas during last stage, the temperature of water is maintained at least 3^0C (and at most 6^0C) below boiling point. The simmering time was also specified as 45 minutes, as opposed to the 30 minutes specified in VITA (Leary et al., 2012).
- ETHOS WBT protocol (2009). Engineers in Technical and Humanitarian Opportunities of Service (ETHOS), in collaboration with the Partnership for Clean Indoor Air (PCIA), revised the WBT 3.0 protocol to create the WBT4.1.2 protocol (Sutar et al., 2017). It also provides instructions for emissions measurement and procedure for testing cook stoves using non-woody solid, liquid or gaseous fuels. Recently, a new version of this protocol designated as WBT 4.2.2(Cookstoves, 2013).
- EPTP protocol (2009): This protocol emphasizes simultaneous measurement of the thermal performance with carbon monoxide and particulate emissions. Similar to WBT3.0, EPTP consists of three phases of operation. The distinguishing features of EPTP are use of a floating layer of foam insulation on the surface of the water in the test pot to reduce vaporization; heating of water only up to 90 ^{0}C during the test; during simmering phase, maintaining water temperature close to 90 ^{0}C; and procedure for testing gasifier, charcoal and coal cook stoves without the high power hot-start phase (DeFoort et al., 2014)

2.6.4. Comparison of Protocols for Thermal Performance

Several testing protocols are recommended in different literature. When one sets out to test a given stove using these different protocols, one gets different values of efficiency and emissions, thus giving rise to a dilemma on which result is more appropriate. Some selecting parameters are discussed below by (Sutar et al., 2015):

Definition of Thermal Efficiency

Thermal efficiency may generally be defined as:

$$\eta = \frac{\text{energy absorbedbypotandwater}}{\text{energy releasedbycombustionoffuel}} \quad (2.6)$$

The two terms in this definition are calculated differently in different protocols, leading to differences in the values of thermal efficiency. Except for BIS (Bureau of Indian Standards), the denominator of thermal efficiency is assumed to be the product of the Lower Heating Value (LHV) of wood and the mass of “equivalentdrywood” used during the test. All of these protocols account for the remaining charcoal at the end of the test by subtracting the mass of charcoal multiplied by its calorific value from the denominator. The definition of equivalent dry wood is different in VITA, WBT3.0, WBT 4.1.2and EPTP protocols. In VITA protocol, mass of equivalent dry wood is defined as the received mass of wood minus its actual moisture content. In the WBT3.0, WBT4.1.2 and EPTP protocols, the energy required to vaporize the fuel moisture is also subtracted from the denominator.

Maximum Temperature of Water

The highest temperature to which the water is heated is one of the main differences between protocols. When this temperature is close to the boiling point, heat transfer coefficients increase by order of magnitude when nucleate boiling is absent. In the high power phase, a protocol such as WBT3.0 or 4.1.2 that requires water to be heated to boiling point is expected to yield a higher thermal efficiency value than a protocol such as BIS that requires water to be heated to a significantly lower temperature than boiling point. Sutar et al., (2015) conclued that after testing using different protocols, the maximum temperature of the water in the test, both during the high power phase and while simmering, can have a significant impact on the test results. L’Orange et al., (2012) reported that an uncertainty of 1^0C in measuring the boiling temperature of water can cause very high uncertainty in the measurement of total test duration. Still et al., (2015) pointed out that simmering at temperature which is only 0.5^0C below boiling point led to 56% more steam than simmering at 4.5^0C below boiling point. These observations clearly support the above explanation.

Uncertainty in Stove Testing

Uncertainty in stove testing is affected by two factors: measurement uncertainty caused by the instrument and measurement uncertainty caused by repeatability issues. Sutar et al., (2015) Conclude that the test-to-test variation in the duration of the test in WBT contributed to 99 percent of the uncertainty in stove power, while the test-to-test variation in evaporation losses contributed to 91 percent of the uncertainty in thermal efficiency. L'orange et al., (2012) showed that WBT 3.0 and EPTP protocols were used to conduct water boiling tests, and it was concluded that the EPTP protocol reduces uncertainty in results when testing cook stoves. Since uncertainties due to boiling are almost completely avoided in EPTP.

- **Use of lid on the pot**

Another important difference between the protocols is the use or not use of the lid, which is expected to have a multilayered impact on the test results. In some stoves, especially heavier ones, the duration of the test has a great influence on the test results. Gupta et al., (1982) conducted laboratory experiments on conventional as well as improved two pot cook stoves using clay or aluminum pots and with or without lids. For both cookstove pot combinations, use of lid ensured higher cook stove efficiencies.

In the BIS protocol, use of a lid with the pot is mandatory, while VITA, WBT3.0 and WBT4.1.2 specifically prohibit the use of the lid to avoid the error caused by the condensation of the water vapor on the interior of the lid. In EPTP, foam insulation is made to float on the water surface to work as a lid without the problem of condensation. However, no foam is used during the simmering phase, the reasons for which are not specified in the EPTP protocol.

2.6.5. Testing Methods for Emissions

The emission performance of biomass stoves is mainly measured by two methods, namely the hood method and the furnace method. In the case of the hood method, an exhaust hood of a suitable shape is constructed to fit the maximum possible range of the test to be performed on this range. The cover is connected to the exhaust port through a duct. In case of chamber method, a typical village kitchen room or any chamber constructed as per the experimental requirements can be used for testing of the cook stoves. Designing a test protocol is a very difficult task, with two conflicting requirements; On the one hand, the protocol must be able to pass tests at the laboratory level to make a fair estimate of the performance of a given stove under field conditions; on the other hand, on the one hand, it must also have the potential of high repeatability to be statistically acceptable and to be able to compare the results of the laboratory and different stoves.

2.7. Insulation Materials for Cooking Stove

An insulator is a material or combination of materials that is used to prevent the flow of thermal energy. The effective installation of thermal insulation materials can significantly reduce heat loss at the surface of the heat storage system. The energy lost by the insulating material largely depends on the thermal properties and thickness of the insulating material. Choosing the appropriate type and form of insulating material depends on the application location of the insulating material, as well as the physical and thermal properties of the material required (Al-Homoud et al., 2005). The basic requirement of insulation is to provide a path with significant resistance to heat flow through the insulation material. For this reason, the insulating material must reduce the conduction heat transfer rate. In the experimental determination of solid thermal conductivity, several different measurement methods are required for various temperature ranges and various materials with different ranges of thermal conductivity values (Bayram et al., 2012).

Clays are basic raw materials for the ceramic industry used in the manufacture of tiles, fireclay refractories and white wares. Typically, the fabrication process involves a forming step where the raw material mixture is worked into the required shape, for example by pressing, and then a firing step to obtain a dense robust object. During firing both structural and micro structural changes take place in the clay material. The original clay is a hydrated aluminium silicate with a layered crystal structure in the form of fine grains. This transforms into an amorphous phase or a mixture of amorphous phase and crystallised phases (mullite and cristobalite) depending on the thermal treatment. Refractories are the fundamental materials for any high temperature operation. Refractory linings are brick materials that can withstand heat above $530\ ℃$ and are alumino-silicates that contained $Al_2O_3.SiO_2.H_2O$ and are often used for reactors, ladles, ovens and furnace as thermal storage facilities in order to prevent escape of heat or heat losses to the surrounding environment.They are physically and chemically stable at high temperatures. Generally, the oxides of aluminum (alumina), silicon (silica) and magnesium (magnesia) are the most important materials used in the production of refractories. Refractory clays consist mainly of oxides of silicon and aluminum hence can be used as raw material for the production of aluminosilicate refractories.

In general, refractory products are classified into two types: brick of fired shapes, and specialties or monolithic refractories. They are made of natural and man-made materials, usually nonmetallic, or combinations of other compounds and minerals such as alumina, fireclays, bauxite, chromite, dolomite, magnesite, silicon carbide, zirconia and a host of others.

Table 2.8: Range Of Chemical Constituent for Fire Clay and Refractory Brick, (Yami et al., 2007)

Chemical Constituent	Fire Clay Brick (%)	Refractory Brick (%)
SiO_2	55-75	51-70
Al_2O_3	25-45	25-40
Fe_2O_3	0.5-2	0.5-2.4
MgO	<2.0	-
K_2O	<2.0	-
Li_2O	12-15	-

2.8 Literature Gap and Summary

In the literatures, characteristic of biomass, biomass energy, biomass cooking stove, modes of heat transfer in cooking stove operation and performance testing of cooking have been discussed. In most of the literatures associated with the biomass cooking are health risks due to incomplete burning of biomass with annual death of about 2.6 million people. Many programs were implemented to develop low emission, high thermal efficient improved cooking stoves throughout the world. It is well known that biomass energy covers the largest world energy demand and the energy lost was high when combusting biomasses. This was due to in appropriate design of the combusting chamber and fuel property. Many studies were done to develop refractory materials to prevent heat loss from the chamber.

- In almost all published papers the fuel energy content has not been reported well, this lead the data collected becomes wrong which was done by different researches using different fuel property have different result while they study the same performances.
- The inlet air temperature to the combustion chamber has been elucidated always at room temperature. In this study pre-heating the inlet air were used, there is no any research paper which study the effect and uses the preheated combustion air, the preheated air can maintained the temperature of the combustion chamber.
- Radiation is the main heat transfer mechanism in cooking stoves operation, so the depth of the chamber and the total surface area where the pot gets heat also studied in this research.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1. Stove Liner Clay Materials

The insulating liner to be used for the stove is made of raw clay, water and silica waste. The raw clay (RC) used as liner for the stove has been collected from Kechene (Addis Ababa,womens manufacturing pottery and local stoves) directly delivered from them (before crushing) and silica waste collected from Awash **Melkasa Aluminum Sulphat Factory(AMWS). To prepare the insulating liner both the collected sample have been crushed by ball mill (FRITSCH ball mill).** Then the crushed raw clay was sieved to sieve size of 500 µm by standard laboratory test sieve (Endecotts Ltd.), and the silica waste from AMWS was sieved to size less than 250 µm at ASTU, Chemical Engineering Laboratory.

For compositional analysis for RC, AMWS and existing stove insulating clay (ESC) has been performed at National Cement S.C. laboratory, Dire Dawa and the result is shown in Table 3.1. Water assists to proper homogenization and keeps fluidity. In this thesis work four parameters were considered. These were35% water or moisture for mixing (Mahdi et al., 2018), particle size of 500 µm, firing temperature at 1000℃ and firing time for one hour to develop high performance refractory brick for the charcoal cooking stove.

Table 3.1: Compositional Analysis for Raw Clay, Silica waste from AMWS and Existing Stove Insulating Clay (ESC)

	SiO_2 %	**Al_2O_3%**	**Fe_2O_3%**	**CaO%**	**MgO%**	**SO_3%**	**LOI%**	**Sum**
Raw clay	47.30	7.45	10.12	2.50	1.80	0.19	15.72	85.08
Silica waste	71.92	7.30	5.36	3.36	2.40	0.70	2.35	93.39
ESC	26.59	5.53	0.12	0.5	1.2	16.83	40.78	91.55

3.2. Experimental Approach in the Preparation of Insulator Liner Clay

The intimate mixing of the raw materials is extremely important to the uniform completion of the solid-state reactions which take place during firing. Optimum parameters are selected by changing one parameter at a time and maintained the other three parameters constant. The parameters used are shown in Table 3.2. After selecting the optimum RC, *Silica waste from* AMWS was added with ratio of (RC: *Silica waste from* AMWS) 90/10, 80/20, 70/30, 60/40, 50/50 to increase the refractoriness. By applying uniform pressing pressure of 5 MPa to all the sample moulded rectangular shape.

Table 3.2: Materials and Equipment's Used for the Experimental Work

Raw **Materials**	**Main significance**
Raw Clay	✓ To improve the plasticity or cohesion during formation
Silica waste	✓ To increase the refractoriness
Water	✓ For wet milling and facilitate clay plasticity during forming
Equipment's For Clay Preparation	
Micro sieve	✓ To get uniform particle sizes and granules
Electronic balance	✓ For weighing the samples
Ball mill	✓ To reduce the particle size
Oven	✓ To remove the moisture content from the sample
Hydraulic pressing machine	✓ To form the rectangular piece /wall tiles
Electric Furnace	✓ To give the sample stable crystalline phase through thermal treatment of samples/wall tiles

3.2.1. Preparation of Fire Clay Bricks

Test samples preparation

Clay sample collected was dried in oven and the impurities were all removed. The clay was crushed in the ball-mill. The standard sieve mash size was used to sieve the clay. The specimen powder was compacted in a mould into rectangular prism using the hydraulic press machine shown on Fig 3.2a and the pressed samples are showed on Figure 3.1. In preparation of clay sample a pressure of 5MPa is to be applied with a holding time of 60 seconds (Amkpa & Badarulzaman, 2017). The rectangular clay specimens were made by pressing using hydraulic press at a pressing pressure of 5MPa using lab press machine (HAN TECH Co.).

Figure 3.1: Pressed Sample of raw clay: Silica waste from AMWS (90:10, 80:20, 70:30, 60:40, 50:50)

Since the study was to partial incorporation Silica waste from AMWS with the raw clay matrix for the developing effective stove heat insulation, the mixture clay compositions was formulated with different weight percent of the raw clay obtained from Kechene and silica waste. The procedures used are as discussed as follows.

Firstly, the grinded raw clay was sieved by using 500 μm sieve size and 100 gram weighed by using electronic balance (G & GR, JJ600 Electronic scale) and water is weighed 35% by mass of the raw clay . Then the weighed compositions were charged into mixing plate and poured to a mould to form rectangular prism. A uniform moisture distribution of the samples was achieved when the desired quantity of water was added and stored away in polyethylene bags. This mode of storing (at least for 24 hours) allowed a uniform distribution of moisture and particle assisted the samples to gain excellent interlock bonding during pressing. After the pressing the clay were placed directly onto a tray dryer operated at temperature value of 105℃. This process allowed air to circulate on all sides of the tiles and instantaneously the samples dried to achieve standard moisture content (< 1%). Finally, a set of dried wall tiles were directly placed onto the refractory plate and fired at 1000℃, using an electric kiln as showed in Figure 3.2 b. All the sample prepared had the same particle size, firing temperature of 1000 ℃ using lab furnace with rising temperature of 2.5 ℃ /min and the firing time for 1 hour.

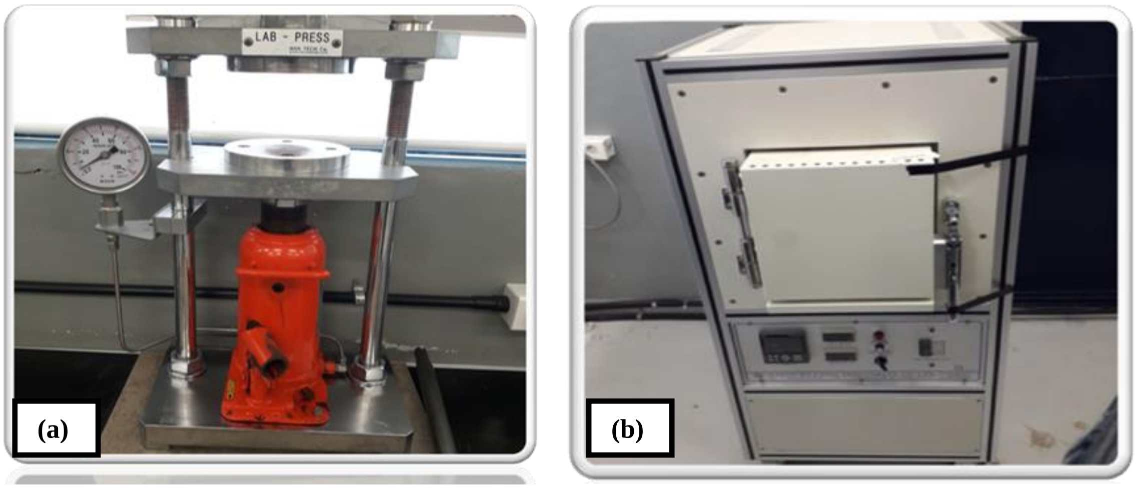


Figure 3.2: (a) Hydraulic Press Machine (b) Electric Kiln

Thermal conductivity

The thermal conductivity of the fireclay brick was determined using hot guided plate method using QTM-500 Kyoto electronics showed on Fig 3.3. It was then transferred to the thermal conductivity apparatus for thermal conductivity measurement at room temperature. In the hot guided plate apparatus, the clay sample was placed in between iron rods at the top and reference sample at the bottom. The instrument records the temperature with respect to time. The thermal conductivity test was conducted according to ASTM C202-86 (C202-93, 2013).

Figure 3.3: QTM-500 Kyoto Electronics

3.3. Experimental Setup for Testing Conventional Stove

The testing of cook stoves was performed in the chemical engineering laboratory at ASTU. Sampling was conducted using ‘Hood method’(Hurtado et al., 2020) and a schematic diagram of the setup is showed in Fig 3.5 (a).

Fuel size is the main factor on increasing of uncertainty. Different size of fuel usage for different cooking stoves may give unacceptable wrong result. For this study average equal fuel size is used and showed in Figure 3.4. The heating value and the constituent of the fuel was analyzed in national geological survey and showed in appendix.

Figure 3.4: Average Fuel Size used

For all three phases of the WBT protocol, measurements include:

- The mass of fuel used; the mass of charcoal consumed
- The mass of water in the pot at the beginning and end of the test phase
- Temperature of the water and
- Time

Boiling time refers to the time the stove takes for 2.5 L of water to reach the local boiling point. From the time when the charcoal was thought to be ignited until the water started to boil, the boiling time in the WBT was recorded. Pollutant emissions were measured with 2-minute intervals during each phase of the WBT protocol. Stoves were carefully operated during the tests. The experiment was carried out in three repetitions, and the consistency of the cook stoves operation was always maintained.

The cook stoves were tested in a controlled area. This area consists of a closed rectangular box, the top of which is covered with a right-angle prism. There is an opening at the top of the prism to connect to the exhaust line shown in the Fig 11 (b). The exhaust pipe has a diameter of 5 cm and a height of 1.3 m. There is a hole at a height of 1m to draw in the exhaust gases through the exhaust gas analyzerand1m long pipe bend to outside.

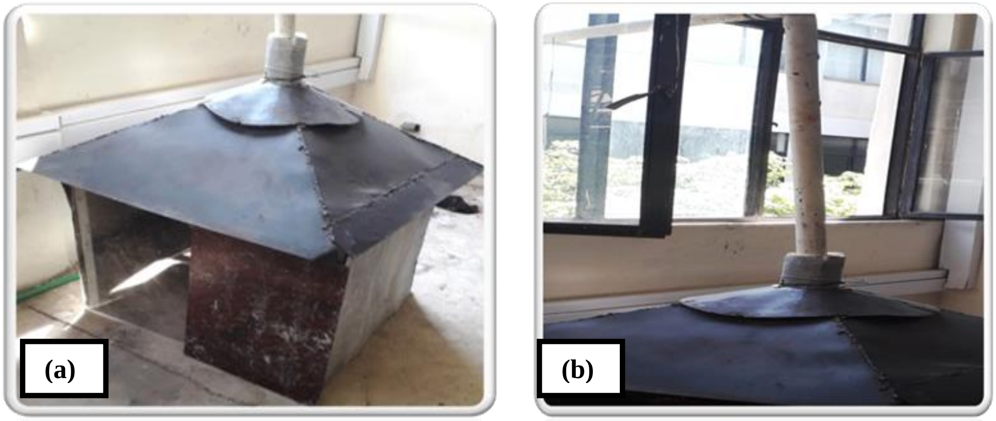


Figure 3.5: (a) Schematic Diagram of the Setup, (b) Exhaust Gases Drawing Pipe

Emissions measured from all six conventional cook stove using flue gas analyzer **(Exhaust Gas Analysing Unit CT159.02, Gunt HAMBURG Inc., Germany),** which can directly sample gas and measure the real-time concentration of CO and greenhouse gas CO_2. The analyzer is shown in Fig 3.6.The emission data was recorded within 3-minute intervals.

Figure 3.6: Flue Gas Analyzer

Laboratory stove testing was conducted by the same investigator to eliminate between-operator differences in test results. Before each test, 2.5 kg of water was collected, and its initial temperature was recorded. The coal is weighed before it is added to the combustion chamber. The mass of fuel loaded in each test is 450 grams (200 grams for cold start, 200 grams for hot start, and 50 grams for simmering).The ignition of the fuel is triggered by kerosene. A computer fan (12V) connected to a PVC pipe shown in Fig 3.7 inserted into the cook stoves door provides a constant air flow for all stoves.

Figure 3.7: Air Supply System

3.4. Experimental Performance of Stoves

Performance testing and fuel technology standard setting can help implementers, investors, donors, and consumers distinguish different levels of product performance, safety, and quality. Standards and testing can also help manufacturers determine ways to improve product performance to differentiate themselves in the marketplace and ultimately have a greater impact. Untested "improved" stoves have higher emissions and lower efficiencies than the traditional options they are replacing, and inappropriate promotion of the technology can reduce the expected impact.

The performance of the stove, especially the reduction of fuel and emissions can only be verified by testing. Standardized laboratory test protocols and metrics allow for reproducibility and comparability between tests and between stoves. Since stoves usually have different performances when they are used in consumers' homes, field tests conducted in consumers' homes can usually reflect the actual performance of stoves more truly. Laboratory tests generally represent the best possible performance under ideal conditions, but stoves that perform well in the laboratory (the standard test is boiling water) may not always perform well when cooking specific local foods or using non-standard fuels.

The three common cook stove standardized tests are the Water Boiling Test (WBT), the Controlled Cooking Test (CCT) and the Kitchen Performance Test (KPT). Laboratory WBT is the most standardized of these three tools and can be compared between furnaces.

In Ethiopia, charcoal stoves are mainly used to make tea, coffee, and watt (mainly shiro), which are mostly made up of water, accounting for around 75% and more. Due to the large amount of water in the cooking process, WBT is selected for the proof-of-work protocol of this paper.

3.4.1. Experimental Setup for Testing Conventional Stove

The testing of cook stoves was performed in the chemical engineering laboratory at ASTU. Adama is located at longitude of 39.2583° E and latitude of 8.5263° N and has elevation from sea level 1,712 m and a boiling point of 94.36 ℃. Two methods are commonly employed for estimating the emission factors of cook stoves, the hood method and the chamber method. The tests held for this paper was conducted using 'Hood method' and a schematic diagram of the setup is showed in Fig 3.4 (a). In the hood method, a hood is placed over the stove to capture emissions.

3.4.2. Efficiency and performance test protocol (EPTP) Cook Stoves Performance Testing Protocols

Stove efficiency and performance test protocol (EPTP) Water Boiling Test (WBT) was used for this thesis work because it is the most recent version of all protocols, considering all the drawbacks of previous protocols, as discussed in the literature review. The Water Boiling test is used to investigate the effect of various parameters on the performance of cook stoves. It measures the amount of heat used by the pot and is applicable to most stoves. It basically measures the important aspects of the stove at both high and low power levels.

Test Sequence

The EPTP consists of three phases. For each charcoal stoves tested, phases 1, 2 and 3 were performed three times in sequence. For each stove, it takes approximately 1½–2 hours to perform one complete high- and low-power test sequence (DeFoort et al., 2010).

Phase 1: Cold Start, High-Power Test

In this first phase, the test begins with the stove at room temperature and uses a pre-weighed charcoal fuel to heat a measured quantity of water to 90°C in a standard pot.

Phase 2: Hot Start, High-Power Test

The second phase immediately follows the first test, while the stove was still hot. The test first replaces water heated in phase 1 with a fresh pot of cold water at the established starting temperature. Again, using a pre-weighed charcoal fuel, the water heated to 90°C in a standard pot. Repeating the heating test with a hot stove helps to identify performance differences when a stove is hot versus cold.

Phase 3: Simmer Test

The third phase continues immediately from the second phase. The test determines the amount of fuel required to simmer a measured amount of water at just above 90°C for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world.

Calculations Used in the EPTP

High-power phase with a cold start, a high-power phase with a hot start, and a low power (simmer) phase are phases to be testing the efficiency of the stoves. Each phase involves a series of measurements and calculations.

Measured Variables

❖ Mass of fuel prior to test	❖ Time at start of test
❖ Mass of fuel after test	❖ Time at end of test
❖ Moisture content of fuel (%), wet basis	❖ Mass of charcoal container prior to test
❖ Water temperature prior to test	❖ LHV Lower Heating Value
❖ Water temperature after test	❖ Local boiling temperature of water
❖ Ambient temperature	❖ sampling location
❖ Instantaneous Pressure at exhaust sampling location	❖ Instantaneous Temperature at exhaust
❖ Instantaneous carbon monoxide emission	❖ Mass of charcoal and container after test

3.4.3 Performance Analysis of Cook Stoves

The performance of Cook stove is generally characterized by reduction of harmful emissions, mainly carbon monoxide (CO) and particulate matter (PM), and improvement of thermal efficiency. The variables to be calculated are discussed below.

❖ Test Duration (t_{dur})

The test duration is simply the amount of time that has passed since the start of the test. Because low power testing is done over a fixed period of time, this parameter is only useful for high power testing.

$$t_{dur} = t_{final} - t_{initial} \tag{3.1}$$

❖ Dry Fuel Consumed (F_{cd})

The fuel consumption for a given test is the amount of equivalent dry fuel burned during the test. This is a calculated value that has been adjusted to account for the humidity in the measured fuel. This parameter is useful for testing at high and low power levels. The following equation is used to determine the amount of dry fuel consumed:

$$FCR(\text{fuel consumed rate}) = \frac{\text{charcoal used (kg)}}{\text{operating time (hr)}} \tag{3.2}$$

$$F_{cd} = (F_i - F_f) * \left(1 - \frac{M}{100}\right) - (F_i - F_f) * \left(\frac{M}{100}\right) * \left(\frac{(c_p * (T_b - T_a) + H_v)}{LHV_{char}}\right) \tag{3.3}$$

❖ Burning Rate (R_b)

The average rate at which dry fuel was consumed during the test is referred to as the burning rate. This parameter is useful for both high and low power tests.

$$R_b = \frac{F_{cd}}{t_c} \tag{3.4}$$

❖ Thermal Efficiency (η_{th})

Thermal efficiency is a measurement of both the stove's combustion efficiency and the heat transfer efficiency to the pot. This parameter is useful for high power tests and is calculated by dividing the amount of energy required to raise the pot's water temperature from its initial to final value by the amount of energy available through ideal combustion of the fuel used in the test.

$$\eta_{th} = \frac{c_p * m_w * (T_f - T_i) + h_v * (m_{w,i} - m_{w,f})}{(F_i - F_f)\left(1 - \frac{M}{100}\right) * LHV_{char} - (F_i - F_F) * \frac{M}{100} * \left(c_p * (T_b - T_A) + h_v\right) - LHV_{char}} \tag{3.5}$$

Charcoal residues the equation will be:

$$\eta_{wc} = \frac{c_p * m_w * (T_f - T_i) + h_v * (m_{w,i} - m_{w,f})}{m_{ch,i} \text{ x } LHV} \text{ x } 100\% \tag{3.6}$$

Considering the carbon residues, the equation we get:

$$\eta_c = \frac{c_p * m_w * (T_f - T_i) + h_v * (m_{w,i} - m_{w,f})}{(m_{ch,i} - m_{ch,l})\text{ x } LHV} \text{ x } 100\% \tag{3.7}$$

Where: Cp is the heat capacity of water (4.186 J/g-K) and Hv is the enthalpy of vaporization of water (2260 J/g).

❖ Overall Firepower (FP_o)

Overall firepower is the average rate of energy released from fuel combustion transferred to the pot, surroundings, and stove over the course of the test. This parameter is useful for testing at both high and low power levels.

$$FP_o = \frac{LHV * F_{cd}}{t_c} \tag{3.8}$$

❖ Useful Firepower (FP_u)

Firepower that is useful the average rate of energy released from fuel combustion that is transferred to the pot over the course of the test is referred to as useful firepower. This parameter is only useful for high power testing.

$$FP_u = \eta_{th} * FP_o \tag{3.9}$$

The convective and conductive heat transfer through the stove wall were calculated using Fourier's heat relation using the thermal resistance concept

$$Q = \frac{A(T_1 - T_2)}{\frac{1}{h_o} + \frac{x}{k} + \frac{1}{h_i}} \tag{3.10}$$

Where h is the convective heat transfer coefficient obtained from

$$h = A\left(\frac{\Delta T}{L}\right) \tag{3.11}$$

Table 3.3: Equipment Used for the Water Boiling Test

Equipment's	**Main significance**
Scale with a capacity of 40 kg	To measure fuel and water
Digital Thermometer measure up to 100 ^oC	To measure the temperature of water to boil
Spatula	To remove charcoal from stove
Tongs	For handling charcoal
Timer	To measure time taken to boil

Metal tray	To hold charcoal for weighing
pots	To hold water to boil
Heat resistant gloves	Safety

3.5. Test Preparation

Preparing supplies

Before beginning the first test, enough fuel must be prepared to run at least three tests. Each stove's fuel was air dried to ensure that there was enough fuel to test each stove three times.200 g of fuel (charcoal briquette) will be used for five conventional stoves due to their size and 400 g for bare metal stove in this thesis work. Water must be available in the working area for all three tests for each stove. This test will use 2500 gram of water.

<u>Phase 1: Cold Start, High Power</u>

This phase counts the time and fuel used by a cold stove to heat a pot of water to 90°C, as well as the emissions produced during that time.

Procedure

1. Starting water temperature, starting charcoal mass and starting pot mass (320g) was recorded.
2. The pot was filled with water. Total weight becomes 2500 g (mass of pot plus mass of water).
3. Thermocouple tip is inserted to the pot covered by insulation approximately 5 cm from bottom of pot.
4. As soon as the fire was caught test start time recorded and data acquisition started.
5. Emission data collected within 3 minutes interval.
6. Stove fire starter was kerosene (5 ml).
7. Charcoal briquette was used for each test'
8. When water temperature reached 90°C, end of test time recorded, and all data collection stopped.
9. All charcoal left was weighed.
10. Water left weighed.

Data to be collected at the end of cold start test

- Time to complete test
- Final Temperature of water in pot was measured
- Amount of charcoal remaining at the end measured
- Weight of pot with remaining water was measured
- Amount of charcoal remaining was measured

Phase 2: Hot Start, High Power

Procedure

1. The pot was filled with water. 2500 g of water weighed.
2. Thermocouple tip is inserted to the pot covered by insulation approximately 5 cm from bottom of pot.
3. Test start time recorded, and data acquisition measurement started.
4. Emission data collected within 3 minutes interval.
5. Stove fire starter was kerosene (5 ml).
6. Charcoal briquette was used for each test.
7. When water temperature reached 90°C, end of test time recorded, and all data collection stopped.
8. Time at end of test recorded.
9. Charcoal left was measured.
10. Water left weighed.
11. Hot water was held for phase 3.

Data to be collected at the end of the test

- Time to complete test
- Final Temperature of water in pot was measured
- Amount of charcoal remaining at the end measured
- Weight of pot with remaining water was measured
- Amount of charcoal remaining was measured

Phase 3: Simmer, low power

The simmer test immediately follows the hot-start test and measures the stove's ability to shift from high to low power. The objective is to simmer water at or just above 90°C for 45 minutes using a minimal amount of fuel.

Procedure

1. The stove and water were still hot.
2. Test start time recorded, and data acquisition measurement started.
3. Cooking pot to stove without insulation returned.
4. Thermocouple placed into water such that tip is approximately 5 cm from bottom of pot.
5. Water temperature held at or above 90°C for 45 minutes.
6. Data collection, acquisition stopped after 45 minutes.
7. Remained charcoal measured.
8. Water left was measured.

Data to be collected at the end of the test

- ❖ Time to complete test
- ❖ Final Temperature of water in pot was measured
- ❖ Amount of charcoal remaining at the end measured
- ❖ Weight of pot with remaining water was measured
- ❖ Amount of charcoal remaining was measured

The results obtained from the performance parameters of the cook stove are test duration, thermal efficiency, Specific Fuel Consumption, Fire Burning Rate, Fire Power and turndown rate (TDR). These parameters are implemented using the Excel WBT 4.2.3 data sheet developed by the Global Clean Cookware Alliance and by analytical calculation using equations mention above.

CHAPTER FOUR

4. PERFORMANCE OF CONVENTIONAL COOKING STOVES

4.1. Introduction

Charcoal cooking accounts for a large portion of Ethiopia's energy usage and most widely used for coffee and tea making, Wat cooking, water boiling, and other related activities in rural and urban areas of Ethiopia. The use of these stoves increases with the rapid growth of urban population of the country. In urban area it is used for coffee making business. Charcoal stoves are lightweight and portable. Heat from charcoal is mainly transferred through radiation. These stoves are provided heat output for one pot at a time and the exhaust or emission gases outflow through the clearance between the pot and the stove.

Charcoal stoves in local market are different in their shape, material of construction (bare metal, clay insulated or cement), number of air holes, height of combustion chamber, etc. Most traditional charcoal stoves are made of scrap metal with no option to regulate the burn-rate of the fuel and often without pot-rests, so that the pot sits directly on the charcoal. This causes high emissions of potentially lethal carbon monoxide and wastes a lot of fuel, as carbon monoxide is unburnt fuel with a high energy value. The inability to regulate the air supply and turn down the heat during the simmer-phase also leads to unnecessary waste of fuel. The most important variables that affect the performance of the stoves are material of construction (insulated or bare), the weight of the stove (light or heavy), the height of the air chamber, the area of the grate hole (which should be about 76 cm^2 for a grate of 14 cm diameter), and the area of the exhaust gap (Stewart et al., 1987).

4.1.1. Parts of Charcoal Stove

The charcoal stove has different parts which are shown in Figure 4.1. The pot support main used to pass the exhaust gas. The exhaust gas obstruction inside the chamber creates high pressures which reduce the flow of fresh air and drop the combustion rate. If the gap allowed is larger which allow more heat to escape to the surrounding. Some stove don’t have pot support and some other has either metal support or clay support.

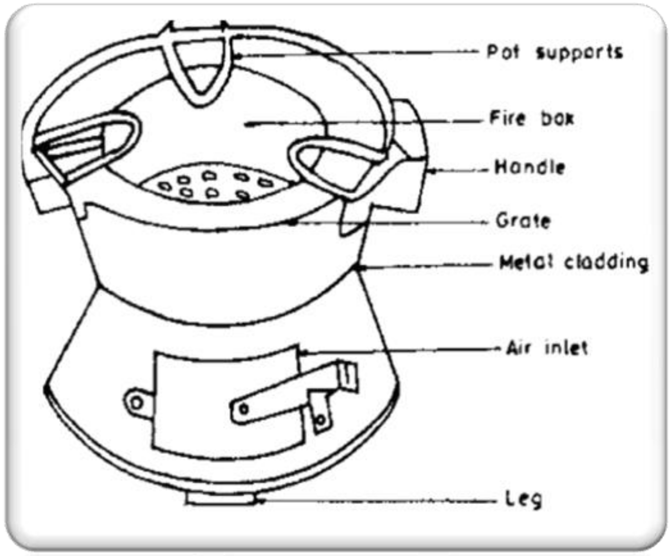


Figure 4.1: Parts of Cooking Stoves (Stewart et al., 1987)

The fire box or the combustion chamber is a place where combustion of charcoal is taking place under complex reactions. Most stoves have the chamber shape cylindrical, which has number of holes (grates) below the charcoal bed to allow primary air to enter. The grate should have sufficient open area to allow good mixing of air and fuel. The width of the opening should be less than 2 cm to reduce the number of small pieces of charcoal falling, but the opening should be greater than 0.5 cm to prevent clogging. If the open area is too small, there will not be enough air to enter the combustion chamber; however, if it is too scarce, the additional air will lower the flame temperature. The final percentage depends on the type and length of coal used. The chambers are made from fired clay to prevent heat loss but there is also bare metal chamber in the market. The thickness of the fired clay insulation has part on resists to flow of heat to the surrounding. Some stoves in market with larger thickness increase the weight of the stove. The space below the combustion chamber has an opening with different shape (circular, rectangular or trapezoidal) which allows the primary air to enter to combustion chamber. The openings of some stoves have a door to control the combustion process of the stove. In most cases the door is excluded in the stove. The volume of the air space plays a great role in the combustion of the fuel.

4.2. Conventional Stoves Selection

In order to answer the research questions, it is doubtful that to collect data from all cases. Thus, there is a need to select a sample. The entire set of cases from which researcher sample is drawn in called the population. Since, researchers neither have time nor the resources to analysis the entire population so it is essential to apply sampling technique to reduce the number of cases. In general, sampling techniques can be divided into two types: probabilistic or random sampling and non-probabistic or non-random sampling. For this study non-random purposive or judgmental sampling method was used to select stoves from the local market for test.

In this study, the performances of six different types of charcoal stoves were tested. The selection is based on judgmental sampling approach and a verbal inquiry to the stove seller. The seller recommends the stove that the society often chooses. There are three sizes (small, medium and large) of each stove available. The medium size was selected for this study based on the frequent selection of the society. Five of them have combustion chamber made of clay and the rest is made of bare metal. Metal, clay, cement, sand and water are the raw materials for the manufacture of stoves. Metal and clay are the main raw materials in the manufacture of stoves. No soldering, soldering or soldering is required as all joints in the housing are riveted or bent. These stoves are taken as traditional charcoal stoves. The basic characteristics of these stoves are briefly described in the Table 4.1 and Figure 4.2.

4.3. Description of Selected Stoves for the Test

4.3.1. Bare Metal Charcoal Stove

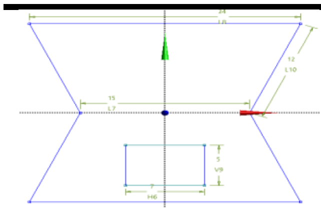
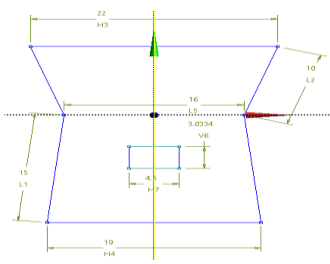
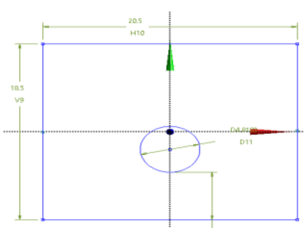
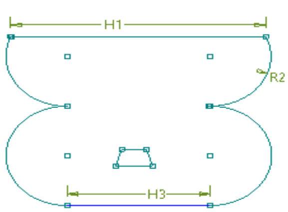
The Bare metal charcoal stove shown in Figure 4.2**.** Ethiopians typically use simple stoves made locally from scrap sheet metal. Bare metal stove is considered a traditional type of portable kitchen stove, which is made of metal plates. There are various shapes on the market, such as square, funnel, and circular. The funnel shaped stove was chosen for this study. The grate is a rectangular plate and the hatched lines are used as holes. The size of the upper combustion zone is equal to the size of the lower air gap. Compared to other ranges selected in this document, this range has the largest valve. The pot is placed directly on the charcoal bed, and the ashes fall in to the tray below.

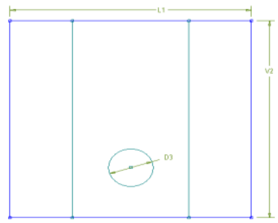
Table 4.1: Part Dimension of Conventional Stoves

No	Stove Name	Total Height (cm)	Combustion Chamber Grate diameter(cm)	Combustion Chamber Surface diameter(cm)	Combustion Chamber Depth (cm)	Combustion Chamber Thickness (cm)	Grate Hole Number of Hole	Grate Hole Hole diameter(cm)	Casing Diameter (cm)	Pan Seat	Air Gate Shape	Air Gate Area (cm2)	Air Gate Door
1	**Hexagonal**	20	12	18	6.5	2.3	12	1.8	26.5	Yes	Circular	38.4	No
2	**Ethio(Rectangular)**	26.5	12	16	8	4	12	2	24x 24	Yes	Rectangular	35	Yes
3	**Tirumbe (circular)**	19.5	13	19	5	3	8	2.5	26	No	Circular	50.2	No
4	**Bare metal(rectangular)**	31	15	26 x26	10	0	5(line cuts)	-	26x 26	Yes	Rectangular	70	No
5	**Obama (Rectangular)**	24	13	15	7.5	5	16	2	23x 23	Yes	Rectangular	40	Yes
6	**Bandura (circular)**	20.5	12	17	6	3	10	2	26	No	Trapizoidal	21	No

Figure 4.2: Bare Metal Charcoal Stove

Table 4.2: Part Dimension of Conventional Stoves

Schematic diagram with dimension		**Specifications**
	Ethio cooking Stove	Chamber volume: 0.0014137167 m^3 Air space volume: 0.0039513382 m^3 Top area: 0.0165129964 m^2 Grate area to Air hole area: 0.011m^2/0.0037m^2
	Obama Cooking Stove	Chamber volume: 0.0013 m^3 Air space volume: 0.00361 m^3 Top area: 0.015m^2 Grate area to air hole area: 0.011m^2/0.003m^2
	Turumbe Cooking Stove	Chamber volume: 0.00117 m^3 Air space volume: 0.0061 m^3 Top area: 0.025m^2 Grate area to air hole area: 0.017m^2/0.0025m^2
	Bandira cooking stove	Chamber volume: 0.00136 m^3 Air space volume: 0.0033 m^3 Top surface area: 0.022m^2 Grate area to air hole area: 0.0122m^2/0.00314m^2

	Hexagon cooking stove	Chamber volume: 0.00134 m^3 Air space volume: 0.0089 m^3 Top surface area: 0.0254m^2 Grate area to air hole area: 0.0103m^2/0.0037m^2

4.3.2. Ethio Charcoal Stove

The Ethio charcoal stove shown in Figure 4.3 the stove casing is rectangular shaped, the combustion chamber is insulated by 4 cm thick baked clay, and the combustion chamber is cylindrical, 8 cm high, and has 12 pores with a diameter of 2 cm. The shape of the shell is two oppositely connected rectangular prisms.

Figure 4.3: Ethio Charcoal Stove

4.3.3. Obama Charcoal Stove

The Obama charcoal stove shown in Figure 4.4 is a clay-insulated stove with a small circular charcoal chamber of depth 7.5 cm and diameter 15 cm. The pot sits on a raised metal wedge above the charcoal bed and the door in front of the stove can be adjusted to control airflow. The shape of the shell is two oppositely connected rectangular prisms.

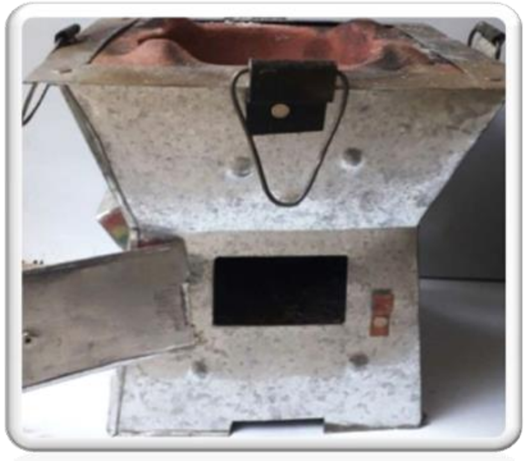


Figure 4.4: Obama Charcoal Stove

4.3.4 Turumbe Charcoal Stove

The Turumbe charcoal stove shown in Figure 4.5 is a metal stove with a fired clay-lined chamber 5 cm deep and 19 cm in diameter. The pot sits on a charcoal bed on three fired clay pole supports. The stove does not have a door in front of the stove, and the air flow is not controlled to remove ashes. The stove is cylindrical shape.

Figure 4.5: Turumbe Charcoal Stove

4.3.5. Bandira Charcoal Stove

The Bandira charcoal stove shown in Figure 4.6.The charcoal chamber is hemispherical 3 cm deep and 17 cm in diameter and the pot is placed directly on the charcoal bed. The furnace is composed of two hemispheres, the upper part is the combustion chamber, and the lower part is the air gap and the ash collector. The bodywork is painted green, yellow and red. The opening on the side of the oven allows air circulation, but there is no door to control air circulation.

Figure 4.6: Bandira Charcoal Stove

4.3.6. Hexagon Charcoal Stove

The Hexagon charcoal stove shown Figure 4.7. The charcoal chamber is circular 3 cm deep and 17 cm in diameter and the pot is placed directly on the charcoal bed. The outer shape is hexagonal. The opening on the side of the oven allows air circulation, but there is no door to control air circulation.

Figure 4.7: Hexagon Charcoal Stove

4.4. Challenges of Conventional Cooking Stoves

Ethiopian cook stove manufacturers generally does not study the performance of the materials of cookstove. There are no regulations on the manufactured cook stoves nor standards on for manufacturing new cook stoves;, so someone can become a manufacturer without any standard comparison. The performances of these cooking stoves where not studied based on the common cook stove test protocol scientifically. This has caused society to suffer from health problems and fuel costs. Without any engineering considerations, the designed stove has a big problem in heat transfer through the side, and the flue gas emission is very high, which greatly affects the health. Local manufacturers have designed combustion chambers in different ways. Cylindrical, prism and rectangular chambers are available on the market. A cylinder chamber is dominantly available. The height and diameter of the combustion chamber have a large impact on heating and emissions. Turumbe, Bandura and Hexagon have short chamber respectively for this reason they were selected for this study.

The hot pot holder is the main heat source in to the environment. When using a small pot, the outside fire is open to the outside world, which will increase fuel consumption, and this waste is not effectively used. The opening in the pot base is used to discharge the flue gas which has high heat energy. When the height of the chamber is short and there is an opening, it emits a high heat level gases without completely burning of CO and other high-energy gases. It is obvious that due to the high thermal conductivity of metal, the exposed bare metal stove emits lot of energy to the environment through its side. It is also dangerous for the user to touch it occasionally or move it from another to another location. Insulated stoves also have a lot of heat lost through the sides. This is due to insufficient firing temperature of the clay. The properties of clay used for insulation have not been fully studied. The main components of clay used for insulation are silica and alumina. The firing temperature also has a great influence on the thermal insulation of clay.

All the challenges of these stoves have important implications in reducing thermal efficiency. The thermal efficiency indicates the amount of heat emitted by the fuel effectively to be transferred to the water in the cooking pot. The heat generated by the charcoal stove in the combustion chamber is not transferred to the water in the pot. This is due to the loss through the side walls, the bottom loss of the air gap, and the heat loss of the exhaust gas. In actual activities, the efficiency will never reach 100%, but by controlling and reducing the heat loss, the efficiency of the stove can be improved. The thermal efficiency of locally available stoves has not been studied. This will increase fuel consumption and emissions, leading to premature death. The local stove has a high emission level, and cooking in a place without ventilation will cause death. The OSHA standard allows the CO concentration in the work area to be 0.002%, and if the concentration is greater than 0.02%, it will cause death (Ezzell et al., 1988). Formation emissions are highly dependent on the amount of air entering, the shape and design of the combustion chamber, the temperature of the entering air, and the nature of the fuel. Overtime, the bare metal stove, due to the environment and frequent heat load, the stove body is severely corroded.

CHAPTER FIVE

5.1. ANALYTICAL ANALYSIS OF THE NEW MODIFIED STOVE

5.1.1. Description of Improvements of Charcoal Stoves

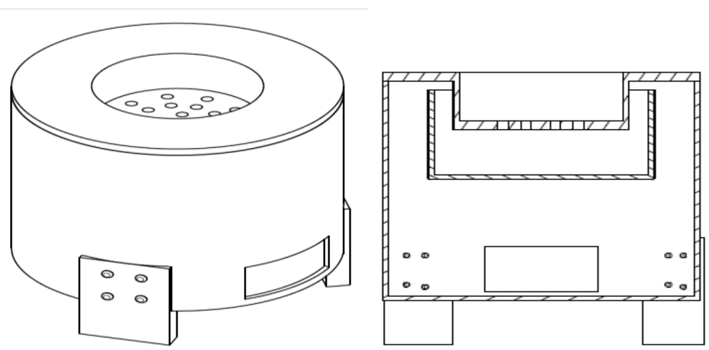
Charcoal stoves can be made more durable and efficient in terms of heat output. Air is the number one controlling agent with inside the combustion of charcoal. The airflow needs to be adjustable with a view to manipulate the heat output. Charcoal emits heat in all directions, not just upwards toward the pot. As a result, it is critical to minimize heat loss to the stove's bottom and sides. Air circulation in stoves can be carefully designed to "re-use" heat and create the draft required for efficient combustion. This can be accomplished, for example, by inserting a deflector plate between the charcoal chamber and the stove bottom to reflect heat back upwards. Although radiation decreases exponentially with distance, the pot should not be placed directly on the glowing char. To achieve maximum combustion of the carbon monoxide, a gap must be permitted through which fresh or even pre-heated secondary air can be directed above the charcoal. This lowers emissions and improves fuel efficiency. Preparing tomorrow

5.1.2. Features of New Improved Stove

The main challenge of cooking stove design is how to reduce losses due to conduction and radiation heat transfers mainly radiation contribute larger amount of loss. The stove showed on Figure 5.1 consists of a combustion chamber constructed using a 2.0 mm thick iron sheet material. The reason behind selecting iron sheet metal used for building the chamber is, it has high capacity to realize the heat by convection. The combustion chamber was designed to receive solid biomass fuel (charcoal) and enhance complete combustion of combustible gas released during charcoal burning process. The iron metal combustion chamber is imbedded in a cylinder (outer retort) constructed using prepared insulating material for this work with thickness of 3 mm. The combustion chamber and outer retort are designed in a way that a 30 mm gap is left in between to provide a free movement of air and enhance resistance to heat transfer to the inner wall of the outer retort.

Between the combustion chamber and the outer body of the stove there is U-shape aluminum metal as showed in Fig

ure 5.1, which is used to pre heat the air by allowing two passes. The heat loss within ash and radiation loss to bottom collected by entering air and which use to enhance combustion and heat transfer efficiency. The increase in temperature of the air also reduces the release of carbon monoxide gas by water gas shift reaction. The reactants are water (in steam form) and CO produces carbon dioxide and hydrogen gas.



(a) 3-D view (b)section view

Figure 5.1: New Improved Stove (a) 3-D view (b) section view

The water gas shift reaction (WGSR) is a moderately exothermic reaction between carbon monoxide and steam to form carbon dioxide and hydrogen. In typical industrial applications, the WGSR is conducted as a two-stage process. The high temperature stage, conducted over an iron-based catalyst in the temperature range 320 – 450 °C. The low temperature stage, conducted over copper-based catalysts in the temperature range 150 – 250 °C. There is no universally accepted reaction mechanism for the WGSR (Baraj et al., 2021).The iron which was used to construct the chamber also facilitate the reaction as a catalyst.

$$CO + H_2O(g) \leftrightarrow CO_2 + H \quad (5.1)$$

5.1.3. Explanation and Analytical Modeling of Heat Transfer of Prototype Stove

In this chapter, the basic stove performance indicator parameters were evaluated. These parameters are stated and evaluated by using fundamental theories, formulas, estimation, assumption and other mechanism from related literature reviews mainly from the paper work of

(Zube et al. 2010). Total heat energy and heat losses from the stove are calculated below. The three modes of heat transfer contribute on heat losses and heat gain. Conduction heat transfer gain only may occur on the stove with no pot sit and large top surface area, unless it contribution is significant. Radiation contributes large portion of heat loss and gain.

5.1.4. Heat Transfer through Different Areas

- **Maximum Heat Generated from Burning of Charcoal**

Energy developed from biomass fuel was obtained by taking assumption from estimated values are(Zube et al., 2010):

- Initial mass of fuel mf = 200 g
- Combusted mass mc =180 g
- LHV wood fuel = (29,800 kJ/kg experimental acceptable
- HHV of wood fuel = 31,000 kJ/kg experimental acceptable

$$\text{Input energy } (Q_{in}) = LHV * m_f - HHV * m_c \tag{5.2}$$

- **Conduction Heat Loss to Base Plate**

- Area of cast iron combustion chamber bed (A) = $0.015m^2$
- Cast iron combustion chamber bed (K) = 52 $\frac{W}{m.K}$
- Thickness cast iron combustion chamber bed (L) = 0.002 m and

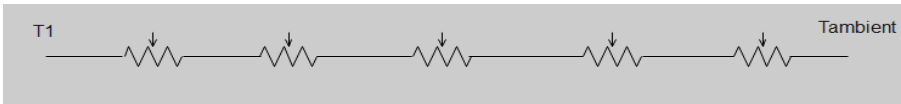
$$R_{\text{cast iron comustion chamber bed}} = \frac{L_{\text{cast iron comustion chamber bed}}}{K_{\text{cast iron comustion chamber bed}}} \tag{5.3}$$

- Temperature of chamber bed = 620K
- Temperature of stove internal= 575K

$$Q_{\text{cond.loss comb.chamber bed}} = \frac{A_{\text{chamber bed}} * (T_{\text{chamber bed}} - T_{\text{internal}})}{R_{\text{chamber bed}}} \tag{5.4}$$

- **Estimated Heat Loss**

There are three modes of heat transfer which are conduction, convection and radiation. In cook stove operation each modes have their own contribution. There is zero energy gains associated with conduction heat transfer to the pot. Hot combustion gases interact with two separate surfaces: the inner surface of the stove (losses) and the outer surface of the pot (gains). The magnitude of convective heat transfer is influenced by the velocity of the gases flowing through the stove, the exposed surface area contacting the gases, and the temperature difference between the gases and the exposed surface. Radiant energy originating from either the coal bed or flames is transferred to the stove body, pot, or ambient surroundings. The thermal resistance diagram for the modified stove is draw from T_1 (temperature in combustion chamber) to the side wall ambient temperature ($T_{ambient}$).



$$\text{Total resistance} = \frac{\ln\left(\frac{r_2}{r_1}\right)}{2\pi k_1 l} + \frac{1}{2\pi r_2 lh} + \frac{\ln\left(\frac{r_3}{r_2}\right)}{2\pi k_2 l} + \frac{1}{2\pi r_3 lh} + \frac{\ln\left(\frac{r_5}{r_4}\right)}{2\pi k_4 l} \qquad (5.5)$$

k_1- Thermal Conductivity of Steel

k_2- Thermal Conductivity of Aluminum

k_4- Thermal Conductivity of Steel

- **Heat transfer analysis between flame and inner combustion chamber wall by convection heat transfer and radiation heat transfer**

Assumptions are taken for analysis of heat transfer equations from (Zube et al., 2010)for simplification of the analysis: and this value was obtained from simulation from basic ideal gasses equation and from.

- $T_{hot\ gas}$= 800 K ………………………………………….……………. Flame Gas Temperature
- T_{pot}= 326 K …………………………………...……... Average Pot Surface Temperature
- $R_{univesal\ gas\ constant}$ = 8.3143$\frac{J}{Kmol}$
- M_{air}= 28.97 $\frac{gm}{mol}$…………………………..……Molecular Mass of Air at P Atm = 76 Kpa
- $D_{chamber}$= 14 cm
- R_{air}= $\frac{R\ universal}{Mair}$ = 286.9$\frac{J}{K.Kg}$
- $\rho_{gas} = \frac{p_{atmospheric}}{R_{air*}T_{gas}} = 0.446\ \frac{Kg}{m^3}$………………………………………..Density of Hot Gas

- $A_{chamber} = \frac{\pi * D^2_{chamber}}{4}$ =0.015m^2

$$\Delta P_{induced} = gh_{chminy}\left(\rho_{ambient} - \rho_{hot\,gas}\right) = gh_{chminy}\,\rho_{ambient}\left(1 - \frac{T_{ambient}}{T_{hot\,gas}}\right) \qquad (5.7)$$

$$\dot{m} = LC * A\left(\frac{\Delta p_{induced}}{R_s T_{hot}}\right)\sqrt{2gh_{chiminy}\left(\frac{T_{hot} - T_{ambient}}{T_{ambient}}\right)} \qquad (5.8)$$

Velocity of gasses in Chamber is given by

$$V_{gas} = \frac{m^{\cdot}}{\rho_{gas} A_{chamber}} \qquad (5.9)$$

From basic Bernoulli's equation:

$$\frac{P_1}{\rho} + \frac{{V_1}^2}{2} + gZ_1 = \frac{P_2}{\rho} + \frac{{V_2}^2}{2} + gZ_2 \qquad (5.10)$$

And from initial boundary condition, inlet velocity assumed to be V_1 =0 (Zube et al., 2010).Then Bernoulli's equation can reduced as follows:

$P_{gauge} = \rho_{gas} * \frac{1}{2}(V_{gas})^2 = 0.047$ pa..................................Gauge Pressure

Nominal absolute viscosity of air at 1atm and T_0 = 273 K is μ_0 = 1.71×10-5 kg/m. s and

$\mu_{gas} = \mu_0 (\frac{T_{gas}}{T_{ambient}})^{0.7}$ .... viscosity of air at T_{gas}

$Re = \frac{\rho_{gas} * V_{gas} * D_{chamber}}{\mu_{gas}}$.................Reynolds Number

For fully developed internal flow Reynolds number less than 2300 (Re < 2300) are laminar flow Reynolds number approximation for fully developed internal flow through circular pipe (Zube et al., 2010).

- **Convection Heat Transfer Loss in Inner Combustion Chamber Wall**

$$Q_{convection,chamber\,wall} = h_{chamber\,wall} A_{surface\,chamber}(T_{flame} - T_{chamber\,wall}) \qquad (5.11)$$

Where

- height of chamber = 55 mm
- Diameter of chamber = 140 mm
- $A_{surface\,chamber} = \pi * D_{chamber} * h_{chamber}$
- $T_{hot\,gas}$=800 K ....Average Chamber Wall Surface Flame Temperature

- $T_{chamber\ wall} = 720$ K …………………. Average Chamber Wall Surface Temperature.

The friction factor between flame gases and wall surface of combustion chamber is assumed to be fully developed internal flow contained by smooth walls:

$$f = \frac{64}{Re} \quad (5.12)$$

- $C_{p,gas} = 1..08 * \ 10^3 \frac{J}{Kg.K}$
- $K_{gas} = 5.7 * 10^{-2} \frac{W}{m.K}$

Prandtl Number

$$Pr = \frac{\mu_{gas} * C_{p,gas}}{K_{gas}} \quad (5.13)$$

Nusselt Number for flow in circular tube. The effects of wall roughness and laminar flow conditions (Re <2300) may be considered by using the Gnielinski correlation, Nusselt Number represents a dimensionless temperature gradient at the surface.

$$Nu = 0.565 * Pr^{0.5} * Re^{0.5} \quad (5.14)$$

$$h_{convection} = \frac{Nu * K_{gas}}{D_{chamber}} \quad (5.15)$$

$$h_{conv,low-flame} = 2.3 * h_{convection} \quad (5.16)$$

- **Heat Transfer by Radiation**

Radiative heat transfer does not require a medium to pass through. Thus, it is the only form of heat transfer present in vacuum. It uses electromagnetic radiation (photons), which travels at the speed of light and is emitted by any matter with temperature above 0 degrees Kelvin (-273 °C). Radiative heat transfer occurs when the emitted radiation strikes another body and is absorbed.

Radiation is modelled by the Stefan-Boltzmann Law,

$$Q = \varepsilon\sigma\left[{T_s}^4 - {T_\infty}^4\right] \quad (5.17)$$

Where,

Q= heat transfer; σ = Stefan-Boltzmann constant; ε = Emissivity; T_s = Surface Temperature; T_∞ = Ambient Fluid (air) Temperature.

- Estimated height of combustion chamber (h_{ch}) = 55 mm

- Estimated effective perimeter of inner combustion chamber (P) = 0.39 m
- Effective radius of outer steel cover walls (R) = 150 mm
- Effective radius of inner combustion chamber (R) = 70 mm
- Surface area of inner combustion chamber (A) = 0.0549778714 m^2
- Surface area of base plate (A) = 0.015393804 m^2

$T_{\text{inner cylinder}}$ = 790 K …………Average steady state surface temperature of inner cylinder

ϵ_{flame} = 0.72…………..……… Estimated emissivity value of diffusion flame from literature

ϵ_{wood} = 0.45……………………..Estimated emissivity value of burning wood from literature

$\epsilon_{\text{cast iron}}$ = 0.26……………………………………………... Emissivity cast iron chamber

ϵ air = 0.8…………………………………………………….………… Emissivity air

$\sigma = 5.67\ \text{x}10^{-8}\ \frac{\text{W}}{\text{m}^2\text{k}^4}$………………………………………Stefan –Boltzmann constant

- **Radiation Loss to Walls of Combustion Chamber (Inner Cylindrical Parts of the Stove):**

Due to radiation heat transfer between the flame and inner part of cylinder, there will be radiation loss occurrences between the flame and wall of the cast iron part. This amount of steady state heat loss can be calculated as:

$$Q_{\text{rad chamber loss}} = \frac{\sigma_{\text{stefan}}\, A_{\text{chamber}}(T^4_{\text{surface chamber wall}} - T^4_{\text{ava temprature}})}{\frac{1}{\epsilon_{\text{ava}}} + \frac{1 - \epsilon_{\text{ava inner chamber}}}{\epsilon_{\text{ava outer chamber}}}} \qquad (5.18)$$

Average steady state surface temperature of flames and wood is estimated as follow: estimated temperature of firewood is equal 353 K.

$$T_{\text{avarage}} = 0.6T_{\text{flame}} + 0.4T_{\text{charcoal}} \qquad (5.19)$$

- height of chamber = 55 mm
- Radius of inner chamber = 70 mm
- Perimeter of inner chamber(P) = 2 ∗ diameter + 2 ∗ height
- $A_{\text{inner chamber}} = 0.054\ \text{m}^2$
- $A_{\text{outer chamber}} = 0.064\ \text{m}^2$

$$\epsilon = \frac{\epsilon_{\text{cast iron}}\, A_{\text{cast iron}} + \epsilon_{\text{air}}\, A_{\text{air cover}}}{A_{\text{cast iron}} + A_{\text{air cover}}} \qquad (5.20)$$

- **Convection Heat Transfer from Gases to Pot Bottom**

The circumference of the chamber is calculated by equation which is used to calculate the gap from the top of the chamber and the bottom of the pot.

- The gap $G_c = \frac{A_C}{C_C}$

The circumference of the pot is calculated by equation which is used to calculate the gap from the bottom of the pot and the top of the chamber.

- $G_c = \frac{A_p}{C_p}$

The minimum gap should be provided is 0.81cm and the maximum is 1.75 cm. for calculation average gap 1.28 cm is used.

$$Q_{convection,pot\ bottom} = h_{pot\ bottom} A_{pot\ bottom} \left(T_{gas} - T_{pot\ bottom}\right) \tag{5.21}$$

Assume the space created by pot gap and stoves pot holder behaves like two parallel plates, air gap between pot and chamber top surface (h_{gap}) was taken as 2.8 mm

- D_{pot} =220mm
- $A_{pot\ bottom} = \frac{\pi D^2}{4}$.... Effective bottom pot exposed surface area to flame gasses
- $A_{pot\ bottom} = \pi * h_{gap} * D_{pot}$

Estimated flame gas velocity flowing through pot and stove gap area can evaluate by Hydraulic diameter definition between two parallel plates:

- $D_h = 2 * h_{gap} =$

$$R_{air\ gap} = \frac{\rho_{gas} * V_{gas} * D_{pot}}{\mu_{gas}} \tag{5.22}$$

The flow through pot gap is less turbulent than in the gap between pot and flame.

Prandtl number (ration of thermal dissipation conduction):

- $Pr = \frac{\mu_{gas} * C_{p,gas}}{K_{gas}}$
- $C_{p,gas} = 1.08 * \ 10^3 \frac{J}{Kg.K}$
- $K_{gas} = 5.7 * 10^{-2} \frac{W}{m.K}$

Where both specific heat capacity of air and Thermal conductivity of air are depending on average gas temperature

- $\mathrm{Nu} = 0.565 * \mathrm{Pr}^{0.5} * \mathrm{Re}^{0.5}$
- $h_{convection} = \frac{\mathrm{Nu} * K_{gas}}{D_{pot}}$
- $h_{conv,low-flame} = h_{convection} * 2.3$

During combustion flame radiation can increase the magnitude of the convective heat transfer coefficient anywhere from 2.3 times to 3.4 times (Viskanta, 1993).

- T_{gas}= 786 K ……… Average estimated gasses pot bottom surface flame temperature
- $T_{pot\ bottom}$ = 397 K ……………………Average estimated pot surface temperature.
- $Q_{convection,pot\ bottom} = 8.76 \frac{W}{m^2 * K} * 0.037\ m^2 * (786\ K - 397\ K) = 126.08\ W$

- **Radiation Heat Transfer from Flame to Pot Bottom**

It is total radiation heat transfer supplied to pot bottom from the flame sheet. Assuming pot is a black body (i.e., ε = α = 1, radiation is diffuse, or directionally independent), and reflectivity of flames is negligible.

$$Q_{rad\ gain\ to\ pot} = \sigma_{stefan} A_{pot\ bottom} \epsilon_{flame} \left[T_{flame}{}^4 - T_{pot\ surface}{}^4 \right] \quad (5.23)$$

Where,

- $T_{flame\ temprature}$= 790 K ……………. Average temperature of emitting area
- $T_{pot\ surface}$= 395 K …………………...Average temperature of pot surface
- r_{flame}= 80 mm……………………… Radius of effective emitting flame area
- $r_{pot\ bottom}$=100 mm………………… Radius of effective pot bottom
- L_{flame}= 20 mm……………………… Separation distance between two effective areas
- $A_{flame} = \pi r_{flame}^2 =$ ……………………Effective emitting flame area
- $A_{pot\ bottom} = \pi\ r_{pot\ bottom}^2 = 0.02\ m^2$…. Effective area intercepted by pot bottom Variable

Radiation heat transfer from the fire bed in a cook stove can be increased, either by increasing the fire bed temperature (by controlling the air supply to the fire bed) or by increasing the View

Factor (VF). The View Factor can be increased by either decreasing the distance between the pot and the fire bed or by increasing the diameter of the pot. The net radiant heat lost or gained by surface i is the difference between the heat it radiates and that which it absorbs from other radiating surfaces.

$$S_{flame-view} = 1 + \frac{1 + (\frac{r_{pot\ bottom}}{L_{flame}})^2}{(\frac{r_{flame}}{L_{flame}})^2} = 2.02 \tag{5.24}$$

$$F_{flame-in\ out} = \frac{1}{2}\left[S_{flame\ view} - \left[S^2{}_{flame\ view} - 4\left(\frac{r_{flame\ in}}{r_{flame\ out}}\right)^2\right]^{\frac{1}{2}}\right] \tag{5.25}$$

$$Q_{rad\ gain\ to\ pot} = \sigma_{stefan} F_{flame} A_{pot\ bottom}\left(\epsilon_{flame} T^4_{flame\ temp} - T^4_{pot\ surface\ temp}\right) \tag{5.26}$$

- **Convection Heat Transfer from Pot Holder to The Surface Pot**

$$Q_{convective,holder} = h_{holder} A_{holder}\left(T_{gas} - T_{pot\ holder}\right) \tag{5.27}$$

Where,

Gas temperature as it exits the pot gap and travels up the sides of the pot is estimated the outlet temperature of flame gases is 730 K.

- $T_{gas} = 730\ ^0K$ …………………Estimated flame gas temperature surface of pot holder
- $T_{pot\ holder} = 452\ ^0K$ ……………………. Estimated average temperature of pot holder
- $H_{pot\ holder} = 12.5mm$
- $Do_{pot\ holder}$ =190mm,
- $t_{pot\ holder} = 3mm$………………………………………. Thickness of pot holder
- $Di_{pot\ holder} = Do_{pot\ holder} - 2 * t_{pot\ holder} =$ 184mm=0.184m
- $A_{pot\ holder} = \pi * H_{pot\ holder} * Di_{pot\ holder} = 0.0072m^2$

Hydraulic diameter definition between two parallel plates

$$D_h = 2 * H_{pot\ holder} \tag{5.28}$$

$$= 0.025m$$

$$V_{gas} = \frac{\dot{m}}{\rho_{gas} * A_{pot\ holder}} \tag{5.29}$$

$$R_{\text{air gap,pot holder}} = \frac{\rho_{gas} * V_{gas} * Di_{pot}}{\mu_{gas}} \quad (5.30)$$

The flow through pot holder and air gap is fully laminar flow.

$$Pr = \frac{\mu_{gas} C_{p,gas}}{K_{gas}}$$

The Nusselt number, assuming fully developed laminar flow, and near the wall of pot holder perfectly insulated and side pot surface held at uniform temperature.

$$Nu = 0.565 * Pr^{0.5} * Re^{0.5} \quad (5.31)$$

$$h_{convection} = \frac{Nu * K_{gas}}{Di_{\text{pot holder}}} \quad (5.32)$$

$$h_{conv,high-flame} = 3.4 * h_{convection} \quad (5.33)$$

- **Wasted Heat out the Top of The Stove**

$$Q_{waste} = m_{\text{flow in stove}} * c_{\text{p,gas out}} * \left(T_{\text{gas out}} - T_{ambeint}\right) \quad (5.34)$$

Where,

- $T_{\text{gas out}} = 430$ K
- $T_{ambeint} = 300$ K
- $C_{p,gas} = 1.029 \frac{kj}{kg.k}$ @ 430 K

Total heat utilized is the summation of both convection heat transfer energy and radiative heat transfer energy total gained by the stove.

$$Q_{utilized} = Q_{\text{convection,pot holder to the surface pot}} + Q_{\text{Radiation,flame to pot bottom}} + Q_{\text{convection,gases to pot bottom}} + Q_{\text{convection,pot holder to pot}}$$

Total heat losses are the summation of all form of the heat transfer losses. Such conduction loss, convection heat transfer loss and radiative heat transfer loss in the stove. $Q_{lost} = Q_{\text{conduction,wall}} + Q_{\text{Radiation,chamber wall}} + Q_{\text{convection,chamber wall}} = 2{,}071$ W

The lost heat is recovered in the new designed cook stove by passing air through double path way and the air is preheated by the heat lost through the sidewall of the stove.

$$\eta_{stove} = \frac{Q_{utilized}}{Q_{total}} \quad (5.35)$$

CHAPTER SIX

6. COMPUTATIONAL FLUID DYNAMICS

6.1 Ansys-Fluent

Computational Fluid Dynamics (CFD) Simulation creates a virtual laboratory in which experiments can be carried out during the early stages of design without the need for physical equipment. The virtual environment reduces the cost of unit design by reducing the number of unsatisfactory experimental equipment that is eventually scrapped.

Otherwise, the expense of the experimental device and its operation will be ridiculously high until acceptable results are obtained. The cook stove fluid flow model includes governing equations such as the conservation of mass (continuity) equation, the conservation of momentum (Navier-Stokes equation), and the conservation of energy (energy equation). When the first law is applied correctly to a cook stove, it allows for a better understanding of the principles governing its operation. The principles of mass conservation and energy conservation for open systems or control volumes apply to systems with mass crossing the system boundary or control surface. Because fluid flows across the boundary of a fixed volume, referred to as a control volume, a cook stove is an open system. A cook stove is evaluated under isobaric steady-flow conditions with a constant bulk mass flow rate. These assumptions ignore transient effects since these add significant complexity to the energy balance calculations with minimal gains in accuracy.

6.1.1. Geometry Design

All the conventional and deigned stoves geometric analysis is provides the configuration and dimensions of the combustion chamber used in the simulations as well as the fuel and air rates passing through. Because of the system's high level of symmetry, the calculation domain can be reduced to a 2D problem presuming no variants in the radial coordinate. If this is done, the computational time required for the calculations is drastically reduced.

6.1.2. Mesh Generation

The system discretisation is the way to assign the mathematical model to a finite element of the system, transform those differential equations in algebraic equations, and then, solve the system. That is called finite element method. The approximation of differential equations to finite increments introduce an error that is where an intense phenomena is occurring (i.e. intense chemical reactions or high energy turbulences), the size of the elements must be reduced to improve solution accuracy.

Because the combustion reaction occurs in the combustion chamber, the mesh must be refined all the way to the centre (symmetry axis) and the fuel inlet must be closed. The combustion chamber was discretised for this purpose using ANSYS's own meshing program, with a sphere of influence and an inflation ratio introduced to refine the mesh in the important zones of the system.

ANSYS has some valid applications available that could solve the problem posed in this work. Inside FLUENT the setup consists in the following parts, necessary to perform the calculations.

- Models' definition: it is the part where is defined which models are selected to as describe the different phenomena present in the system.
- Boundary Conditions: Set the different inlets, outlets and limits of the system.
- Calculation Parameters: Set the solution methods and controls.

6.1.3. Models Definition

CFD calculation and mathematical processes are governed by fluid flow governing equations. The equations are series of balances and fluid properties, which are the overall mass balance (continuity equation) (equation 6.1), momentum balance (equation 6.2), energy balance (equation 6.3).

Those governing equations are:

Continuity

$$\frac{D\rho}{Dt} + \rho\frac{\partial U_i}{\partial x_i} = 0 \quad (6.1)$$

Momentum

$$\rho \frac{\partial U_J}{\partial t} + \rho U_i \frac{\partial U_J}{\partial x_i} = -\frac{\partial P}{\partial x_j} + \mu \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_j \qquad (6.2)$$

Energy equation

$$\rho C_\mu \frac{\partial T}{\partial t} + \rho C_\mu U_i \frac{\partial T}{\partial x_i} = -p \frac{\partial U_i}{\partial x_i} + \mu \frac{\partial^2 T}{\partial x_i^2} - \tau_{ij} \frac{\partial U_J}{\partial x_i} \qquad (6.3)$$

FLUENT discretizes the governing equations for each system point. To obtain the various properties required to solve those discretized equations (e.g., viscous behavior, radiation energy transfer, or chemical reactions), FLUENT employs various models to estimate these parameters. The application and selection of these models is determined by the nature of the problem to be solved. All of these equations must be solved for this work, and the following models must be used to estimate the turbulences (viscous model), the radiation term, and the species distribution and kinetics

6.2. Heat Transfer Modeling Fluent

General

FLUENT uses two numerical methods either pressure based or density-based solver. For this study CFD analysis the pressure-based solver system is used to analyse the heat transfer and fluid flow simulation of some biomass cook stoves which as different geometry to accurately predict temperature and velocity field above the fuel bed.

Models

To model heat, transfer the energy equation must be activated.

Radiation DO Model

The DO radiation model provides a high degree of accuracy, but it can be CPU intensive. In cases where the computational expense of the DO model is deemed too great, the P1 model may provide an acceptable solution more quickly. Effects of particles, droplets, and soot can be included. It Works reasonably well for applications where the optical thickness is large.

Viscous Model

The viscous model must be activated because there is a fluid flowing through the system. One of the most accepted and used models to estimate the turbulent-flow behavior of the combustion systems is the k-epsilon model (Iglesias Fernández, 2016).This model is practical for many flows and its convergence is usually easy. The model is composed by two equations including the turbulent kinetic energy (k) and the turbulent dissipation rate (ϵ).

MATERIALS

In this section, the materials specified for the different stove components and some of their important properties are stated.

Solid

The internal body part and base plate are made of aluminum for comparison of the geometry. Aluminum is included in fluent material data base.

Species Transport

The coal combustion is represented as 'pyrolized volatiles' burning, hence the working fluid is a mixture of volatiles and air (Mapelli et al., 2013). The 'coal-volatile-air' was thus selected under the species transport settings. Reactions calculations were enabled by turning on 'volumetric' with 'laminar finite-rate' as turbulence-chemistry interaction. The discrete phase model setting was turned on to introduce fuel injection sources at 4 points in x-position (-4, -2, 0, 2, 4 cm) on y-position at 1.5 cm , to simulate the burning of coal in the combustion chamber for all stoves. The algorithm of the solution in the form of flow chart showed on Figure 6.1.

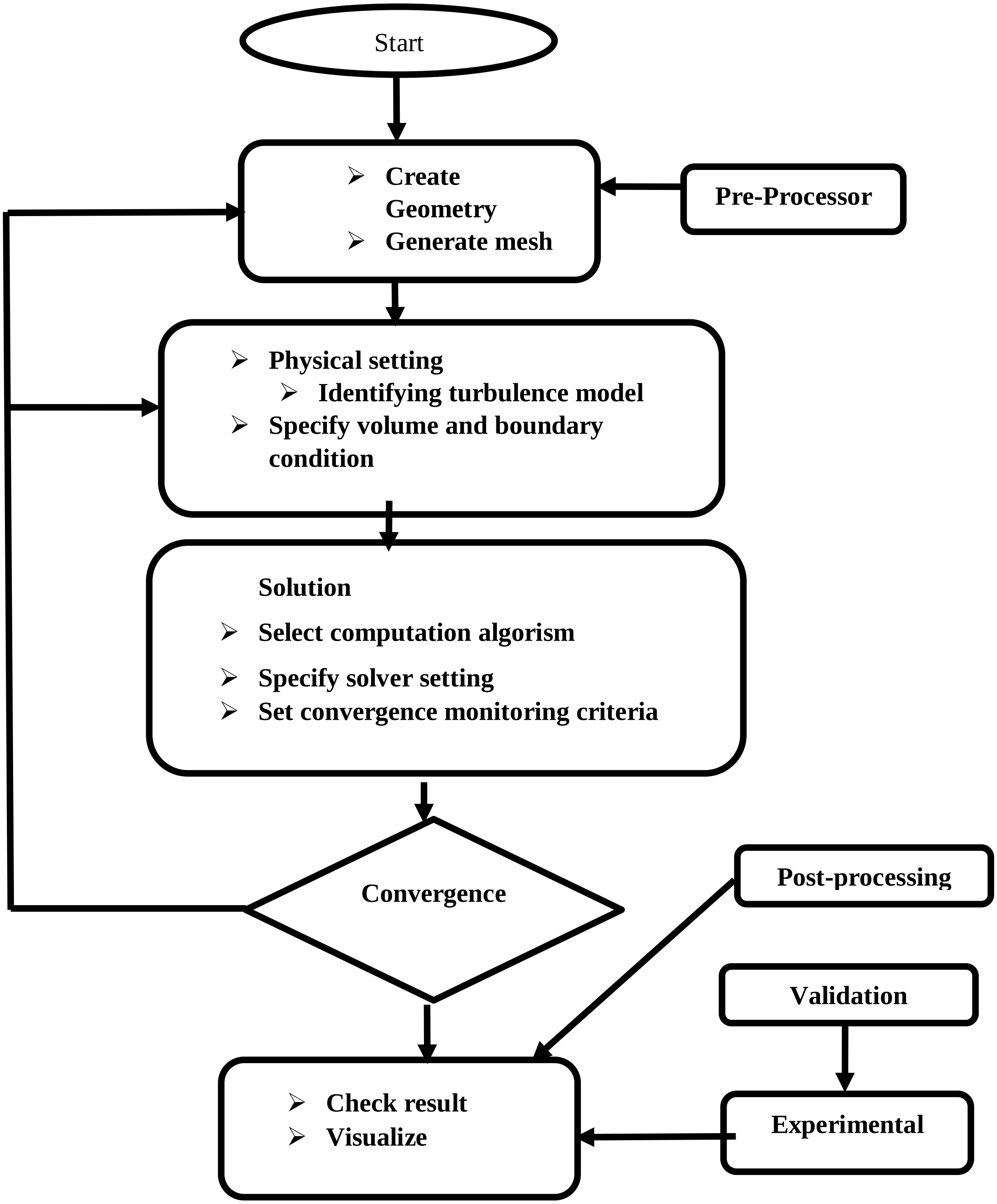


Figure 6.1. Algorithm of the solution in the form of flow chart

CHAPTER SEVEN

7. RESULT AND DISCUSSION

This chapter presents the results obtained from the experimental analysis using four performance parameters which are applicable to efficient cookstove design: time-to-boil, specific fuel consumption, thermal efficiency and fire power. The first section presents the results of experimental investigations made on each cooking stoves. Time-to-boil was found to be extremely important parameter to define the performance of cooing stove; users not like to use a stove that lengthens usual cooking time. Specific fuel consumption indicates if fuel savings occur, which is important to both the users and environmental agencies. Thermal efficiencies is relevant to stove designers, while the emissions data provides information on the release of pollutants to the environment, important information for funding and public health agencies, governments, and policy makers. The next section presents the numerical investigation of all cooking stoves using ANSYS software: temperature, velocity, CO_2 mass fraction, volatile matter and oxygen mass fraction are also presented and discussed.

7.1. Performance of the Conventional Cook Stoves

7.1.1. Time-To-Boil

It can be seen from Figure 7.1 that for the cold start phase, Obama, Ethio and modified stoves boil water in 26, 31 and 27 minutes, respectively, which is faster than any other stove on average. Other stoves such as Hexagon, Bandira and Turumbe take longer to boil 44, 46 and 68 minutes, respectively. This slowest stove has no space between the stove and the pot, the space allows air to blow across the surface of the stove, and indicating that the convective heat transfer is reduced and these stoves performed fairly similarly to one another.

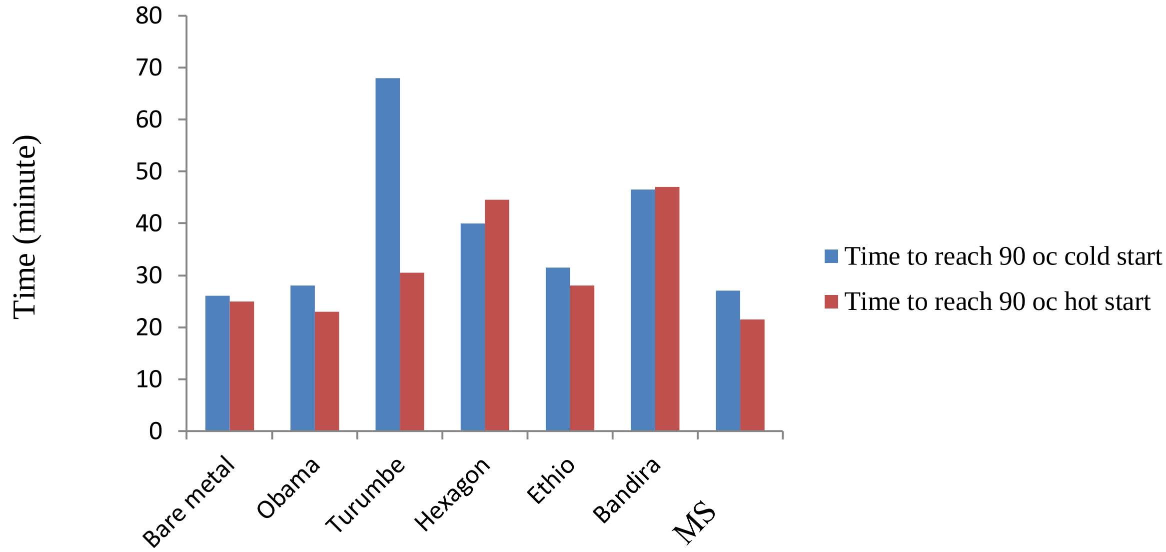


Figure 7.1: Time to Boil 2.5 kg of Water of Conventional and modified Stoves

The gap between stove and pot of the modified was 1.7 cm which was showed on analytical analysis of the modified stove on the above chapter. Table 7.1 showed the gap of the conventional stoves and the relation between time to boil, efficiency, SFC and fire power. The amount of time required for cooking is very important to the end user and can save time wasted in cooking. During the hot start phase, the modified stove also has the fastest boiling time; however, Obama and Ethio are only slightly slower than the modified stove. A trend can be noticed in the average times-to-boil for the cold and hot start phases due to the differences in the thermal masses of the stoves. During a hot start, the Obama and Ethio stoves, which are insulated and retain heat, are comparable in time-to-boil with the traditional stove, while during the cold start they take a longer time.

Table 7.1: Stove-Pot Gap Relation between Time to Boil, Efficiency, SFC and Fire Power.

Cooking stoves	Number of hole	Efficiency (%)		Time to boil(min)		SFC($\frac{g}{min}$)		Fire power (kW)	
		CS	HS	CS	HS	CS	HS	CS	HS
Bare metal	5 line cuts	16	17	26	25	43	38	2260	2780
Modified stove	14	28	30	27	21.5	36	34	1885	2205
Obama	16	22.6	24.5	28	23	43	38	2583	2267
Ethio	12	22.6	24.5	31.5	28	44	41	1867	1961
Hexagon	12	23	24. 5	40	44.5	43	40	1308	1222
Bandura	10	25.5	27.5	46.5	47	39	26	1166	1004
Turumbe	8	27.8	31	68	30.5	35	31	712	1480

7.2. Fire Power (FP)

The power of the stoves varied between 2.66 kW (Bare metal) and 0.712 kW (Turumbe) for the cold start phase, and among 2.78 kW (bare metal) and 1 kW (Bandira) for the hot start. While the firepower in the cold start phases of modified stove was1.85 kW which was similar with Ethio cooking stove but for hot start phase the modified stove showed 2.2kW which is almost equal with Obama cooking stove.

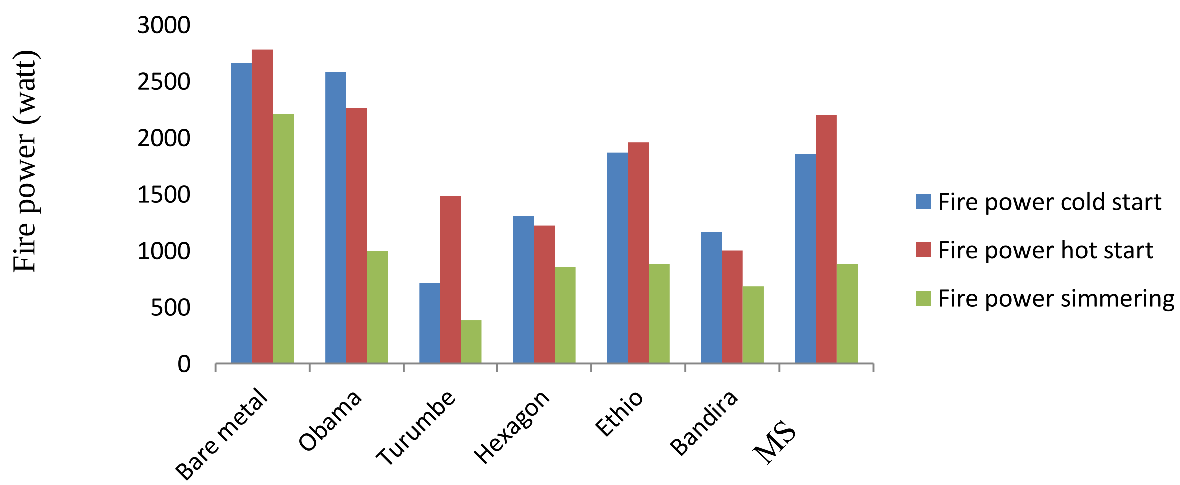


Figure 7.2: Fire Power of Conventional and modified Stoves

7.2.1. Thermal Efficiency

The average thermal efficiency results for the five conventional stoves and the modified stove were better than that of the traditional bare metal stove (Figure 7.3).The modified stove cold start efficient was larger from all stoves. Obama (22.6% or Tier 2), Ethio (22.2% or Tier 2) and Bandira (25.47% or Tier 2) were the efficient and the modified (28% or Tier 2) and Turumbe (27.8% or Tier 2) were the most efficient. The bare metal, demonstrated much lower efficiencies (16% or Tier 1) in the high-power cold start and somewhat lower efficiencies in the high-power hot start (17% or Tier 1) compared to the low-power phases (31%)or Tier 2. The higher thermal efficiencies are achieved by combining smaller fires with small channel gaps around the pot, as forcing the hot gases to flow in narrow channels close to the bottom and sides of the pot increases the convective heat transfer. The thermal efficiency of the new modified stove increased because of the grate and the ash tray is made from sheet metal and aluminum, respectively. This facilitates high convective heat transfer coefficient and sheet metal does not store and absorb vast amount of heat in its body like ceramic stoves. Aluminum foil in ash tray is used to reflect radiant heat back to the combustion chamber. For a household size stove, firepower of 2 kW or less optimizes thermal efficiency when combined with a channel length of 20 cm and a gap of 6 mm (Baldwin 1987). Although the firepower is low, the higher thermal efficiencies heat the pot more efficiently.

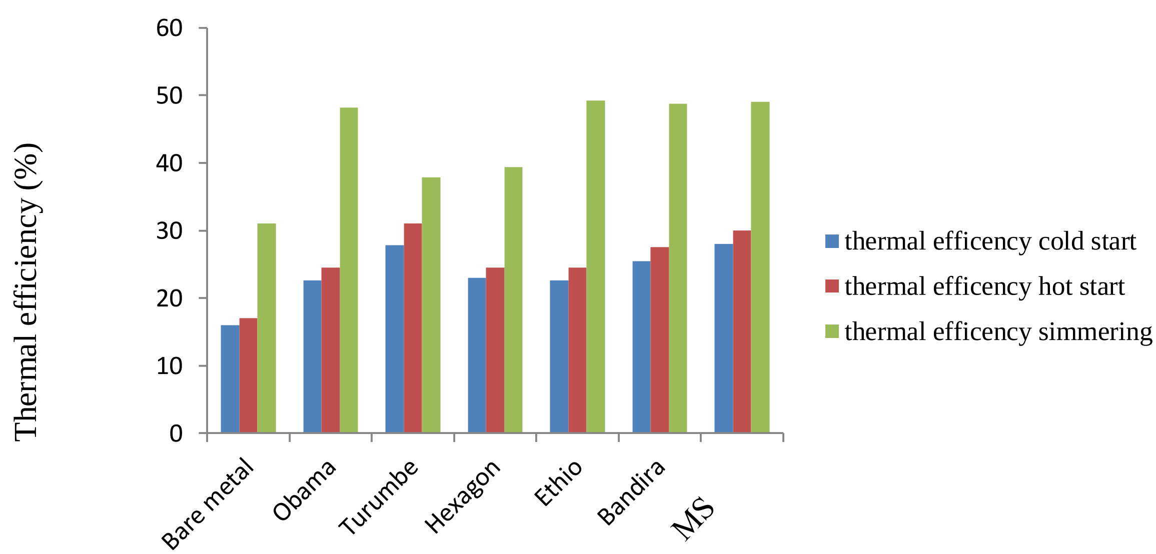


Figure 7.3: Average thermal efficiency of conventional and modified stoves

Efficiency results from this experimental test are almost closer to those of other researches on charcoal cooking stove, for which thermal efficiency values of stoves in Ghana, the thermal efficiency of Gyapa and Ahinbenso charcoal stoves are 23% and 31.3 %, respectively (Grimsby et al., 2016)and in Tanzania traditional charcoal stove and Jiko Bora charcoal stove have a thermal efficiency of 21% and 24%, respectively have reported(Boafo-Mensah et al., 2013).

7.2.2. Specific Fuel Consumption (SFC)

Study of specific fuel consumption is the main step in quantifying the difference between cooking stoves. Figure 7.4 showed that in all the three-phase bare metal cooking stove has larger specific fuel consumption. On the other hand, turumbe showed the least fuel consumption in all the three phases. The bare metal in appropriate fuel consumption was due to heat release through the side wall and some part of the top surface is open to the surrounding.

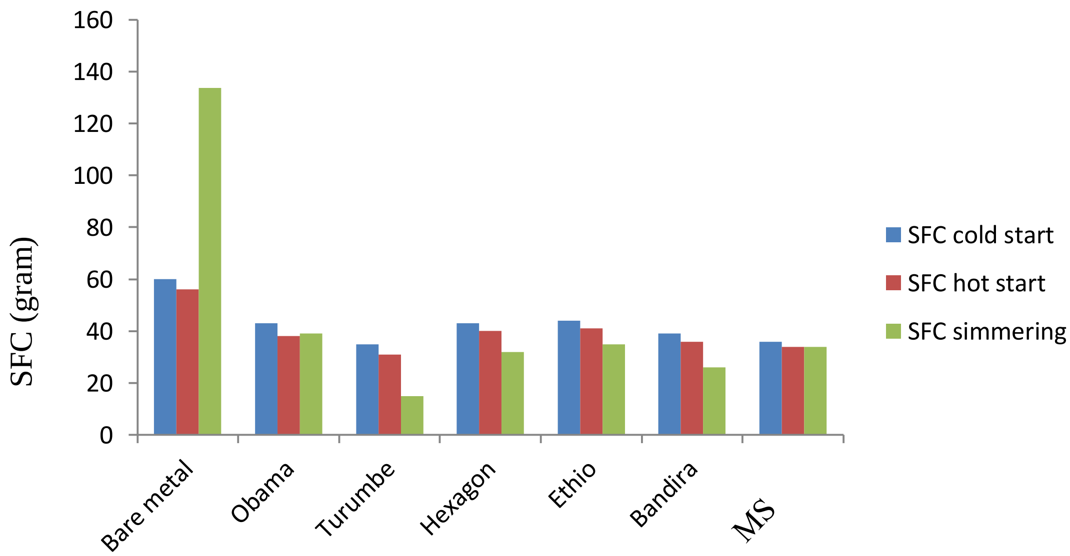


Figure 7.4: Specific Fuel Consumption

In the low-power phase, however, specific fuel consumption was much greater for all cook stoves compared each other this is due to all the stove start operation from ambient temperature. The modified stove SFC is almost the same for all the three phases this is due to the combustion chamber was made of sheet metal which improves the convective heat transfer. The specific fuel consumption of the new modified charcoal stove shows 66.7% improvement compared to the traditional charcoal stove.

7.3. Numerical Analysis of Cooking Stoves

The reports of a numerical simulation of the six cooking stoves and modified stove are described in this section. To investigate the heat transfer and fluid flow characteristics in the domain of stoves the results of the analysis in FLUENT can be shown by using graphical displays and numerical outputs.

7.3.1. Temperature Contours

It can be observed the heat energy exiting the flue gases outlet and transferred to the bottom of the pot is uniformly distributed. The heat output of Obama and Ethio cooking stove had better from other all cooking stoves. The same result also obtained from numerical value of the simulation below showed on Figure 7.5. The least temperature distribution and numerical value was seen on turumbe cooking stove.

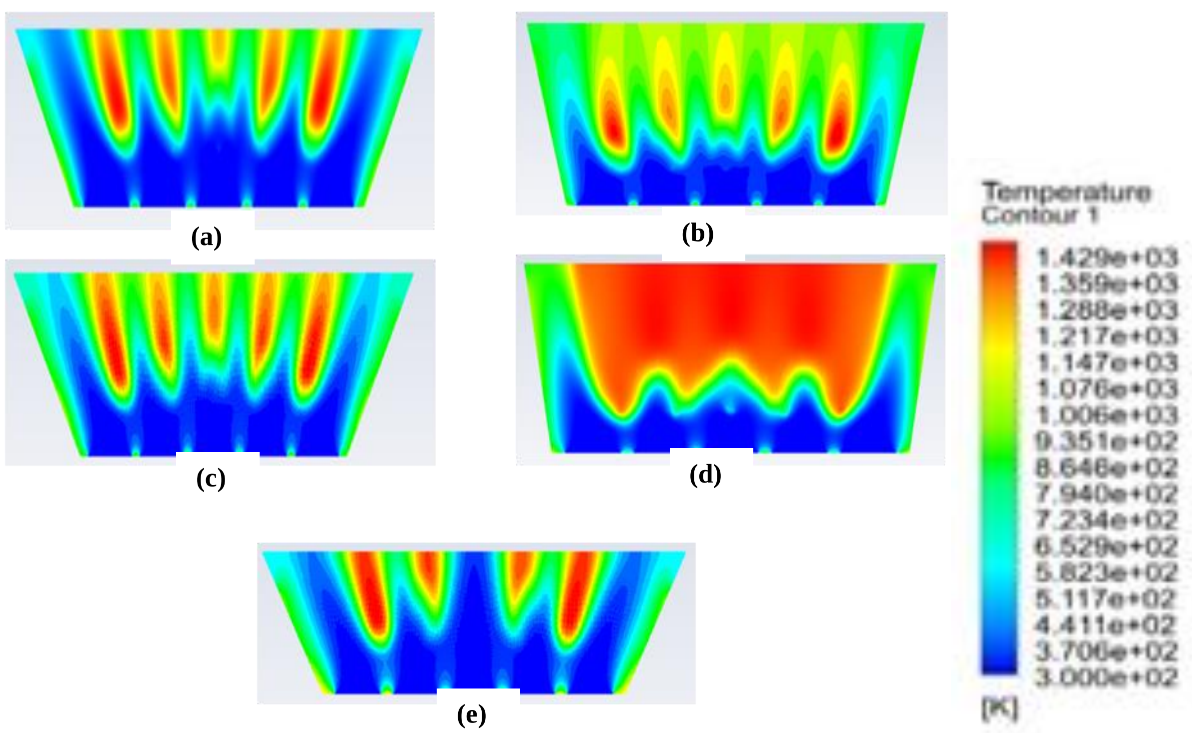


Figure7.5: Temperature Contours (a) Bandura (b) Ethio (c) Hexagon (d) Obama (e) Turumbe

(a)

Area-Weighted Average Total Temperature	(k)
air_inlet	306.83506
bottom_wall	1054.6292
interior-surface_body	790.58138
outlet	1096.7054
side_wall	1056.1897
surface_body	812.03477
Net	791.7194

(b)

Area-Weighted Average Total Temperature	(k)
air_inlet	305.32705
bottom_wall	937.90807
interior-surface_body	861.06039
outlet	1090.9647
side_wall	958.21878
surface_body	881.35336
Net	860.99041

(c)

Area-Weighted Average Total Temperature	(k)
air_inlet	305.13345
interior-surface_body	812.07359
outlet	1079.085
surface_body	838.51691
wall	1012.055
Net	813.22976

(d)

Area-Weighted Average Total Temperature	(k)
air_inlet	301.16199
bottom_wall	437.13009
interior-surface_body	464.35537
outlet	575.5244
side_wall	480.86509
surface_body	491.43574
Net	464.44698

(e)

Area-Weighted Average Total Temperature	(k)
air_inlet	308.05663
bottom_wall	1138.362
interior-surface_body	764.94181
outlet	1009.3073
side_wall	1043.84
surface_body	743.51659
Net	766.75175

Figure 7.6: Net Total Temperature (a) Bandura (b) Ethio (c) Hexagon (d) Obama (e)Turumbe

In case Obama cooking stove, which has 16 air inlets holes at the bottom of the combustion chamber have a significant impact in terms of feeding the extra streams of air/oxygen into the chamber. In contrast Turumbe cooking stove has only 8 air inlet holes which do not contributing sufficient air supply to the increased combustion and thus increased heat energy generated.

7.3.2. Velocity Contour

The outcome of the velocity magnitude shows that it is less near the walls and zero at the wall boundaries. The wall is not moving and there is no slip condition. There is high velocity at the entrance of the great holes and gradual decreases along the height of the combustion chamber. There exists a zero-velocity region in the combustion chamber. This to the blocked region where there is limited fluid flow. Figure 7.7 shows the simulated velocity fields due to combustion in all stoves. As expected, Obama and Ethio cook stove increased high velocity zones. It is thus estimated that increased velocity in the cook stove will have well-known impact on emission limits and performance of the cook stove.

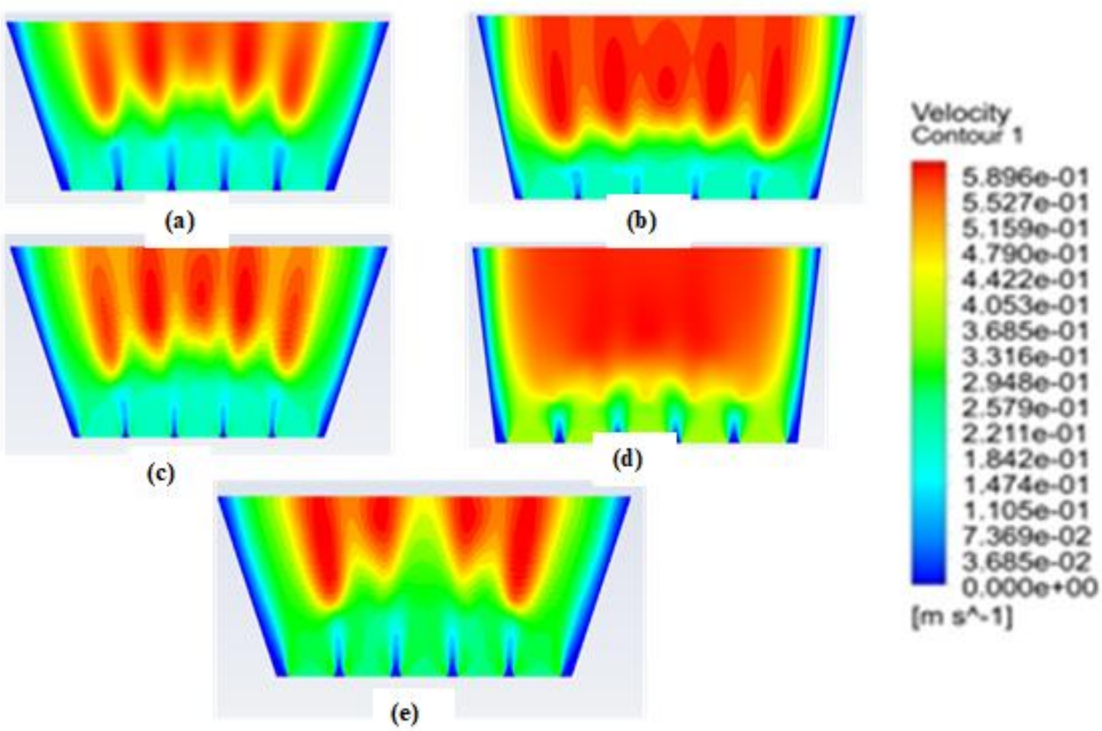


Figure 7.7: Velocity Fields (A) Bandura (B) Ethio (C) Hexagon (D) Obama (E) Turumbe

(a)

Area-Weighted Average Velocity Magnitude	(m/s)
air_inlet	0.050000001
bottom_wall	0
interior-surface_body	0.077696759
outlet	0.10878063
side_wall	0
surface_body	0.083789921
Net	0.077487534

(b)

Area-Weighted Average Velocity Magnitude	(m/s)
air_inlet	0.049999996
bottom_wall	0
interior-surface_body	0.10271514
outlet	0.12657973
side_wall	0
surface_body	0.10671128
Net	0.10234335

(c)

Area-Weighted Average Velocity Magnitude	(m/s)
air_inlet	0.049999996
interior-surface_body	0.076441368
outlet	0.10729779
surface_body	0.089386894
wall	0
Net	0.07609364

(d)

Area-Weighted Average Velocity Magnitude	(m/s)
air_inlet	0.05
bottom_wall	0
interior-surface_body	0.051089569
outlet	0.067053827
side_wall	0
surface_body	0.059582801
Net	0.050817541

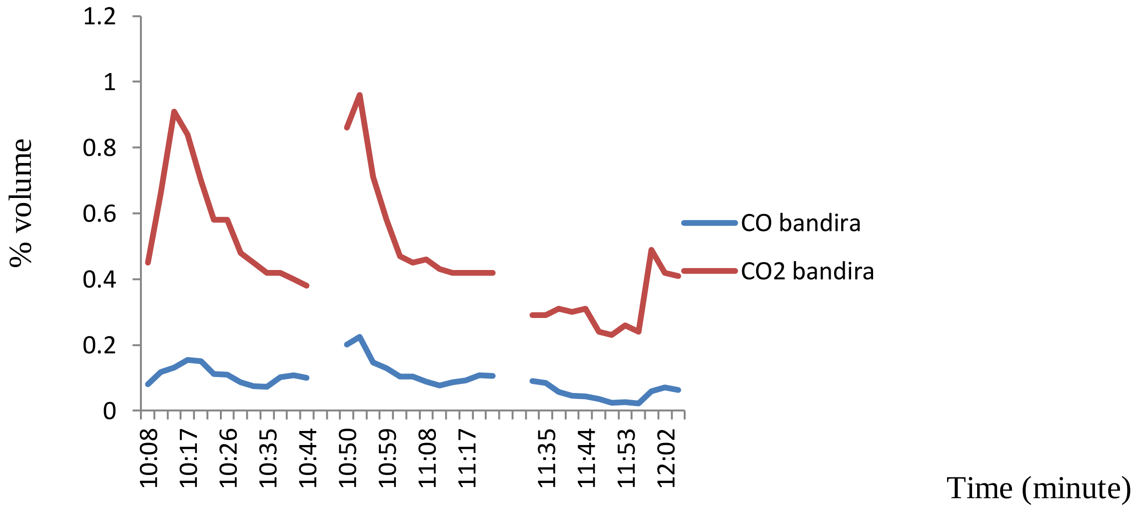
(f)

Area-Weighted Average Velocity Magnitude	(m/s)
air_inlet	0.05
bottom_wall	0
interior-surface_body	0.061735497
outlet	0.090162382
side_wall	0
surface_body	0.070089515
Net	0.06154509

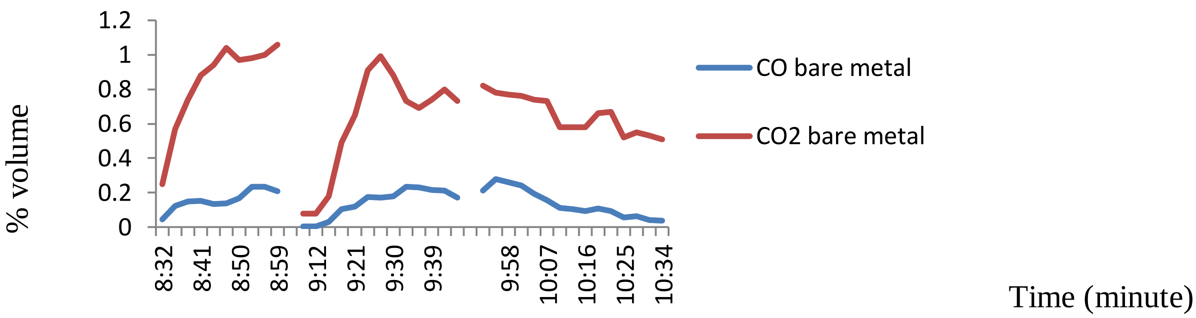
Figure 7.8:Net Total Velocity(a) Bandura (b) Ethio (c) Hexagon (d) Obama (e)Turumbe

7.3.4. CO_2 Mass Fraction

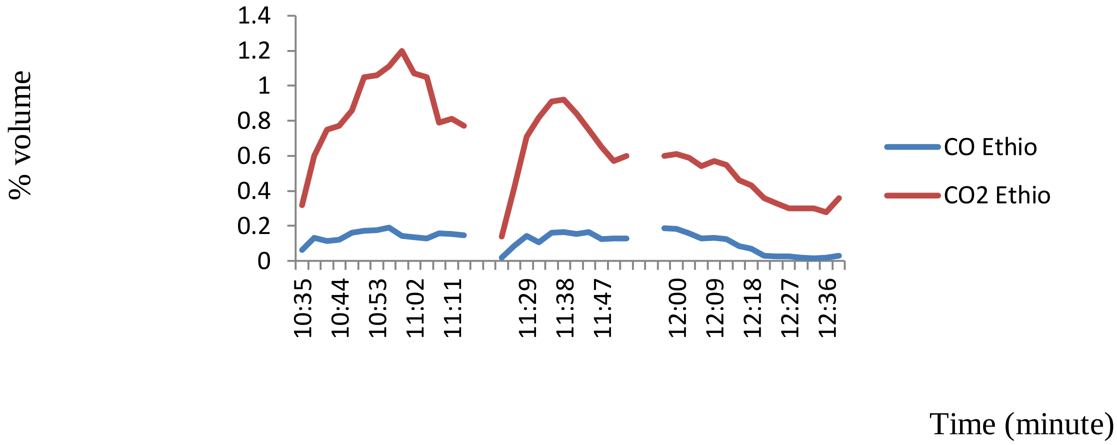
Experimental emission result list on the Figure 7.9, for cold and hot start phase Obama showed the largest CO_2 emission 1.25 and 1.02 %vol, respectively and the least was 0.91%vol for Bandira cooking stove for cold start and 0.81%vol for Hexagon for hot start. The CO emission for both phases bare metal showed the largest value 0.236 and 0.233 %vol, respectively. The least value measured was 0.15% vol for modified for cold start and 0.125% vol for ethio cooking stove for hot start phase.



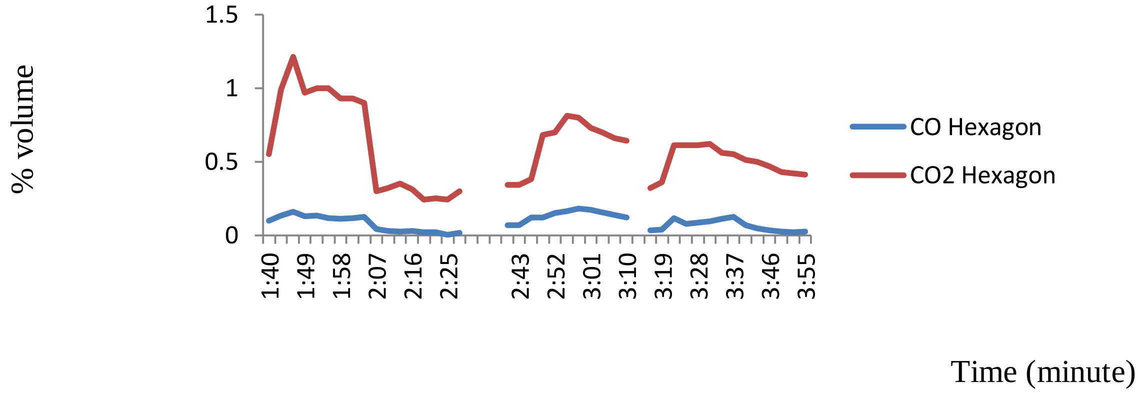
(a)



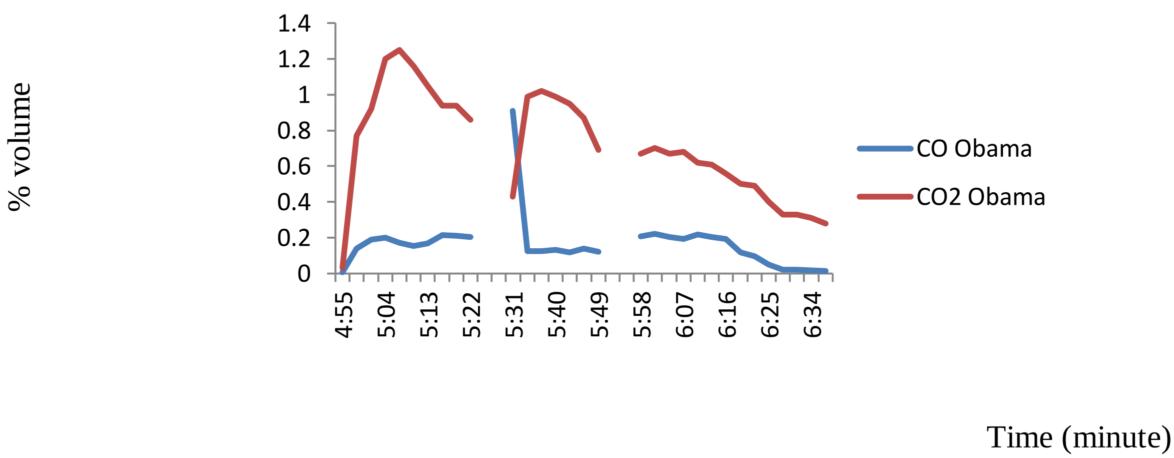
(b)


% volume
CO Ethio
CO2 Ethio
Time (minute)

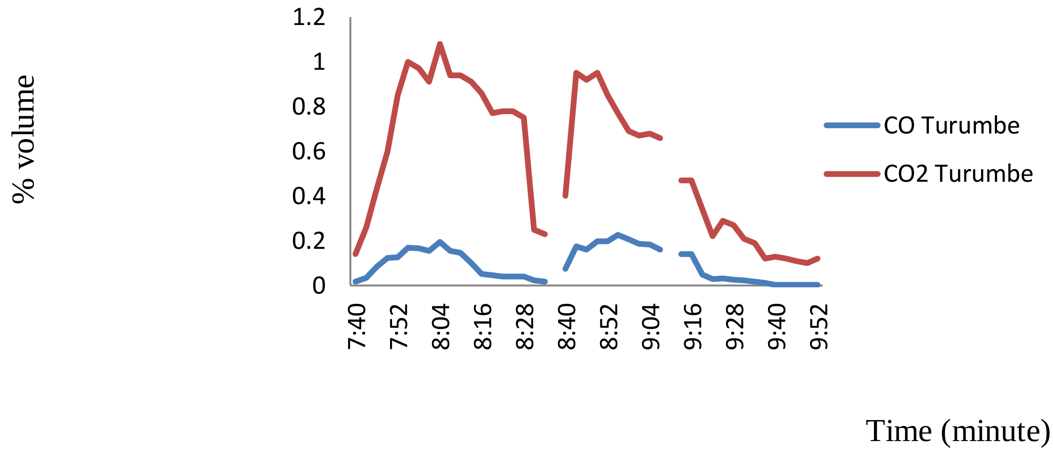
(c)


% volume
CO Hexagon
CO2 Hexagon
Time (minute)

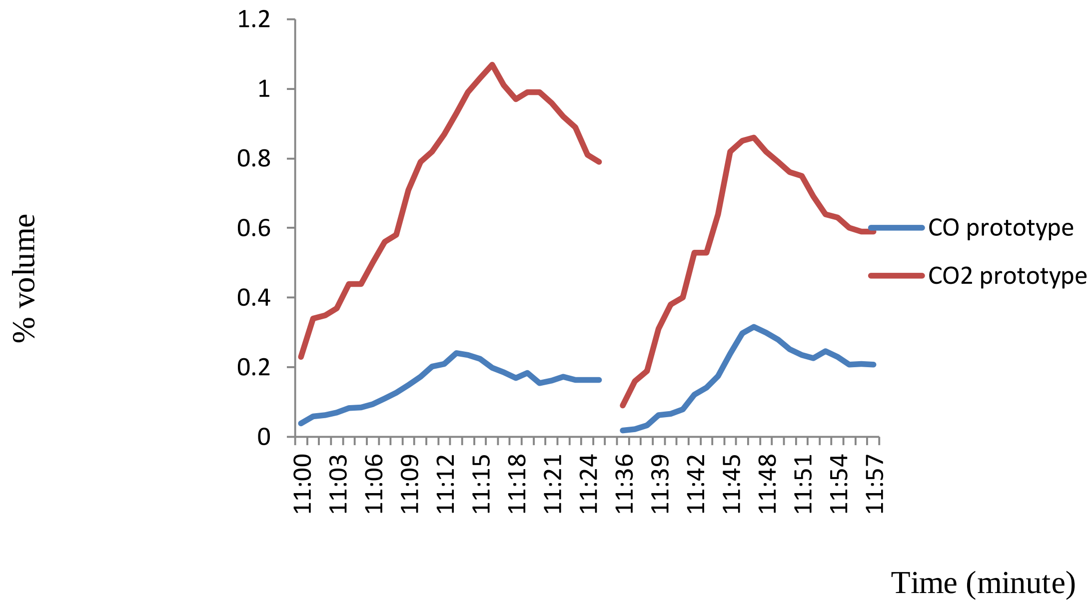
(d)


% volume
CO Obama
CO2 Obama
Time (minute)

(e)



(f)



(g)

Figure 7.9: Emission of CO and CO_2 of Conventional Stoves and modified Stove

7.4. Modified Stove Design

For the improved stove design, the same solid fuels were used for test. The charcoal fuel was taken based on local availability within Ethiopia. The maximum amount of heat required to boil 2500 gram of water is calculated by using equation 7.1.

$$Q = mc_p\Delta T \quad (7.1)$$

Where:

m - Mass of water (2500 gram)

c_p- Specific heat capacity of water (4.186 $\frac{J}{g.K}$)

ΔT – Change in temperature (boiling temperature minus ambient temperature)

The total heat of $Q = 707{,}434$ J energy was used to water to raise the temperature to 90^0c. The designed cooking stove was needed to transmit 707,434 J of energy to a pan to boil 2500g of water from ambient temperature (297.54 K) to 365.14 K (as per EPTP standard) given its specific heat capacity of 4.186 $\frac{J}{g.K}$ .At 100% efficiency whereby all the fuel is transferred to the water, the fuel required was 23.73 g.

The fuel consumed by the stove was 90 gram, so the efficiency becomes the ratio of mass consumed for 100% to 88 grams multiplied by 100.for 27% of efficiency the required fuel was88 gram.

The new feature of this modified cooking stove is the entering air was preheated and the temperature increased continually from cold start phase to high start phase as showed on Figure 7.10.

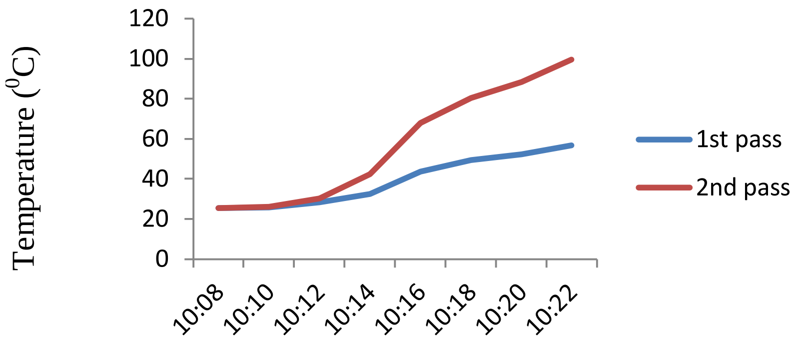
For heating processes, one of the most potent ways to improve efficiency and productivity is to preheat the combustion air going to the chamber. The source of this heat energy is the heat lost through the side wall of the cooking stove. By allowing the air two passes before entering to the chamber through the side, can extract a large portion of the thermal energy which will be lost and transfer it to the incoming combustion air. Recycling heat this way will reduce the amount of the purchased fuel needed.

Industrial Heating Equipment Association (IHEA) Combustion Technology Manual showed that the preheating of air before entering to the furnace and Fuel (for natural gas) savings for different furnace exhaust gas temperature and preheated combustion air temperatures can be found in the table below and can be used to estimate reductions in energy costs.

Table 7.2: Percent Fuel Savings Gained from Using Preheated Combustion Air before Entering to Engine (source: IHEA Combustion Technology Manual)

Furnace Exhaust Temperature, °F	**Preheated Air Temperature, °F**					
	600	**800**	**1,000**	**1,200**	**1,400**	**1,600**
1,000	13	18	-	-	-	-
1,200	14	19	23	-	-	-
1,400	15	20	24	28	-	-
1,600	17	22	26	30	34	-
1,800	18	24	28	33	37	40
2,000	20	26	31	35	39	43
2,200	23	29	34	39	43	47
2,400	26	32	38	43	47	51

The preheating of combustion air which enters to the modified stove temperature increment showed on Figure 7.10.Maximum temperature measured for cold start phase was in the first pass 56.7 ^{0}C and for second pass 99.6 ^{0}C was measured. For hot start phase the maximum temperature measured was 91.6 ^{0}C for first pass and186.2^{0}C for second pass. For cold start phase the minimum temperature was equal to the ambient temperature of the day where measurement was taken and the first and the second passes have the same value and for hot start phase the first pass measured 45.1 and 68.9^{0}C.the time interval between the two phases lead the temperature difference between the maximum temperature of the cold start and the initial temperature of the hot start.



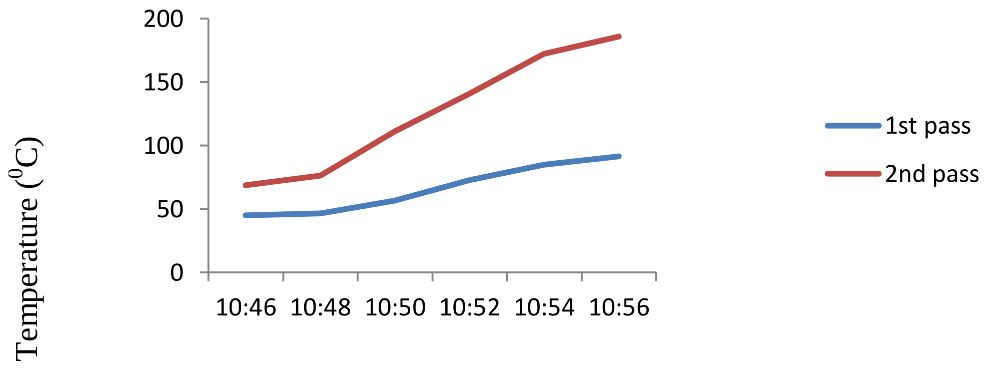


Figure 7.10: Preheating of Combustion Air Which Enters to the modified Stove (a) cold start (b) Hot start

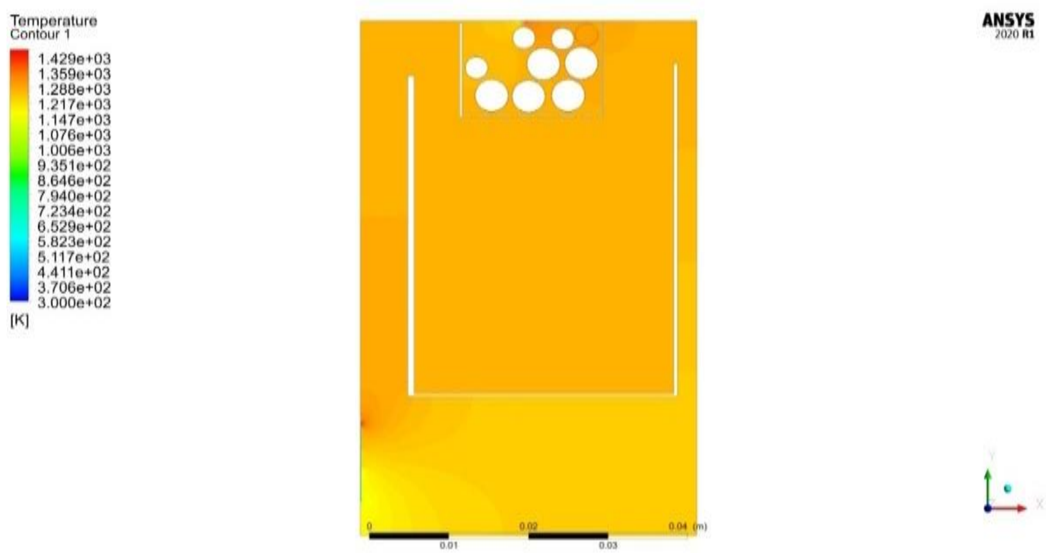


Figure 7.11: Temperature Contour of modified Stove

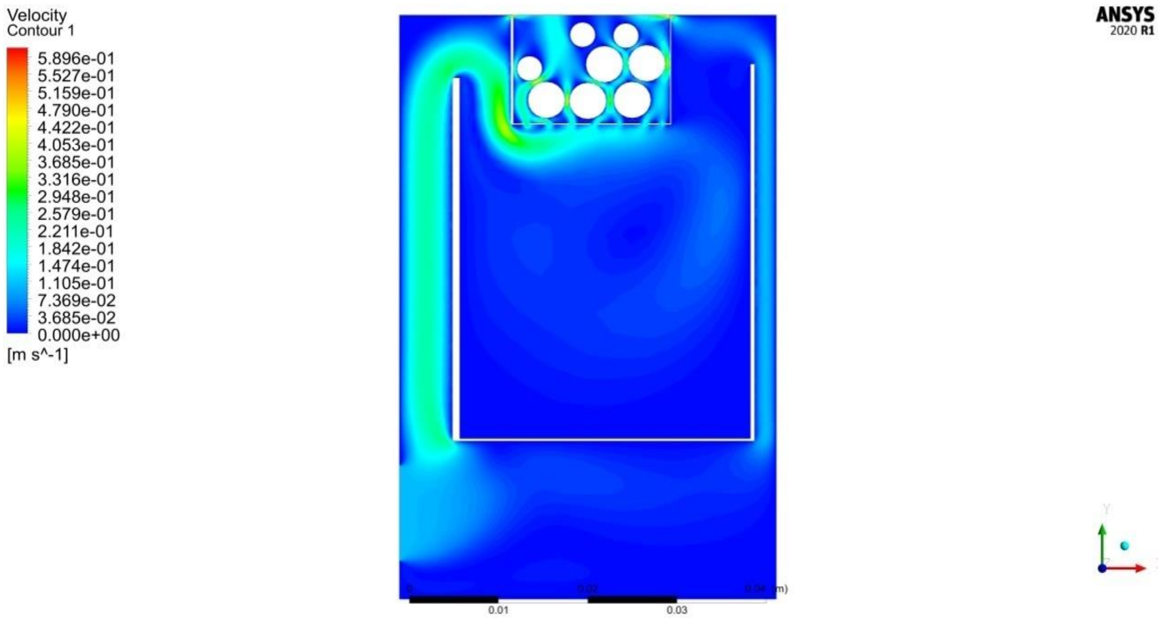


Figure 7.12 : Velocity Contour of modified Stove

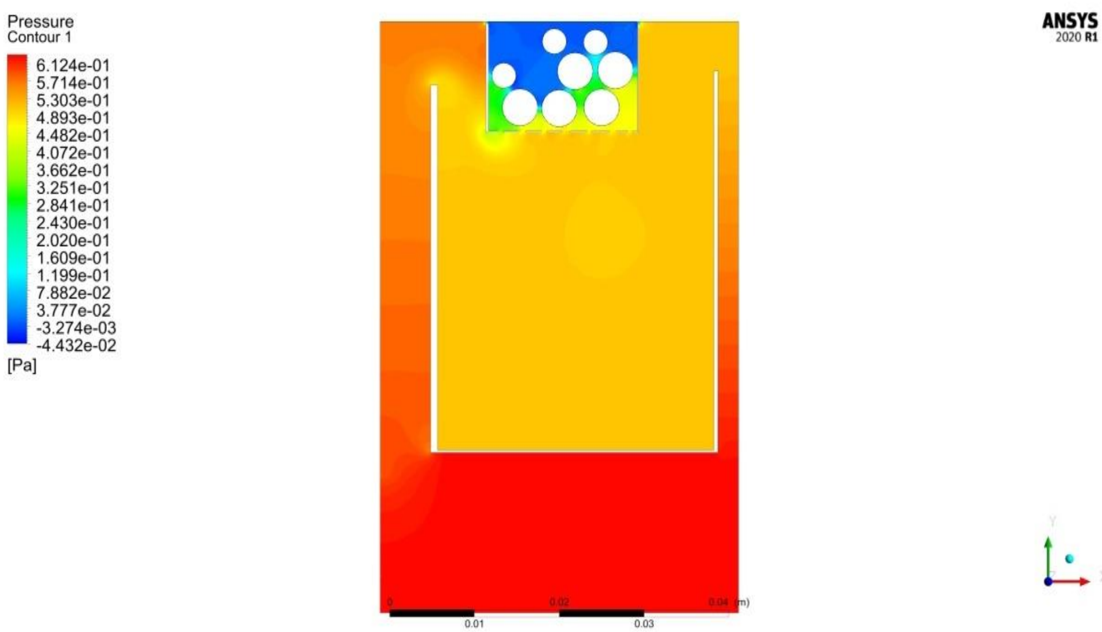


Figure 7.13: Pressure Contour of modified Stove

7.5 Insulating Clay

Fired clay bricks are the most well-known type of brick and one of the oldest building materials. Bricks, in addition to being a popular building material used in walls, can also be used in furnace lining. The performance of the brick is determined by the raw chemical compositions, method of production, firing technique, and firing temperature. The primary objective of firing is to increase the durability gaining process of the clay brick, which is accomplished through sintering. Sintering is the bond formation process of clay mineral, and it can only be achieved under the action of heat.

7.5.1. Dimensional Change after Sintering

The dimensions are re measured following firing at the same firing temperature, and the percentage change is calculated. For linear changes, the result is expressed as follows:

$$\Delta L = \frac{L_i - L_f}{L_i} * 100\%$$

Where

Li = initial length

Lf = final length

Increase of firing temperature causes an increase in total linear shrinkage of brick samples. With increasing temperature, alkali oxides in the clay causes an increase in melted phase products in the structure, so more shrinkage occurs. The firing temperature of this study was 1000 ^{0}c and the dimensional change is showed on table 7.3. Increase of firing temperature increases the verification in the structure, so increases the shrinkage values as well. So, the values obtained from samples with less clay are lower than values obtained from higher clay amount.

Table 7. 3: Dimension Change of Molded Clay-Silica Mixture Before and After Firing

Mixing Ratio	Length		Width		Thickness	
	L_1	L_2	W_1	W_2	T_1	T_2
50%	11 Cm	9.7 Cm	5.5 Cm	5 Cm	0.8 Cm	0.7 Cm
60%	11 Cm	9.8 Cm	5.5 Cm	4.8 Cm	1.4 Cm	1 Cm
70%	11 Cm	9 Cm	5.5 Cm	4.5 Cm	1.2 Cm	0.9 Cm
80%	11 Cm	9 Cm	5.5 Cm	4.3 Cm	1 Cm	1 Cm
90%	11 Cm	9.3 Cm	5.5 Cm	4.4 Cm	1.2 Cm	0.9 Cm

7.5.2. Thermal Conductivity

According to the thermal conductivity coefficient of samples, it was seen that conductivity values of all brick samples increase from 50% to 80% and radically decreased above 80% of clay amount. The highest thermal conductivity value was obtained as 1.548 W/m K for 90% clay which was fired at 1000 ^{0}C and the lowest thermal conductivity values were obtained 0.3998 W/m K from 50% clay composition, the instrumental result showed on Appendix I. bricks with 50% silica have the best insulating property and this brick have the lowest thermal conductivity.

It was mentioned that thermal conductivity coefficients were related to unit weight and porosity in bricks. For this reason, it is thought that when porosity in the structure increases, thermal conductivity coefficient will decrease. Also, a decrease in unit weight is expected with increased porosity.

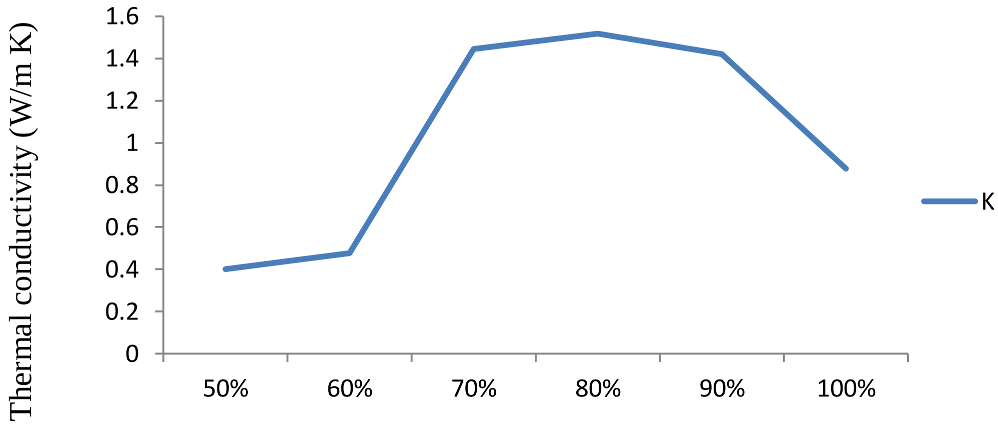


Figure7.14: Thermal Conductivity of Clay Mix with Silica with Different Ratio

CHAPTER EIGHT

8. CONCLUSIONS AND RECOMMENDATIONS

8.1. Conclusions

The study conducted an experimental study of six locally available cooking stoves and a newly constructed modified stove. Almost all traditional ovens have the same operating mechanism, but different shapes. The modified cook stove has an air preheating path that increases radiant heat transfer by reducing the depth of the chamber according to calculated values. The temperature at the point of entering the chamber reached about 180 ° C. The main challenges in conducting experimental testing of the oven were uncertainty due to fuel shape, manual measurement of emissions, and air flow to the chamber. The main goal of this thesis was to develop an efficient, low-emission stove. The following conclusions are drawn from this study:

- Cooking time is important in cooking mode. Some traditional ovens take a long time to boil a certain amount of water (in this study Turumbe, Bandura, and Hexagon take about 40 minutes or more). This makes the user feel uncomfortable.
- Examining the results of the stoves, including the modified, reveals the value of comparing performance and emissions based on cooking tasks simulated in the three test phases of the WBT protocol.
- The thermal efficiency and the time to boil of the new designed cooking stove is increased the radiation heat transfer to the pot, this achieved by reducing he depth of the chamber.
- Pre-heating the air entering to the chamber reduces heat loss and maintained the combustion temperature.
- The thermal conductivity of clay was reduced by adding silica powder and which increases the refractoriness.

8.2. Recommendations

According to the observation made during this thesis, the following recommendations can be reached that can be conducted for the better prediction of the thermal performance of the stove.

- Air allowed to flow was preheated by passing on a smooth surface. The flow channel allows the fins to raise the temperature of the air before entering the chamber.

- The thermal conductivity of the insulating material is low, which is 0.5 W/m K, and the air flowing as the heat insulating material reduces heat loss to the environment. It is advisable to use a thermoelectric generator to reduce some of the remaining heat loss. This is useful for mobile charging and lighting purposes in rural areas.

- The lowest thermal conductivity obtained was a ratio of 50%: 50% of silica powder to raw clay. As the amount of silica increased, the thermal conductivity decreased. Further research is being done to determine the effects of silicon dioxide used above 50%.

- This thesis work covers mainly the experimental for all stoves and analytical study for the modified stove. It is recommended to determine the efficiency of the stove using boiler performance test indirect method. The indirect method is showed in appendix 5.

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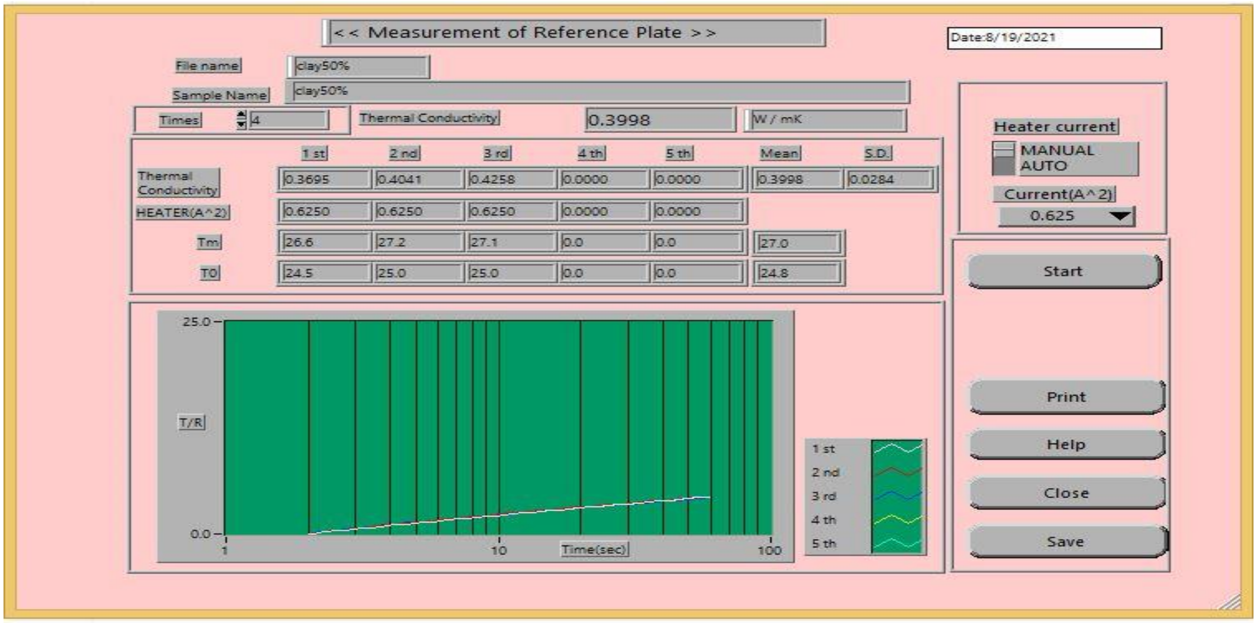
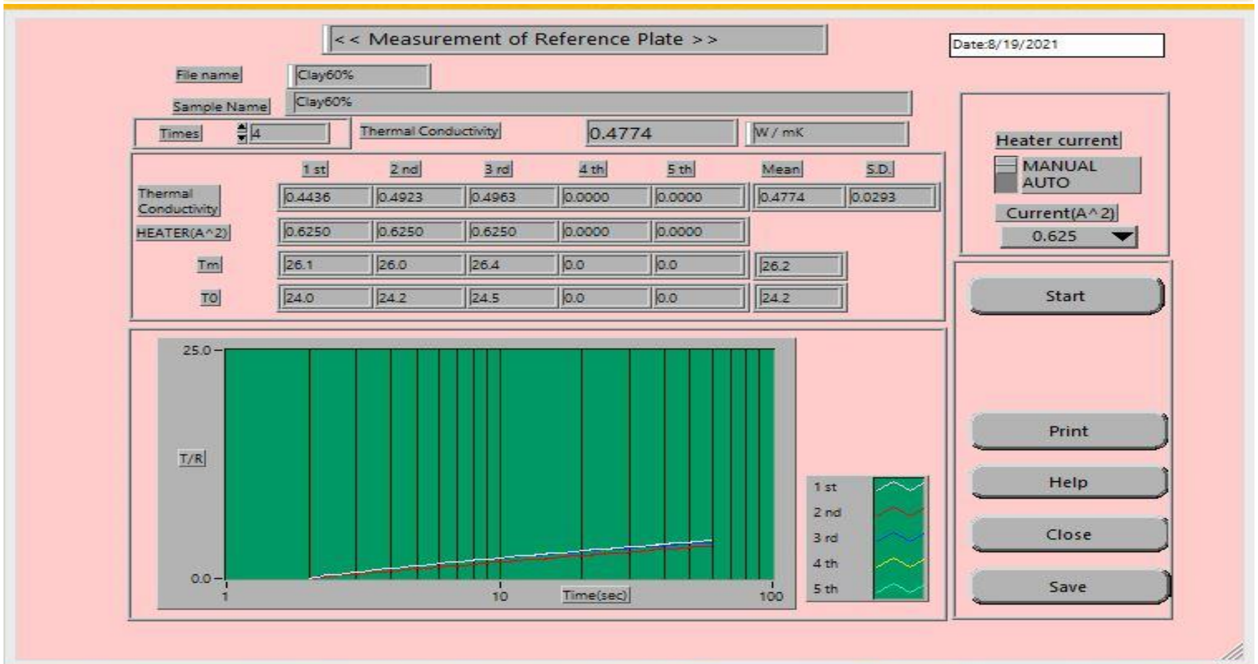
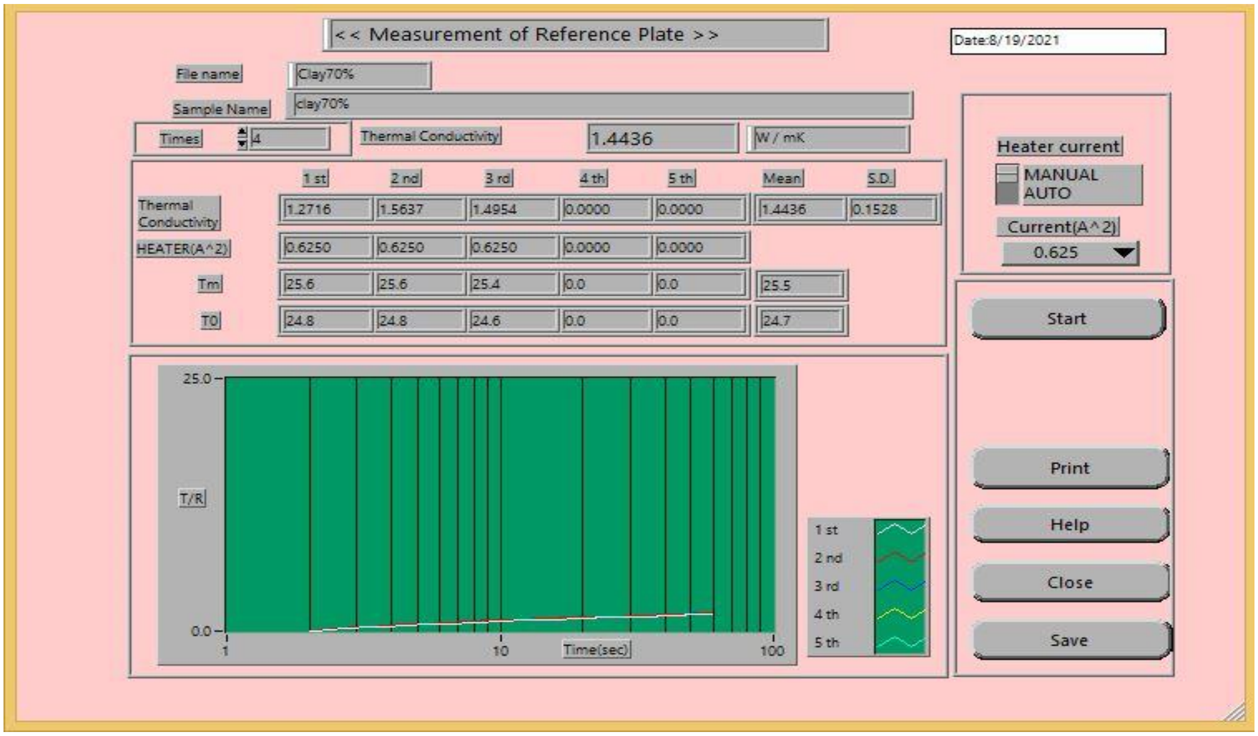
APPENDIX

Appendix 1: QTM-500 Thermal Conductivity of RC-AMWS







<< Measurement of Reference Plate >>
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File name
Clay70%
Sample Name
clay70%
Times
4
Thermal Conductivity
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W / mK
1 st
2 nd
3 rd
4 th
5 th
Mean
S.D.
Thermal Conductivity
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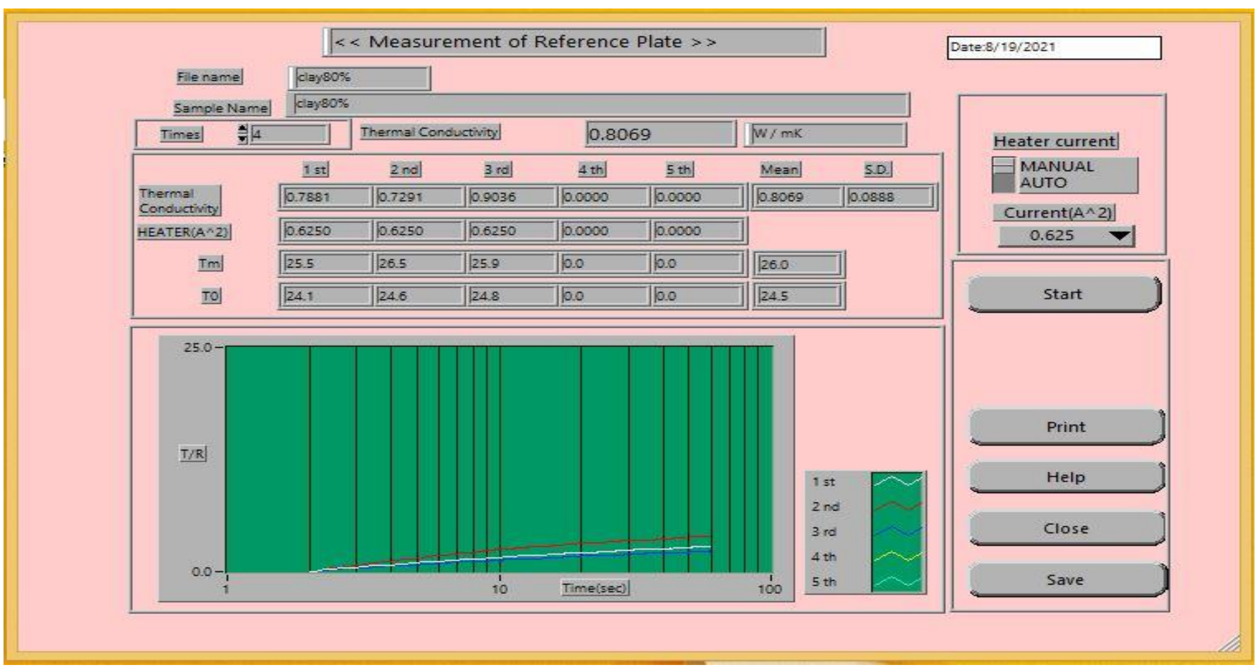
1.5637
1.4954
0.0000
0.0000
1.4436
0.1528
HEATER(A^2)
0.6250
0.6250
0.6250
0.0000
0.0000
Tm
25.6
25.6
25.4
0.0
0.0
25.5
T0
24.8
24.8
24.6
0.0
0.0
24.7
Heater current
MANUAL
AUTO
Current(A^2)
0.625
Start
Print
Help
Close
Save
25.0
T/R
0.0
1
10
Time(sec)
100
1 st
2 nd
3 rd
4 th
5 th



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Sample Name
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W / mK
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2 nd
3 rd
4 th
5 th
Mean
S.D.
Thermal Conductivity
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0.7291
0.9036
0.0000
0.0000
0.8069
0.0888
HEATER(A^2)
0.6250
0.6250
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0.0000
0.0000
Tm
25.5
26.5
25.9
0.0
0.0
26.0
T0
24.1
24.6
24.8
0.0
0.0
24.5
Heater current
MANUAL
AUTO
Current(A^2)
0.625
Start
Print
Help
Close
Save
25.0
T/R
0.0
1
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Time(sec)
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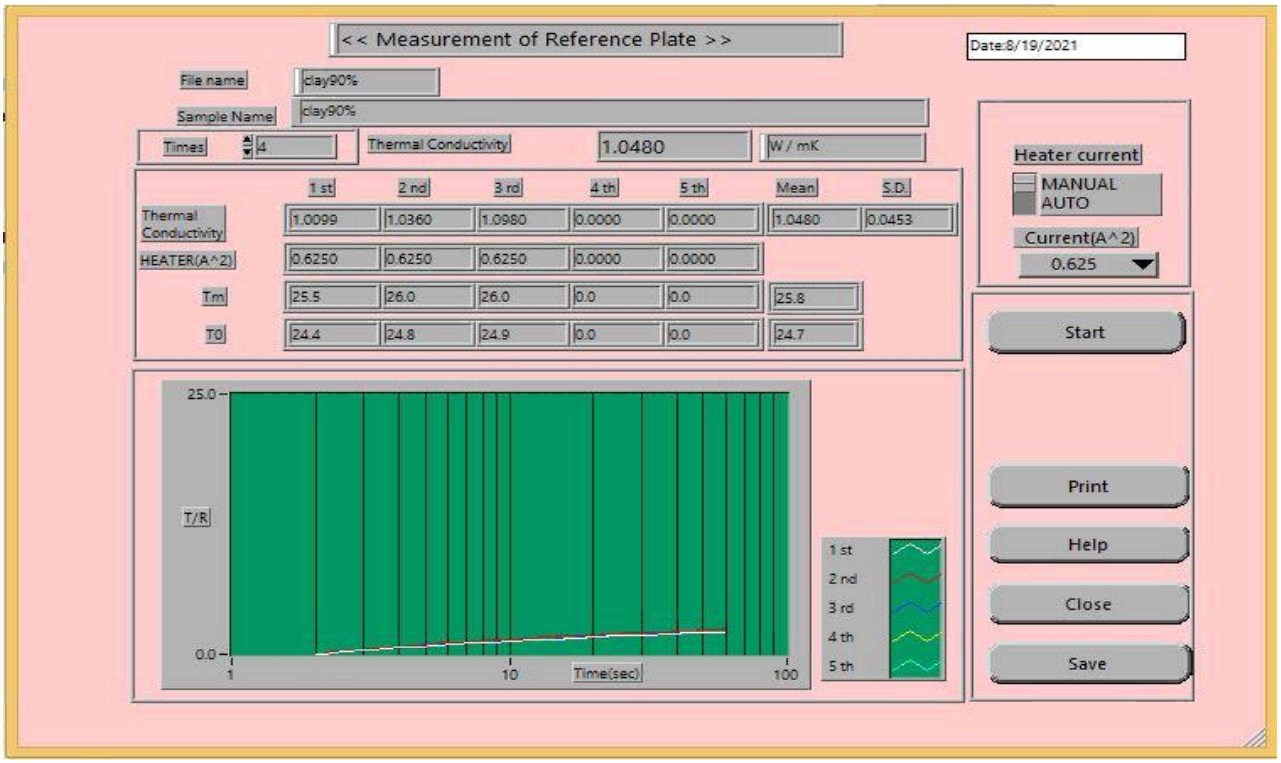
2 nd
3 rd
4 th
5 th



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Sample Name
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MANUAL
AUTO
1 st
2 nd
3 rd
4 th
5 th
Mean
S.D.
Thermal Conductivity
1.0099
1.0360
1.0980
0.0000
0.0000
1.0480
0.0453
Current(A^2)
HEATER(A^2)
0.6250
0.6250
0.6250
0.0000
0.0000
0.625
Tm
25.5
26.0
26.0
0.0
0.0
25.8
T0
24.4
24.8
24.9
0.0
0.0
24.7
Start
25.0
T/R
0.0
1
10
Time(sec)
100
Print
Help
Close
Save

Appendix 2*:* WBT test results

WATER BOILING TEST - VERSION 4.2.3

All cells are linked to data worksheets, no entries are required

Stove type/model	Bandira Cook Stove
Location	Adama Science and Technology University
Fuel description	Charcoal
Wind conditions	Forced
Ambient temperature	22.4 °C

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	42	51	47	46.66666667	4.5	9.7%
Temp-corrected time to boil Pot # 1	min	47	57	53	52	5.0	9.6%
Burning rate	g/min	3	2	2	2	0.6	24.7%
Thermal efficiency	%	24%	27%	25%	0.253333333	1.53%	6.0%
Specific fuel consumption	g/liter	42	36	39	39	3.0	7.7%
Temp-corrected specific consumption	g/liter	43	40	44	42	2.1	4.9%
Temp-corrected specific energy cons.	kJ/liter	1,379	1,200	1,305	1295	89.9	6.9%
Firepower	watts	1,359	974	1,141	1158	193.1	16.7%

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	23	47	31	33.66666667	12.2	36.30%
Temp-corrected time to boil Pot # 1	min	26	53	35	38	13.7	36.18%
Burning rate	g/min	5	2	3	3	1.5	45.83%
Thermal efficiency	%	27%	28%	28%	0	0.58%	2.09%
Specific fuel consumption	g/liter	38	34	35	36	2.1	5.84%
Temp-corrected specific consumption	g/liter	42	38	39	40	2.1	5.25%
Temp-corrected specific energy cons.	kJ/liter	1,248	1,123	1,164	1178	63.7	5.41%
Firepower	watts	2,267	1,004	1,554	1608	633.3	39.37%

3. LOW POWER (SIMMER)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Burning rate	g/min	1	1	1	1	-	
Thermal efficiency	%	48%	49%	89%	0.62	23.39%	37.72%
Specific fuel consumption	g/liter	24	27	25	25	1.5	6.03%
Temp-corrected specific energy cons.	kJ/liter	727	795	739	754	36.3	4.82%
Firepower	watts	648	717	662	676	36.5	5.40%
Turn down ratio	--	2.10	1.36	1.72	2	0.4	21.43%

BENCHMARK VALUES (for 5L)		Test 1	Test 2	Test 3	Average	St Dev	COV
Fuel Use Benchmark Value	g	342	328	331	334	7.4	2.21%
Energy Use Benchmark Value	kJ	10,201	9,785	9,867	9951	220.4	2.21%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Average	St Dev	COV
High Power Thermal Efficiency	%	25.3%	27.9%	26.3%	0.265	1.31%	4.95%
Low Power Specific Fuel Consumption	MJ/(min L)	0.016	0.018	0.016	0.017	0.00	6.93%

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	2
Low Power Specific Fuel Consumption	4

WATER BOILING TEST - VERSION 4.2 TEST #

All cells are linked to data worksheets, no entries are required

Stove type/model	Ethio Cook Stove
Location	Adama Science and Technology University
Fuel description	Charcoal
Wind conditions	Forced
Ambient temperature	22.4 °C

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	29	34	32	31.66666667	2.5	7.9%
Temp-corrected time to boil Pot # 1	min	30	38	36	35	4.2	12.0%
Burning rate	g/min	4	3	4	4	0.6	15.7%
Thermal efficiency	%	22%	23%	22%	0.223333333	0.58%	2.6%
Specific fuel consumption	g/liter	46	42	41	43	2.6	6.2%
Temp-corrected specific consumption	g/liter	48	47	46	47	1.0	2.1%
Temp-corrected specific energy cons.	kJ/liter	1,432	1,392	1,383	1402	26.1	1.9%
Firepower	watts	2,055	1,680	1,785	1840	193.5	10.5%

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	26	30	39	31.66666667	6.7	21.03%
Temp-corrected time to boil Pot # 1	min	27	34	33	31	3.8	12.08%
Burning rate	g/min	4	4	4	4	-	
Thermal efficiency	%	25%	25%	24%	0	0.58%	2.34%
Specific fuel consumption	g/liter	42	39	39	40	1.7	4.33%
Temp-corrected specific consumption	g/liter	43	44	44	44	0.6	1.31%
Temp-corrected specific energy cons.	kJ/liter	1,296	1,312	1,323	1310	13.6	1.04%
Firepower	watts	2,101	1,821	1,884	1935	146.9	7.59%

3. LOW POWER (SIMMER)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Burning rate	g/min	2	2	2	2	-	
Thermal efficiency	%	45%	53%	48%	0.486666667	4.04%	8.30%
Specific fuel consumption	g/liter	37	33	35	35	2.0	5.71%
Temp-corrected specific energy cons.	kJ/liter	1,096	970	1,029	1032	63.0	6.11%
Firepower	watts	938	828	883	883	55.0	6.23%
Turn down ratio	--	2.19	2.03	2.02	2	0.1	4.59%

BENCHMARK VALUES (for 5L)		Test 1	Test 2	Test 3	Average	St Dev	COV
Fuel Use Benchmark Value	g	413	390	400	401	11.5	2.88%
Energy Use Benchmark Value	kJ	12,302	11,609	11,908	11940	347.6	2.91%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Average	St Dev	COV
High Power Thermal Efficiency	%	23.4%	23.8%	23.2%	0.234666667	0.31%	1.30%
Low Power Specific Fuel Consumption	MJ/(min·L)	0.024	0.022	0.023	0.023	0.00	4.35%

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	1
Low Power Specific Fuel Consumption	3

WATER BOILING TEST - VERSION 4.2 TEST #

All cells are linked to data worksheets, no entries are required

Stove type/model	Hexagon Cook Stove
Location	Adama Science and Technology University
Fuel description	Charcoal
Wind conditions	Forced
Ambient temperature	22.4 °C

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	40	48	44	44	4.0	9.1%
Temp-corrected time to boil Pot # 1	min	42	54	50	49	6.1	12.6%
Burning rate	g/min	3	2	3	3	0.6	21.7%
Thermal efficiency	%	23%	23%	24%	0.233333333	0.58%	2.5%
Specific fuel consumption	g/liter	44	41	40	42	2.1	5.0%
Temp-corrected specific consumption	g/liter	47	47	45	46	1.2	2.5%
Temp-corrected specific energy cons.	kJ/liter	1,402	1,393	1,330	1375	39.2	2.9%
Firepower	watts	1,427	1,190	1,242	1286.333333	124.6	9.7%

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	51	38	40	43	7.0	16.28%
Temp-corrected time to boil Pot # 1	min	54	43	45	47	5.9	12.38%
Burning rate	g/min	2	3	3	3	0.6	21.65%
Thermal efficiency	%	24%	25%	24%	0	0.58%	2.37%
Specific fuel consumption	g/liter	42	37	39	39	2.5	6.40%
Temp-corrected specific consumption	g/liter	44	42	43	44	1.0	2.27%
Temp-corrected specific energy cons.	kJ/liter	1,324	1,254	1,323	1300	40.1	3.09%
Firepower	watts	1,071	1,372	1,366	1270	172.1	13.55%

3. LOW POWER (SIMMER)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Burning rate	g/min	2	2	2	2	-	
Thermal efficiency	%	35%	44%	37%	44	37.00%	0.84%
Specific fuel consumption	g/liter	35	29	33	32	33.0	102.06%
Temp-corrected specific energy cons.	kJ/liter	1,038	853	979	957	94.5	9.88%
Firepower	watts	938	773	883	865	84.0	9.72%
Turn down ratio	--	1.52	1.54	1.41	1	0.1	4.70%

BENCHMARK VALUES (for 5L)		Test 1	Test 2	Test 3	Average	St Dev	COV
Fuel Use Benchmark Value	g	403	365	387	385	19.1	4.96%
Energy Use Benchmark Value	kJ	12,005	10,882	11,527	11471	563.6	4.91%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Average	St Dev	COV
High Power Thermal Efficiency	%	23.4%	24.4%	24.3%	0.240333333	0.55%	2.29%
Low Power Specific Fuel Consumption	MJ/(min L)	0.023	0.019	0.022	0.021	0.00	9.76%

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	1
Low Power Specific Fuel Consumption	3

VATER BOILING TEST - VERSION 4.2 TEST #

All cells are linked to data worksheets, no entries are required

Stove type/model	Obama Cook Stove
Location	Adama Science and Technology University
Fuel description	Charcoal
Wind conditions	Forced
Ambient temperature	22.4 °C

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	26	24	25	25	1.0	4.0%
Temp-corrected time to boil Pot # 1	min	28	27	28	28	0.6	2.1%
Burning rate	g/min	5	5	5	5	-	
Thermal efficiency	%	22%	25%	15%	0.206666667	5.13%	24.8%
Specific fuel consumption	g/liter	46	39	64	50	12.9	26.0%
Temp-corrected specific consumption	g/liter	49	44	73	55	15.5	28.0%
Temp-corrected specific energy cons.	kJ/liter	1,473	1,311	2,165	1650	453.6	27.5%
Firepower	watts	2,292	2,276	2,285	2284.333333	8.0	0.4%

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	23	23	27	24.33333333	2.3	9.49%
Temp-corrected time to boil Pot # 1	min	24	26	30	27	3.1	11.46%
Burning rate	g/min	5	4	4	4	0.6	13.32%
Thermal efficiency	%	24%	27%	17%	0	5.13%	22.64%
Specific fuel consumption	g/liter	42	35	56	44	10.7	24.12%
Temp-corrected specific consumption	g/liter	44	40	63	44	12.3	27.93%
Temp-corrected specific energy cons.	kJ/liter	1,313	1,177	1,872	1454	368.3	25.33%
Firepower	watts	2,375	2,159	1,840	2125	269.1	12.67%

3. LOW POWER (SIMMER)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Burning rate	g/min	2	2	2	2	-	
Thermal efficiency	%	45%	51%	48%	44	37.00%	0.84%
Specific fuel consumption	g/liter	39	39	72	50	33.0	66.00%
Temp-corrected specific energy cons.	kJ/liter	1,161	1,176	2,154	1497	569.0	38.01%
Firepower	watts	966	993	993	984	15.6	1.58%
Turn down ratio	--	3.46	2.29	2.30	3	0.7	25.10%

BENCHMARK VALUES (for 5L)		Test 1	Test 2	Test 3	Average	St Dev	COV
Fuel Use Benchmark Value	g	429	406	700	512	163.5	31.96%
Energy Use Benchmark Value	kJ	12,770	12,102	20,865	15246	4,877.9	32.00%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Average	St Dev	COV
High Power Thermal Efficiency	%	23.2%	25.9%	26.2%	0.251	1.65%	6.58%
Low Power Specific Fuel Consumption	MJ/(min L)	0.002	0.026	0.048	0.025	0.02	90.82%

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	2
Low Power Specific Fuel Consumption	3

WATER BOILING TEST - VERSION 4.2 TEST #

All cells are linked to data worksheets, no entries are required

Stove type/model	Turumbe Cook Stove
Location	Adama Science and Technology University
Fuel description	Charcoal
Wind conditions	Forced
Ambient temperature	22.4 °C

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	68	58	62	62.66666667	5.0	8.0%
Temp-corrected time to boil Pot # 1	min	72	65	70	69	3.6	5.2%
Burning rate	g/min	1	2	2	2	0.6	34.6%
Thermal efficiency	%	28%	18%	17%	0.21	6.08%	29.0%
Specific fuel consumption	g/liter	37	54	57	49	10.8	21.9%
Temp-corrected specific consumption	g/liter	39	61	64	55	13.7	25.0%
Temp-corrected specific energy cons.	kJ/liter	1,153	1,826	1,915	1631	416.6	25.5%
Firepower	watts	694	831	817	780.6666667	75.4	9.7%

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	36	40	37	37.66666667	2.1	5.53%
Temp-corrected time to boil Pot # 1	min	38	45	42	42	3.5	8.43%
Burning rate	g/min	2	3	3	3	0.6	21.65%
Thermal efficiency	%	31%	18%	18%	0	7.51%	33.61%
Specific fuel consumption	g/liter	32	56	53	47	13.1	27.82%
Temp-corrected specific consumption	g/liter	34	63	60	44	15.9	36.25%
Temp-corrected specific energy cons.	kJ/liter	1,019	1,878	1,784	1560	471.2	30.20%
Firepower	watts	1,172	1,242	1,275	1230	52.6	4.28%

3. LOW POWER (SIMMER)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Burning rate	g/min	1	1	1	1	-	
Thermal efficiency	%	37%	28%	15%	44	37.00%	0.84%
Specific fuel consumption	g/liter	17	38	36	30	33.0	108.79%
Temp-corrected specific energy cons.	kJ/liter	514	1,125	1,058	899	335.1	37.27%
Firepower	watts	690	662	662	671	16.2	2.41%
Turn down ratio	--	1.47	1.25	1.23	1	0.1	10.11%

BENCHMARK VALUES (for 5L)		Test 1	Test 2	Test 3	Average	St Dev	COV
Fuel Use Benchmark Value	g	268	499	488	418	130.3	31.15%
Energy Use Benchmark Value	kJ	7,999	14,883	14,537	12473	3,878.5	31.09%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Average	St Dev	COV
High Power Thermal Efficiency	%	29.7%	17.8%	17.7%	0.217333333	6.90%	31.75%
Low Power Specific Fuel Consumption	MJ/(min L)	0.034	0.025	0.024	0.028	0.01	19.91%

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	1
Low Power Specific Fuel Consumption	3

WATER BOILING TEST - VERSION 4.2 TEST #

All cells are linked to data worksheets, no entries are required

Stove type/model	Modified Cook Stove
Location	Adama Science and Technology University
Fuel description	Charcoal
Wind conditions	Forced
Ambient temperature	22.4 °C

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	25	29	30	28	2.6	9.4%
Temp-corrected time to boil Pot # 1	min	28	33	34	32	3.2	10.2%
Burning rate	g/min	4	3	3	3	0.6	17.3%
Thermal efficiency	%	29%	28%	27%	0.28	1.00%	3.6%
Specific fuel consumption	g/liter	39	34	36	36	2.5	6.9%
Temp-corrected specific consumption	g/liter	44	38	40	41	3.1	7.5%
Temp-corrected specific energy cons.	kJ/liter	1,299	1,142	1,202	1214	79.2	6.5%
Firepower	watts	2,085	1,627	1,656	1789.333333	256.5	14.3%

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	20	23	24	22.33333333	2.1	9.32%
Temp-corrected time to boil Pot # 1	min	23	26	27	25	2.1	8.22%
Burning rate	g/min	5	4	4	4	0.6	13.32%
Thermal efficiency	%	28%	28%	27%	0	0.58%	2.09%
Specific fuel consumption	g/liter	34	33	35	34	1.0	2.94%
Temp-corrected specific consumption	g/liter	39	38	40	44	1.0	2.27%
Temp-corrected specific energy cons.	kJ/liter	1,152	1,124	1,183	1153	29.5	2.56%
Firepower	watts	2,358	2,051	2,069	2159	172.3	7.98%

3. LOW POWER (SIMMER)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Burning rate	g/min	2	2	2	2	-	
Thermal efficiency	%	50%	49%	52%	44	37.00%	0.84%
Specific fuel consumption	g/liter	32	36	34	34	33.0	97.06%
Temp-corrected specific energy cons.	kJ/liter	961	1,082	1,019	1021	60.5	5.93%
Firepower	watts	828	938	883	883	55.0	6.23%
Turn down ratio	--	2.25	1.73	1.88	2	0.3	13.70%

BENCHMARK VALUES (for 5L)		Test 1	Test 2	Test 3	Average	St Dev	COV
Fuel Use Benchmark Value	g	367	372	371	370	2.6	0.72%
Energy Use Benchmark Value	kJ	10,930	11,076	11,056	11021	79.2	0.72%

IWA PERFORMANCE METRICS	units	Test 1	Test 2	Test 3	Average	St Dev	COV
High Power Thermal Efficiency	%	28.6%	28.2%	26.8%	0.278666667	0.95%	3.39%
Low Power Specific Fuel Consumption	MJ/(min·L)	0.029	0.024	0.023	0.025	0.00	12.69%

IWA PERFORMANCE TIERS	Tier
High Power Thermal Efficiency	2
Low Power Specific Fuel Consumption	3

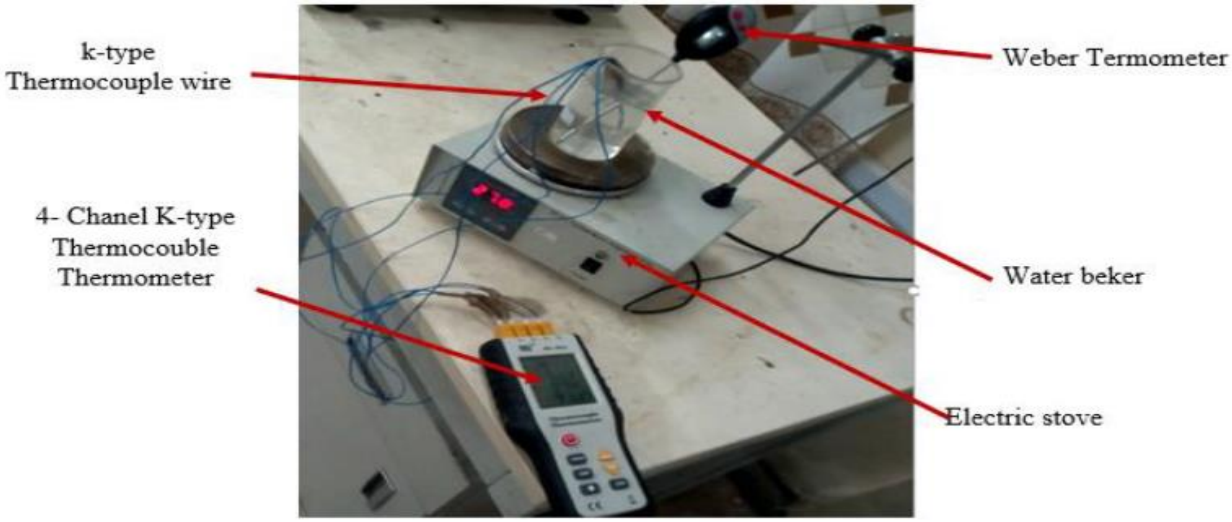
Appendix 3: Experimental Activity

(a) First Pass Air Temperature

(b)Second Pass Air Temperature

Appendix 4. Calibration of the Thermocouple Thermometer

Thermometer calibration can be performed using a reference thermometer in a temperature calibration test by comparing the readings of both the reference thermometer and other thermometers. Calibration tests for digital 4-channel thermocouple type K were performed in a chemical engineering laboratory using a Weber thermometer. 0.3kg. A 35 minute water boiling and cooling test was performed.



Time	**T_1 weber thermometer (^{o} c)**	**T_2 K-Type thermocouple (^{o} c)**	**Uncertainty(%)** $\frac{T_1-T_2}{T_{w2}} * 100\%$
1	24.6	24.8	0.8065
3	31.2	30.9	0.9615
5	38.8	38.5	0.7732
7	42.6	42.3	0.7042
9	51.3	51	0.5848
11	60.2	59.8	0.6645
13	63.5	63	0.7874
15	69	68.5	0.7246
17	71.2	70.8	0.5618
19	73.1	72.8	0.4104
21	77.1	76.6	0.6485
23	81.2	80.6	0.7389
25	82.2	81.8	0.4866
27	83.5	83	0.5988
29	87.5	87.1	0.4571
31	89.3	88.8	0.5599
33	91.1	90.8	0.3293
35	92	91.6	0.4348
37	92.9	92.5	0.4306
Average uncertainty (%)			0.6139

Appendix 5: Indirect method analysis

ASME Standard: PTC-4-1 Power Test Code for Steam Generating Units

The Indirect Method: In this method, the efficiency can be obtained by subtracting the heat loss fractions from 100.

Boiler efficiency = 100 – (L_1 + L_2 + L_3 + L_4 + L_6 + L_7 + L_8).

Where:

L_1 = Loss due to dry flue gas

L_2 = Loss due to hydrogen in fuel

L_3 = Loss due to moisture in fuel

L_4 = Loss due to moisture in air

L_5 = Loss due to partial combustion to CO

L_6 = Losses due to radiation, convection and unaccounted

L_7 = Unburnt losses in fly ash

L_8 = Unburnt losses in bottom ash.

Basic equations to calculate efficiency by indirect method

a. Carbon percentage of fuel
b. $\%C = 0.97FC + 0.7(VM + 0.1A) - M(0.6 - 0.01M)$Hydrogen percent of fuel

$$\%H_2 = 0.036FC + 0.086(VM - 0.1A) - 0.0035M^2(1 - 0.02M)$$

c. Nitrogen percentage f fuel

$$\%N_2 = 2.1 - 0.02VM$$

Where:
FC-% of fixed carbon
A-% of ash
VM-% of volatile matter
M-% of moisture

d. The theoretical or stoichiometric air fuel ratio can be determined as
e. $= \frac{11.6C + \left(34.8 * \left(H_2 - \frac{O_2}{8}\right)\right) + 4.35S}{100 \frac{kg}{kg}}$% Excess air supplied(EA)

$$= \frac{O_2\%}{21 - O_2\%} * 100$$

f. Actual mass air supplied/kg of fuel

$$= \left(1 + \frac{EA}{100}\right) * theoretical\ air$$

Heat loss due to dry flue gas

$$L_1 = \frac{m * C_p * (T_f - T_a)}{GCV\ of\ fuel} * 100$$

Heat loss due to evaporation of water formed due to H_2 in fuel (%)

$$L_2 = \frac{9 * H_2 * (584 * C_p\left(T_f - T_a\right))}{GCV\ of\ fuel} * 100$$

Heat loss due to moisture present in fuel

$$L_3 = \frac{M * (584 * C_p\left(T_f - T_a\right))}{GCV\ of\ fuel} * 100$$

Heat loss due to moisture present in air

$$L_4 = \frac{AAS * humidity\ factor * C_p\left(T_f - T_a\right)}{GCV\ of\ fuel} * 100$$

Heat loss due to incomplete combustion

$$L_5 = \frac{\%CO * \%C}{\%CO * \%CO_2} * \frac{5744}{GCV\ of\ fuel} * 100$$

Heat loss due to radiation and convection

$$L_6 = 0.548 * ((\frac{T_s}{55.55})^4 - \left(\frac{T_a}{55.55})^4\right) + 1.957 * (T_s - T_a)^{1.25} * sqrt\ of\ (\frac{(196.85 * V_m) + 68.9}{68.9})$$

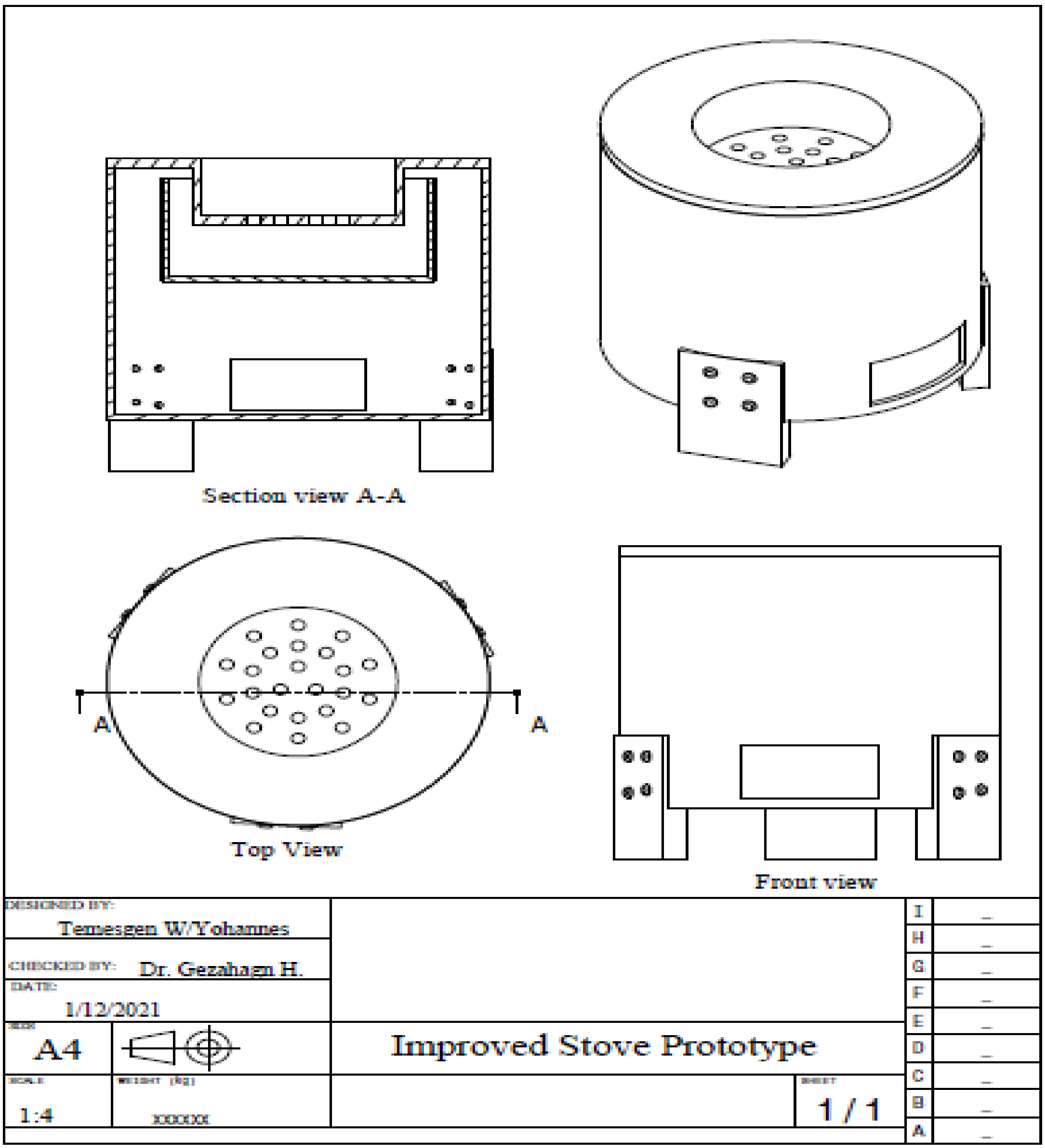
Heat loss due to unburnt in fly ash (%)

$$L_7 = \frac{\frac{Total\ ash\ collected}{kg\ of\ fuel\ burnt} * GCV\ of\ fly\ ash}{GCV\ of\ fuel} * 100$$

Heat loss due to unburnt in bottom ash (%)

$$L_8 = \frac{\frac{Total\ ash\ collected}{kg\ of\ fuel\ burnt} * GCV\ of\ bottom\ ash}{GCV\ of\ fuel} * 100$$

Appendix 6: CAD drawing of new improved stove



Appendix 7: Charcoal proximity and calorific result

	GEOLOGICAL SURVEY OF ETHIOPIA	Doc.Number: GSE/F 5.10-2	Version No: 1
	GEOCHEMICAL LABORATORY DIRECTORATE		Page 1 of 1
ument Title:	Hydrocarbon Laboratory Analysis Report	Effective date:	May, 2017

Customer Name:-Temesegen W/Yohanis

Issue Date: - 25/11/2021

Request No: - GLD/RN/326/21

Report No: - GLD/TR/1023/21

Sample Preparation : - 60 Mesh

Sample type: -Carcole

Number of Sample: -One (01)

Date Submitted: -11/11/2021

Elements to be determined:- (Moisture, Volatile matter, Fixed carbon , Ash) & Calorie

Method of analysis:- Proximate Analysis & Adiabatic Calorie Metter .

Collectors' Code	Moisture %	Volatile Matter %	Fixed carbon %	Ash %	Calorific Value Cal/gm.
ASTU/CH-01	4.41	14.37	75.95	5.27	4905.86

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

Analysts
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Quality Control
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Geological Survey of Ethiopia
Central Geological

Appendix 8: New developed modified stove