Addis Ababa University

Addis Ababa Institute of Technology

School of Multidisciplinary

Energy Center

Designing, Simulating and Manufacturing of Improved Charcoal Stove

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Award of the Degree of Master of Science in Energy Technology

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December, 2020

CERTIFICATION

I, the undersigned, certify that I read and hear by recommend for the acceptance by Addis Ababa university, Addis Ababa Institute of Technology, Energy Center a thesis entitled “Designing, Simulating and Manufacturing an Improved Charcoal Stove”. This certificate used as a partial fulfillment of the requirement for the degree of Master of Science in energy technology.

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Date ______________________

DECLARATION

I, Lemma Kahsay, I declare that this thesis is the result of my own work and that all source and material used for this thesis have been duly acknowledged. This thesis is submitted in partial fulfillment of the requirement for master's degree in energy technology at Addis Ababa university and to be made available at the at the university's library under the role of the library. I confidently declare that this thesis has not been submitted to any other institutions anywhere for the award of any academic degree, diploma, or certificate.

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ACKNOWLEDGMENT

First of all, I am very grateful to Almighty of God, This thesis has not been possible without His blessing and graces.

Then I would like to express my sincere gratitude to my advisor Dr. Kamil Dino Adem, who has been a great source of inspiration for me, supportive in the entire activity and works actively to the completion of this research with a day to day follow up, guidance and also for sharing his knowledge and experience in stove designing, manufacturing, modeling and testing, this research could not have been possible without his support and care.

I am also grateful to Dr. Solomon T/Mariam and Dr. Wondwosen Bogale, for their valuable comment, suggestion and for providing useful measuring device. Then I would like to express my sincere appreciation to Mr. Anteneh, for his skillful works, suggestion, and valuable comment while developing and constructing the actual prototype, his support made this project possible.

Finally, I would like to express my deepest gratitude and appreciation for my wife, sons and younger brother for their continuous love, help and support.

ABSTRACT

Nearly 2.7 billion people in the world depend on biomass for cooking. Charcoal fuel is a solid biomass fuel which is widely used in urban and semi-urban areas of Ethiopia. However, these fuels are combusted inside thermally inefficient stoves. One solution to such problem could be designing, manufacturing and disseminating improved stoves. Thus, this study aims at designing, simulating and manufacturing an improved charcoal stove to maximize the thermal performance. Designing the stove has been performed by solid work. Besides, simulation has been performed by CFD module which is found in COMSOL Multiphysics software. This module includes coupled sub models representing fluid flow and heat transfer. From the simulation temperature distribution, velocity distribution and pressure distribution in the grate holes and on the combustion chamber of the stove were analyzed. The simulation shows that the increased temperature results in higher firepower, which leads to higher thermal performance of the stove.

The prototype was tested using the Water Boiling Test (WBT) protocol. The simulation results were compared and validated with experimental results. Based on simulation thermal efficiency obtained was 34.7%. With regard to experimental investigation, the thermal efficiency of the stove is 32.6% and its specific fuel consumption is 56 g of fuel/ liter of water. The study showed an improvement in thermal performance of the charcoal stove. The specific fuel consumption of the prototype charcoal stove shows 70% improvement compared to the three-stone fire. Generally, the new prototype charcoal stove has better thermal performance compared to the previous designs proposed by other researchers. Therefore, disseminating our improved charcoal stove at a larger scale in Ethiopia will be beneficial in preservation of forests and associated ecosystem services and will improve health for households.

Key words: Computational Fluid Dynamics, Charcoal stove, Water Boiling Test, Simulation, Improved cookstove, Design principle

NOMENCLATURE

Symbol	Description and units
U_i	useful energy delivered(kJ)
$C_{p,\,w}$	Isobaric mass specific approximate heat capacity of water (kJ/kg. k)
W_1	Initial mass of water in the pot(kg)
W_2	Final mass of water in the pot (kg)
T_1	Initial temperature of water in the pot (℃)
T_2	Final temperature of water in the pot (℃)
Ψ	Latent heat of water vaporization at the local point(kJ/kg)
C_p	Cooking power(kW)
T_4	Final time at the end of the test phases (s)
T_3	Starting time at the starting of a test phase (s)
η_e	Cooking thermal efficiency without energy credit for remaining char (%)
A	Mass of fuel fed (kg)
$L_{net\ f}$	Lower heating value of fuel, as fired (kJ/kg)
Ω	Cooking thermal efficiency with energy credit for remaining char (%)
R_c	Mass of remaining char(kg)
$L_{net\ c}$	Lower heating value of remaining char(kJ/kg)
E_F	Pollutant emission factor(mg/s)
X_t	Total mass of pollutant emission during the test (mg)
SFC	Specific fuel consumption(g/liter)

Fc	Fuel consumed (g)
W_pW	Weight of pot with water after test (g)
P_t	Weight of pot (g)
E	Surface emissive power(W/m^2)
T_s	Absolute temperature of the surface(k)
Q_{conv}	Convective heat transfer (W)
h	Average convective heat transfer coefficient (W/m^2K)
A_T	Area of heat transfer (m^2)
T_{sur}	Surface temperature (K)
T_f	Temperature of fluid at a distance from the surface (K)
Q_y	Heat transfer rate only in the Y-direction
$\frac{\partial T}{\partial x}$	Temperature gradient in the direction of the heat flow
K	Thermal conductivity of the material
ρ	Density of the fluid (kg/m^3)
U	Velocity vector (m/s)
P	Pressure(p_a)
F_v	Volume force vector(N/m^3)
µ	Dynamic viscosity (P_a. s)
S_r	Strain rate tensor
U_g	Velocity of fluid through grate holes(m/s)

D	Diameter of the grate hole (m)
F_B	Body force
S_t	Surface force
Re	Reynolds number
Q	Heat source (W/m^3)
q	Heat flux vector (W/m^2)
w	Mass flow rate (kg/s)
T	Temperature (K)

GREEK SYMBOLS

Symbol	Description
σ	Stefan Boltzmann's constant
α	Transmitted irradiation
τ	Reflected irradiation
γ	Absorbed irradiation

SUBSCRIPTS

f	Final
i	Initial
sur	Surface
B	Body
g	Grate

v	Volume
y	y-direction
p	Power
r	Rate tensor

ABREVIATION

Abbreviations	Description
AAU	Addis Ababa University
AAiT	Addis Ababa institute of Technology
KPT	Kitchen performance test
CO	Carbon monoxide
PM	Particulate matter
CFD	Computational Fluid Dynamics
WBT	Water boiling test
CO_2	Carbon dioxide
NMHCs	Non-methane hydrocarbons
OC	Organic carbon
OM	Organic matter
EC	Elemental carbon
NO_x	Oxides of Nitrogen
N_2O	Nitrous oxide

UCODEA	Urban Community Development Agencies
IWA	International Workshop Agreement
LHV	Lower Heating Value

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CHAPTER ONE

INTRODUCTION

1.1. Background

Since the beginning of human history open fires and primitive stoves have been used to burn a biomass fuel which includes wood, charcoal, dung, crop and plant residues for cooking, heating, lighting and other purposes. Currently about 2.7 billion people on the world depend on biomass as their primary fuel for cooking and this is linked to more than 2.6 million permanent deaths per year. In sub-Saharan Africa 890 million people rely on biomass for cooking particularly in rural areas and only 17% of the populations have clean cooking access (IEA, 2018). It has been studied that the use of solid biomass fuels in open fires and traditional stoves for cooking, heating, lighting and other purposes leads to adverse health effects, high levels of indoor air pollution, increased probability of death, climate change, deforestation and loss of biodiversity. Exposure to smoke from open fires and traditional stoves contributes to respiratory diseases such as; pneumonia, tuberculosis, lung cancer, asthma and non-respiratory diseases such as; low birth weight, infant mortality, cardiovascular disease and cataract (Sutar et al., 2015).

A stove is called an improved cook stove if it is highly efficient, safe and emits fewer emissions (Kshirsagar and Kalamkar, 2014). There are a lot of reasons for the development of improved biomass stoves such as environmental, health, and socio-economic benefit. Improved stoves can be designed to be more efficient, clean and to reduce the emissions of several pollutants, which include carbon monoxide (CO), particulate matter (PM), black or elemental carbon (EC), oxides of nitrogen (NOx), methane (CH_4), nonmethane hydrocarbons (NMHCs), organic carbon (OC) and organic matter (OM). There are also other benefits due to the production improved charcoal stoves. As one study indicates in china, adoption of improved cook stoves reduced fuel wood consumption, tree felling and wood collection time by 40.1%, 23.7%, and 38.2% respectively (Zhang et al., 2000). The implementation of improved cook stoves in Tanzania saved wood fuel consumption, reduced women’s workload by reducing time required for fuel collection, created business for the stove producers (Mwampamba et al., 2013). Similarly, in china improved cook stoves reduce the emissions of healthy risky pollutants like carbon monoxide (CO) in the short term and reduce greenhouse gas emissions in the long term (Zhang et al., 2000). Improved cook stoves in Mexico reduced particulate matter (PM) by 74% and carbon monoxide (CO) concentrations by 78% (Pine et al., 2011) . Improved cook stoves (Patsari) reduced concentrations of carbon monoxide (CO) and fine particulate matter (PM) by 66% and 67% respectively. They also improved health, climate, environment and socio-economic benefit (Masera et al., 2007). Improved stoves can be designed to be more efficient, clean and to reduce the emissions of several pollutants.

Biomass cook stoves are classified on the basis of; use of technology, type of draft used, application type, purpose served, chimney use, portability, construction materials and on the basis of fuel used (Kshirsagar and Kalamkar, 2014). Biomass stoves that are classified on the basis fuel type used are fuel-wood cook stoves, charcoal cook stoves, Agri-residue cook stoves, dung cake cook stoves and miscellaneous and multi-fuel cook stoves. On the basis of use of technology, they are classified into traditional cook stoves and improved/advanced cook stoves. There are two types of traditional stoves; 'three stone fires" and "built on stove" or "mud stove". Three stone fires are characterized by low efficiency, least costly and least safe stove. In the laboratory these stoves showed high carbon monoxide (CO) and particulate matter (PM) emissions, high fuel usage, and 10% thermal efficiency and moderate time to boil (Kshirsagar and Kalamkar, 2014).

Charcoal fuel is one of the biomass fuels which are used broadly in developing countries. The production, trade and consumption of charcoal fuels for household food preparation are characterized by conflict, misconceptions and stereotyping (Mwampamba et al., 2013). These fuels are combusted and burnt in charcoal stoves. In many parts of the world there are different types of improved charcoal stoves; such as Kenyan charcoal Jiko (Kenya), Mali charcoal (Mali), Gyapa charcoal (Ghana), UCODEA charcoal stove (Uganda), and Lakech stove (Ethiopia) are the stoves which are found in Africa (Kshirsagar and Kalamkar, 2014)

Ethiopian households dominantly use solid biomass fuels for cooking, water heating and coffee making. The cookstove technologies which are found in Ethiopia are classified as injera baking cookstoves and non-baking cookstoves (pot sized stoves). Non-baking cookstoves are referred to cookstoves that are used for cooking, water heating and coffee making. In Ethiopia improved cookstoves; reduce fire wood consumption and harmful emissions, the drudgery of fuel wood collection is diminished saving time and effort, small scale stove producers benefit from self-sustaining income-generating opportunities as well as low-income households, social facilities and small and medium enterprises gain sustainable access to improved cookstoves technologies and services. Improved cookstoves reduce deforestation and offer more time for education and improved living conditions especially for women and children.

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*. *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., 2017).

Stoves are usually designed using trial and error processes i.e. manufacturing a prototype, and testing it for different types of performance, then changing parameters until successful design found. The design process depends on previous engineering design, experience and experimental works. This trial and error process results in greater resource and time consumption on manufacturing prototype and testing it (Nordica Ann MacCarty, 2013). Application of computational modeling used for product design would help to answer these problems. In the past 30 years above 500 scientific articles have been published which examined various aspects of biomass cookstoves; however, only less than 6% of the scientific articles have answered numerical simulation of fluid flow, heat transfer processes in traditional biomass stoves and none of these coupled, provide detailed simulation validation of the experimental results (Nordica MacCarty and Bryden, 2016). Among the cookstove modeling software's is the CFD package which is found is found in COMSOL Multiphysics. CFD modules can solve temperature profiles, velocity distribution and pressure distributions (Sengupta et al., 2019).

Even though CFD models have advanced the art of modeling cook stoves, they have largely been validated without considering real stove design principles and used very small number of stove geometries. Combustion has been modeled with simple reaction and heat transfer is often modeled without considering the presence of remaining char. The remaining char highly affects the temperature distribution, velocity distribution and heat transfer from cook stoves to the pot. The influence of design principles such as secondary air entrance, grates, pot support height, cone deck, ash tray, bottom body of the stove and outer casing on the stove thermal performance has not been studied. The fundamental physics behind why certain arrangements result in better thermal performance and emissions has not been fully studied (Pundle et al., 2019 ;Varunkumar et al., 2012).

1.2. Statement of the problem

Charcoal is a solid fuel used for cooking, water boiling, and coffee/tea making, and heating in many developing countries, like Ethiopia. Charcoal is widely used fuel both in urban and rural areas of Ethiopia. Currently they are burnt and combusted in charcoal stoves which are characterized by the problems of inefficient fuel use which leads to deforestation, environmental degradation, high indoor and outdoor emission, another extra cost to buy charcoal fuels. Moreover, charcoal fuels are typically burned with substantial production of products of incomplete combustion, which include CO, and other particles that affect global climate change as well as toxic air pollutants that adversely affect human health. Charcoal fuels emit huge amount of carbon monoxide which is odorless and colorless when enters in to human body through the respiratory system it combines with hemoglobin (Hb) and thus prevents oxygen transfer to the blood and when hemoglobin carbon monoxide blood level reaches 80% it directly causes instantaneous death.

Currently in Ethiopia traditional metal charcoal stoves, *lakech* and *merchaye,Shekela* charcoal stoves are used to burn and combust these fuels. *Merchaye and Shekela* stoves are new to the market. So *lakech* stove and the traditional stoves are well familiar to the market. Shekela charcoal stove has the highest thermal efficiency i.e., 29% and Merchaye charcoal stove has the lowest thermal efficiency i.e., 67 g/liter. The traditional metal charcoal stoves are manufactured through traditional way and it is not scientific. So, the aim of the current research is to address these problems by designing, simulating, manufacturing and testing charcoal stove using scientific principles.

1.3. Objectives

The main objective of the research is to design, simulate, manufacture and test improved domestic charcoal stove.

The Specific objectives include;

- Designing charcoal stove using solid work.
- Simulating the stove.
- Manufacturing the stove
- Testing the performance of the improved charcoal stove.

1.4. Significance of the research

This research focuses on designing, simulating and manufacturing a charcoal stove which will be more efficient and user friendly. The benefits of this research include reduced concentrations of smoke and indoor air pollutions, money and time will be saved in acquiring charcoal fuels, reduction in the quantity of fuels usage, reduction in greenhouse gas emissions, job creation to the community and reduce health risks for all users. The peoples who are living in urban and semi-urban areas of Ethiopia will get an improved charcoal stove after successful completion of the research and implementation of the result. Up to now there is no charcoal stove which is designed using scientific principles. Thus, the research will help as a reference for other studies, which may focus on similar issues, related to the designing, simulating and manufacturing of an improved charcoal stove.

1.5. Limitations

The limitation of this work is that Computational Fluid Dynamics models have problems in predicting the complex phenomenon of turbulence and combustion, model assumption and non-availability of accurate reaction mechanisms result in the predictions deviating from the experimental data significantly. In terms of its setting up of the model and its actual computations Computational Fluid Dynamic models are significantly time consuming. The second limitation of this research will be the indoor air pollution measuring instruments are not available. The emissions of CO, CO_2 and PM are not measured in the experiment.

1.6. Scope of the study

This study focuses on the designing, simulating and manufacturing an improved charcoal stove. Geometry of the new prototype charcoal stove was designed on SOLID work 2020 and it is used to manufacture the prototype. The simulation is done using CFD package which is found in COMSOL Multiphysics software. Different types of charcoal stove design principles are used like sizing the combustion chamber for the required task, maintaining constant cross-sectional area etc. the prototype was manufactured using locally available materials and it was tested using WBT protocol and instruments like thermocouple, environmental meter mass balance and moisture meter were used.

1.7. Organization of the research

The structure of the research is organized as follows: chapter one discusses about the introduction of the research which includes background of the research, problem of statement and objective of the research. Chapter two discusses the different reviews of the research and the research gap is clearly explained in this chapter. Chapter three discusses about the design principles and manufacturing materials used for the new prototype and testing procedures using WBT protocol. Chapter four discusses about the simulation process. Here in this chapter the following topics are discussed; the physics used, fluid flow governing equations, heat transfer mechanisms, the type of geometry, material selection, the different types of boundary conditions and model assumptions. Then results and discussion part is discussed in chapter five of this research paper. Thermal performance results of the stove are discussed in this chapter and are compared with other charcoal stove types. The CFD simulation results are also discussed and compared with other similar papers. The experimental and simulation results are validated. The last chapter discusses about conclusions, and recommendations for future works.

CHAPTER TWO

LITERATURE REVIEW

In this chapter, the different types of literatures reviewed are discussed. Stove construction materials, stove design principles, biomass testing protocols, the main components of charcoal stove, development of charcoal stove in Ethiopia, research gap and CFD models are discussed.

2.1. Biomass classification and composition

Biomass is the plant material that comes from the reaction between water, sunlight and CO_2 in the air, through photosynthesis, to produce carbohydrates (starch, sugars and cellulose) that form the building blocks of biomass. Not more than 1% of the available sunlight is converted to stored chemical energy by photosynthesis (McKendry, 2002).

A lot of biomass resources can be changed to enable energy supply. These can be divided into six groups, based on their properties such as forestry products, wastes, and residues, agricultural wastes and residues (herbaceous species), Industrial and municipal organic wastes, aquatic species, energy crops, which are grown with the aim to supply energy carriers and derivatives. Cellulose, hemicellulose, linin and chitosan are the main structural organic constituents of biomass fuels. Together with the main structural organic constituent’s biomass fuels contains other minor constituents such as oils, fats (lipids), proteins, star and sugar as well as spectrum of organic extractives (McKendry, 2002).

2.2. Biomass fuels consumption in Ethiopia

In 2013, Ethiopia’s total national biomass fuels consumption was estimated to be 105.2 million tons per year with 5.7 million tons of charcoal fuel. From 2000-2013 there was massive increase in charcoal consumption in nearly all regions of Ethiopia. There are different reasons behind increase in rural charcoal consumption such as increase in rural income, creation of rural markets, and increase in rural infrastructure as well as reduction of transportation costs (Geissler et al., 2013). Table 2-1 shows the biomass consumption in Ethiopia in 2013.

Table 2-1: Biomass fuel consumption in Ethiopia (2013) (Geissler et al., 2013)

Region	2000(ton/yr.)	2013(ton/yr.)
Addis Ababa	-	-
Afar	1,905	214,677
Amara	-	1,083,524
BSG	3,787	34,953
Diredawa	-	7,841
Gambella	32	9,638
Harari	-	8,656
Oromiya	5,031	1,554,763
SNNPR	149	448,436
Somali	18,131	498,389
Tigray	19,545	271,996
Total	48,581	4,132,873

2.3. Stove design principles

Mostly, improved biomass cook stoves are designed based on the principles of Dr. Larry Winiarski. These design principles focus on the selection of best materials like heat resistant insulation around the fire which reduces smoke. There must be properly sized gaps between the fire and the pot to maximize heat transfer. Less amount of draft produces lots of smoke and charcoal but too much of it cools the fire. If too much charcoal is produced this results in the emission of harmful carbon monoxide. The intensity of the fire is dependent on how many sticks are pushed into the fire (Bryden et al., 2005). Proper air circulation is needed for efficient combustion. The amount of heat transferred to the pot can be increased by maintaining a constant cross-sectional area of the flow path. Properly utilization of heat transfer by radiation and increase the surface area of the pot in contact with the hot and fast-moving flue gases improve the heat transfer rate (Thompson et al., 2011). For the design and construction of a stove the following parameters are needed such fuel type, insulation, local resources, stove power output, safety consideration, air flow rate, reactor cross sectional area, diameter and height (Bantu et al., 2018).

2.4. Charcoal stove design principle

there are about eight charcoals stove design principles (Still et al., 2015). This design principle combines both optimized heat transfer and clean burring characteristics. most of these design principles were used in designing the new prototype charcoal stove and it was a successful procedure. Table 3-3 shows charcoal stove design principles.

Table 3-3 Charcoal stove design principle (Still et al., 2015)

Principles	Description
Principle one	Size the combustion chamber for the required task. The amount of fuel loaded in to the stove will be proportional to the amount of air made available to it. More fuel loaded means there is always excess air which reseals in more fire power. For cooking small amount of food load, a small amount of fuel in to the stove, or use a stove with a small combustion chamber. The opposite is true for cooking lots of food at a time or for boiling large amount of water.
Principle two	Charcoal stove can have a high turn down ratio.
Principle three	Secondary airs are required to burn up the remaining CO. In most charcoal stove design, the Air must pass through the burning charcoal before it reaches to the top where the CO is. To burn up the remaining CO hot air must be added above the charcoal fuel.
Principle four	Put the pot close to the charcoal. This will maximize heats transfer by conduction & radiation from the charcoal fuel to pot.
Principle five	Insulators like clay, ceramic fiber, rock wool and sheet of foil, etc. are required in order to achieve a temperature of 609℃ or above five minutes or less than five minutes after lighting
Principle six	Small channel gaps are required between the pot and the stove. Radiative and convective heat transfer are the main modes of heat transfer in charcoal stoves. In order to increase heat transfer by convection to the pot a skirt is needed around the pot. The pot should be located very close to the top of the burning charcoal.
Principle seven	Maintain a constant cross-sectional area. Maintain a constant cross section area during the stove to start the design process and decrease as intended for by experimentation. This will maintain the velocity of the draft as high as possible
Principle eight	Provide huge amount of primary air to ensure adequate fire power.

2.5. Stove construction materials

Materials used for stove construction are selected based on different criteria's such as fire resistivity, easy portability, durability, thermal conductivity, cost, maintenance as well as minimizing safety risks, failure and deterioration. By many designer's metal is selected as the construction material because it has the advantages of easy portability, low thermal inertia as well as high performance but metals can result in higher heat losses due to its higher thermal conductivity. Mud, cement and brick can be used for stove construction and they are poorer conductor of heat. But these materials store huge amount of energy in the stove body (Sutar et al., 2015). In natural draft wood stoves combustion liners are exposed to temperatures of 600-800℃ and in charcoal stoves it is from 600-1100℃ (Global Alliance for Clean Cookstoves, 2014a**)**. Corrosion of metallic components, unavailability and cost of materials are the challenges faced by designers. Small amounts of salts, like chlorine and sulfur which are present in many solid fuels and high temperature environments speed up the rate of corrosion. The advantages and disadvantages of some cook stove materials are shown in Table2-2 below.

Table 2-2: Advantages and disadvantages of cookstove construction materials (Global Alliance for Clean Cookstoves, 2014a)

Material	Advantages	Disadvantages	Stove components
Aluminum	Low density Moderate strength Easy to form	Low availability high conductivity high cost	Radiative insulation
Cast iron	High strength High service and melting temperature Can be cast into different shapes	Low availability Melting and casting is difficult Low availability of scrap iron Very high conductivity	Cone deck and pot supports Grate
Calcium silicate	Very low thermal conductivity Low density	Low strength Aerosol dust is harmful if inhaled High cost Not widely available	Insulation layer
Ceramic fiber	Very low thermal conductivity Low density	High cost Not widely available Very low strength Exposed fibers irritate skin Aerosol fibers are harmful if inhaled	Insulation layer
Mild steel	Widely available Low cost	Low service and melting temperature Poor corrosion resistance	External component (door, handles, legs,etc)

2.6. Biomass stove Testing Protocols

2.6.1. Water Boiling Test (WBT)

Water boiling test is a type of laboratory testing protocol that is planned to provide repeatable and reproducible outcomes. The testing protocol was originally done for wood stoves, but later it is also suitable for charcoal stoves. This test protocol consists of three phases: high power cold start, high power hot start and low power. The difference in stove performance is calculated by the first two phases i.e., from cold and hot start. It is the most widely used test protocol because it is easy to conduct and quick to do procedures (Kshirsagar and Kalamkar, 2014). The main parameters that are tested in the laboratory are time to boil thermal efficiency, specific fuel consumption, burning rate, fire power and turn down ratio. WBT is dependent on temperature change and mass loss of water on a pot. Because this test is planned to be repeatable and reproducible procedure it is useful and suitable as an aid to the design process in the ability of identifying areas of poor performance and for comparing the performance of different stoves. However, the WBT also has weakness; it cannot provide necessary information about how the stove performs when cooking actual foods and the fuel type, composition, moisture and size may vary (Taylor, 2009).

2.6.2. Controlled cooking test (CCT)

Controlled cooking test takes place under controlled settings to use the stove to its best performance, but it has its own weakness during cooking real meals in actual households. It is more suitable lab based stove testing method, for forecasting actual household performance. Controlled cooking test which acts as a bridge between Water Boiling Test (WBT) and Kitchen Performance Test (KPT), accounts for 12% of all the tests performed on cook stoves (Delapena et al., 2016).

2.6.3. Kitchen Performance Test (KPT)

Kitchen performance test is the main field-based technique to determine the effect of stove intervention on household fuel consumption. It is among the most accepted testing protocols for cookstoves. It includes an assessment of the qualitative aspects of stove performance through household survey and to compare the impact of improved stoves on fuel consumption in the kitchens of real households (Delapena et al., 2016).

2.7. Charcoal stoves

Charcoal stoves are the most widely used devices for cooking, coffee making, water boiling and other related activities in many parts of the world. To minimize absorption and storage of heat charcoal stoves should be lightweight. To further reduce this stored heat combustion chamber must be isolated from the other parts of the stove. In charcoal stoves an insulated combustion chamber wall and insulated stove bottom may help reduce the heat that radiates away from the pot (Baldwin, 1987). The main components of a charcoal stove are listed below.

2.7.1. Combustion chamber

In improved charcoal stoves the shapes of the combustion chambers have been noted to be slightly conical. The advantage of this shape is that it keeps the charcoal to be packed as it burns down and it is used to hold charcoal fuels. The combustion chamber is the area where combustion takes place (Stewart, 1987).

2.7.2. Grate

The advantage of a grate is to improve the combustion efficiency, due to improved supply of primary air under the bed and better contact of this air with the fuel. It should have sufficient open area to allow good mixing of air under the charcoal. The openings should be greater 0.5cm wide in order to prevent blocking, but less than 2cm wide to reduce the amount of small charcoal pieces that will fall through. If the open area is too large excess air enters the combustion chamber and this decreases the flame temperature, but if the open area is to small sufficient will not enter the combustion chamber (Stewart, 1987).

2.7.3. Air entrance

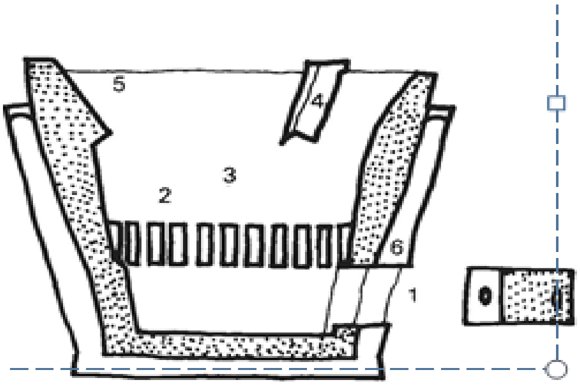
There are different ways in which biomass cook stoves can be classified. One method is based on air entrance, and these are the natural draft cooks stoves and forced draft cook stoves. Natural draft cook stoves are free convection driven cook stoves. These stoves are preferable because of low-cost and ease of manufacturing. Air enters the combustion chamber due to the natural process that involves the hot air in the combustion chamber rising and being replaced by cold air from outside. Forced draft cook stoves are fan operated stoves. Fans create high velocity air jets that mix fuel, air, and flame. Forced draft cook stoves reduce emissions through improved combustion as well as improve heat transfer to the cooking vessel (Global Alliance for Clean Cookstoves, 2014a).

2.7.4. Stove body

A lot of studies indicate that the weight of the stove has a relationship with efficiency; the heavier and very light stoves have lower efficiencies. Heavy stove body results in major penalty of stored energy in the stove body whereas; lightweight stoves (metallic body) can result in higher heat losses from the stove body due to its higher thermal conductivity. Insulating the combustion chamber with heat resistant insulators such as calcium silicate, ceramic fiber, perlite, low-density pottery, a clay/rice-husk ash mix, pumice stone, cement/vermiculite mixtures, and fired pottery usually increased the efficiency significantly. Insulating the outside of a cast-iron combustion chamber also increases the efficiency considerably (Stewart, 1987).

2.7.5. Pot seat

It is made on top of the stove to accommodate a range of pot sizes. If the combustion chamber is made of a weaker material many designs have the pot supported on metal supporters(Stewart, 1987).



1=air entrance 2=grate
3=combustion chamber 4=pot seat
5=pot shield 6=stove body

Figure 2-1:Main components of charcoal stoves (Stewart, 1987)

2.8. Development of Charcoal stoves

Charcoal stoves are widely used in urban and semi-urban areas of Ethiopia. However, these stoves are less efficient, environmentally unfriendly and high emission. Different charcoal stoves are present; some of these stoves are *mirchaye*, *lakech* and traditional charcoal stoves (Mamuye et al., 2017).

2.8.1. *Lakech* charcoal stove

Lakech charcoal stove has been used in Ethiopia for more than two decades .Majority of the stoves has been produced in large cities like Addis Ababa and has been transported to other different regions(SNV, 2018). Metal, clay, cement, sand and water are the raw materials to produce the stove. Metal and clay are the main raw materials in the production of the stove. No welding, soldering or brazing is required because all the joints in the casing are either riveted or folded. The adoption of *Lakech* charcoal stoves is negatively affected by the presence of other metal charcoal stoves. It has daily specific fuel consumption reduction efficiency of 23%. CO emission reduction of 15%, the CO_2 emission per 2.5L of water is 625g, $PM_{2.5}$ emission reduction of 13 % (Mamuye et al., 2017).

2.8.2. *Merchaye* charcoal stove

Merchaye charcoal stove uses briquette fuels and it looks like *lakech* stoves. Because it is new to the market it is becoming preferable by refugee camps rather than the households (SNV, 2018). It has daily specific fuel consumption reduction efficiency of 32%, CO emission reduction of 28%, and $PM_{2.5}$ emission reduction of 27%.

2.8.3. Traditional charcoal stoves

There are different type's traditional charcoal stoves in the local market. Square and funnel shaped stoves are the most widely ones. The grates of these stoves are removable unlike the other improved charcoal stoves. The main physical characteristics of the above-mentioned stoves are described Table 2-3 (Gashie, 2005).

Table 2-3: Different types of traditional charcoal stoves in Ethiopia (Gashie, 2005)

No	Stove type	Weight(gm)	Combustion camber		Upper rim area(cm^2)	Pan rest	Air Grate		
			Area(cm^2)	Depth (cm)			Shape	Area (cm^2)	Door
1	Funnel traditional metal	783	161.7	6	20*20	yes	trapezoid	21	no
2	Square traditional metal	2060	161.3	8.5	20*20	yes	rectangle	70	no

a b c

Figure 2-2: Charcoal cook stoves which are widely used in Ethiopia a) *Merchaye* stove b) *Lakech* stove c) traditional stove
(Mamuye et al., 2017)

The *Merchaye* charcoal stove is lighter, with a smaller depth, upper surface area and combustion chamber area. It has combustion chamber area of 169 cm^2, depth of 7.8 cm and upper surface area of 324 cm^2 as well as it has 1.8 kg weight. The grate holes are 1-2 cm in diameter. *Lakech* charcoal stove has an upper surface area of 400 cm^2, combustion area of 179 cm^2 and depth of 8.5 cm. It weighs 1.9 kg with a bowl-shaped combustion chamber. The grate holes are 0.5 cm in diameter. The traditional metal charcoal stove weighs1.5kg with combustion area of 180 cm2, depth of 9.5 cm and an upper surface area of 441 cm^2. The cooking pot seats directly on the charcoal in the chamber. *Merchaye* and *lakech* charcoal stoves are made from clay and sheet metal while the traditional stove is made only from sheet metal (Mamuye et al., 2017). Figure 2-2 shows the different charcoal stoves which are found in Ethiopia.

2.9. Other Charcoal Stoves

2.9.1. Ghanan charcoal stoves

Ahinbenso charcoal stove, Gyapa charcoal stove and the traditional coal pot stoves are the three commonly used charcoal stoves in Ghana. Figure 2-3 shows the three types of charcoal stoves which are present in Ghana.

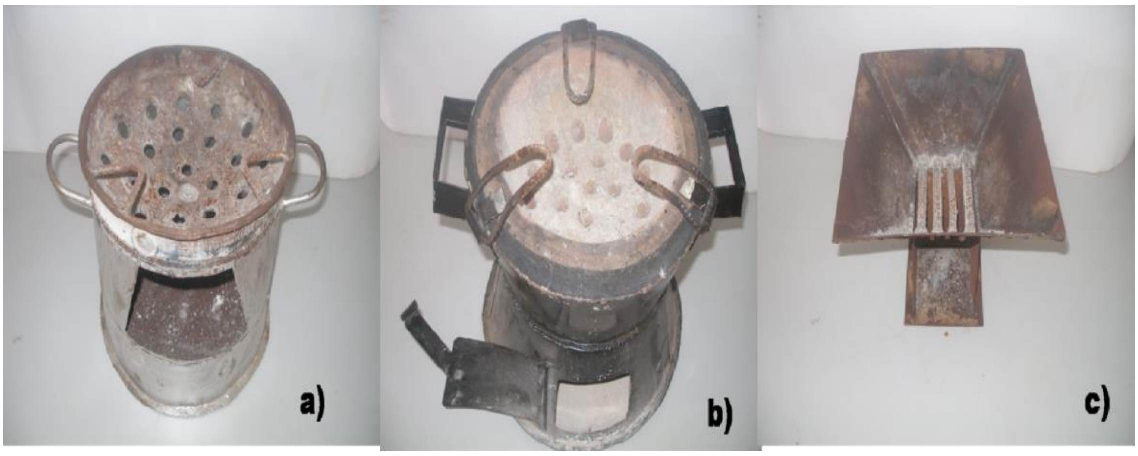


Figure 2-3: charcoal cookstove which are widely used in Ghana a) Ahinbenso b) Gyapa c) Traditional stove (coal pot)

The Ahinbenso charcoal stove has hemispherical combustion chamber with curved surface area of 942.82 cm^2. The combustion chamber and the grate are made from sheet metal. Gyapa charcoal stove also has a hemispherical combustion chamber with surface area of

726.10 cm^2. The combustion chamber and grate are made from clay material. The Traditional coal pot stove had a truncated pyramidal combustion chamber with a surface area of 1093.00 cm^2.

2.9.2. Ugandan charcoal stove

The Ugandan charcoal stove is made from fiber glass, stainless steel and granite rocks. The combustion chamber of the stove 100 mm with 120 mm diameter.

Figure 2-4: Ugandan charcoal stove with pot

The outer chamber was fabricated at an internal diameter of 170 mm using granite rock, glass wool and stainless steel at 23 mm, 48 mm and 1.0 mm thick, respectively.

2.10. Research gap

Simulation models are done at steady state conditions while experimental tests are not. Simulation models may not consider the real conditions like air temperature, wind conditions, moisture content of the fuel and relative humidity. As shown in table 2.4 the thermal efficiency of charcoal stoves is very low as well as their fuel consumption is very high. In general, from the reviewed articles gaps are recognized. Therefore, in this study integrating design, simulation, manufacturing and testing stoves is more reliable than the previously done articles.

Table 2-4: Different types of charcoal stoves reviewed in the thesis

Stove type	Thermal performance (%)	Specific fuel consumption (g/liter)	Reference
Laketch charcoal stove	26	81.1	(Mequaninte et al., 2013)
Merchaye charcoal stove	27	67.3	(Mequaninte et al., 2013)
Ethiopian traditional charcoal stove	18	89.3	(Mequaninte et al., 2013)
Kenyan traditional charcoal stove	21	74	(Grimsby et al., 2016)
Shekela (clay) charcoal stove	29	77.4	(Mequaninte et al., 2013)
Kenyan Jiko Bora charcoal stove	24	62	(Grimsby et al., 2016)
Ghanan Gyapa charcoal stove	23	63.3	(Boafo-Mensah et al., 2013)
Ghanan Ahinbenso charcoal stove	31	58.3	(Boafo-Mensah et al., 2013)
Ugandan granite charcoal stove	29		(Bantu et al., 2018)

All the improved charcoal stoves had higher thermal efficiencies than the traditional charcoal stoves. The improved thermal efficiency is due to the fact that more heat being transferred to the cooking pot and less heat are being lost to the surroundings mainly due to the use of insulating material in the combustion chamber of the improved stove. The thermal efficiency of the different charcoal stoves which are found in Ethiopia ranges from 18% to 29%. The difference between the highest and lowest thermal performance is 11%. Ugandan Ahinbenso Charcoal stove had the highest thermal performance. In terms of specific fuel consumption, the traditional metal charcoal stove consumes more fuel than the other charcoal stoves. From stoves tested in Ethiopia *Merchaye* charcoal stove offered significant fuel savings of 59.5% compared to the traditional metal square charcoal stove. The Ethiopian *Shekela* (clay) charcoal stove and the Ugandan charcoal stove had the highest thermal efficiency next to the Ghanan Ahinbenso charcoal stove. In terms of specific fuel consumption, the Ethiopian traditional charcoal consumes the highest fuel and

Ghanan Ahinbenso charcoal stove consumes the least fuel. Table 2-4 shows the different types of charcoal stoves reviewed in the thesis.

2.11. Computational Fluid Dynamics (CFD) Module

The Computational Fluid Dynamics (CFD) module in COMSOL Multiphysics is a commercially available package that can be used to simulate a variety of flows and is a well-known field within many different engineering disciplines such as aeronautical, biomedical engineering, civil, chemical, mechanical, petroleum and geophysics. It is cost effective way for engineers and scientists to understand, control, optimize and develop designs and process. Modeling of fields flow is an important part in development of new equipment and process. The main focus of flow in the simulation process is to know how the flow affects others processes and application parameters.

The module uses the newest research possible to simulate fluid flow; it offers the most manageable simulation environment for CFD applications. It is used to models laminar and turbulent single or multiple flow, stirred vessels etc. CFD models includes all the steps available for the modeling process such us creating , importing and manipulating the geometry , definition of parameters and component variables , specifying the materials to be includes in the component, setup an appropriate mesh for the modeling domain , defining the physics of the fluids flow on boundaries and in domains ,solving the equations that describe a system for stationers or time dependent behaviors as well as collecting and analyzing results to presents for furthers use in others analysis (Comsol AB, 2019).

COMSOL Multiphysics is an influential modeling environment used to model and answer all types of engineering and scientific problems. The software offers combined desktop environment with a model builder that gives a full overview of the model and access to all functionality. Using COMSOL Multiphysics can extend conventional models for type of physics in Multiphysics models. Accessing this software does not require an in-depth knowledge of Mathematics and numerical analysis. It is easy to build models by defining the relevant physical quantities such as fluxes, sources, material properties and fluxes rather than by defining the underlying equations. The expressions, numbers and variables can apply directly to solid or fluid domains, boundaries, edges and points independently of the computational mesh. The software can perform various types of studies such as stationary, time-dependent, linear, non-linear, eigenfrequency, modal and frequency response studies.

COMSOL Multiphysics software gathers and answers problems using a set of advanced numerical analysis tools. It runs the analysis together with adaptive mesh refinement and error control using a variety of numerical solvers. It also creates arrangements to record all steps that create the geometry, physics, mesh studies, solver settings, visualization and results presentation. This makes to easily change a node in the model tree and rerun the sequences. COMSOL Multiphysics software can be applied in many engineering and science areas, such as; fluid dynamics, heat transfer, geophysics and geomechanics, metal processing, micro fluidics, microwave engineering, pipe flow, porous media flow, semi-conductor devices, structural mechanics, transport phenomena, quantum mechanics, multibody dynamics, chemical reactions, fuel cell and batteries. The software also offers modeling and analysis power for many application areas. There are optional adds-on modules for several key application areas. The module also includes comprehensive application libraries with example models that show the use of the product within its application areas.

CHAPTER THREE

MATERIALS AND METHODS

In this chapter the manufacturing process of the stove, design principles and experimental setup are discussed. It is divided into three sections. The first section discusses about the manufacturing materials and in the second section design principles of charcoal stoves are discussed. The last section discusses about the experimental test set up.

3.1. Type of stove and materials for manufacturing

A charcoal stove as is shown in Figure 3-1 has been developed at Addis Ababa university-Addis Ababa Institute of Technology (AAU-AAiT), Addis Ababa -Ethiopia. All the dimensions were based on the laketch charcoal stove because of its prominence on the Ethiopian local market and availability of dimensional data. The charcoal prototype stove is 260 mm high with a diameter of 250 mm. the stove was designed for a pot with 300mm diameter and the combustion chamber for this type of pot is 180 mm (Bryden et al., 2005). The whole diameter of the stove was calculated from the combustion chamber. The height of the stove is the sum of the height of the combustion chamber, pot support height, height of air entrance and the bottom casing of the stove. In the following sections the materials needed for manufacturing the new prototype charcoal stove will be separately discussed.

Figure 3-1: New prototype charcoal stove

Primary air enters via the grate holes below the fuel bed. The door remains completely open for high power operation and can be almost completely closed to create a large degree of turndown for lower phase (simmering). Figure 3-2 shows the full drawing of the new prototype charcoal stove and table 3-1 shows part drawing names.

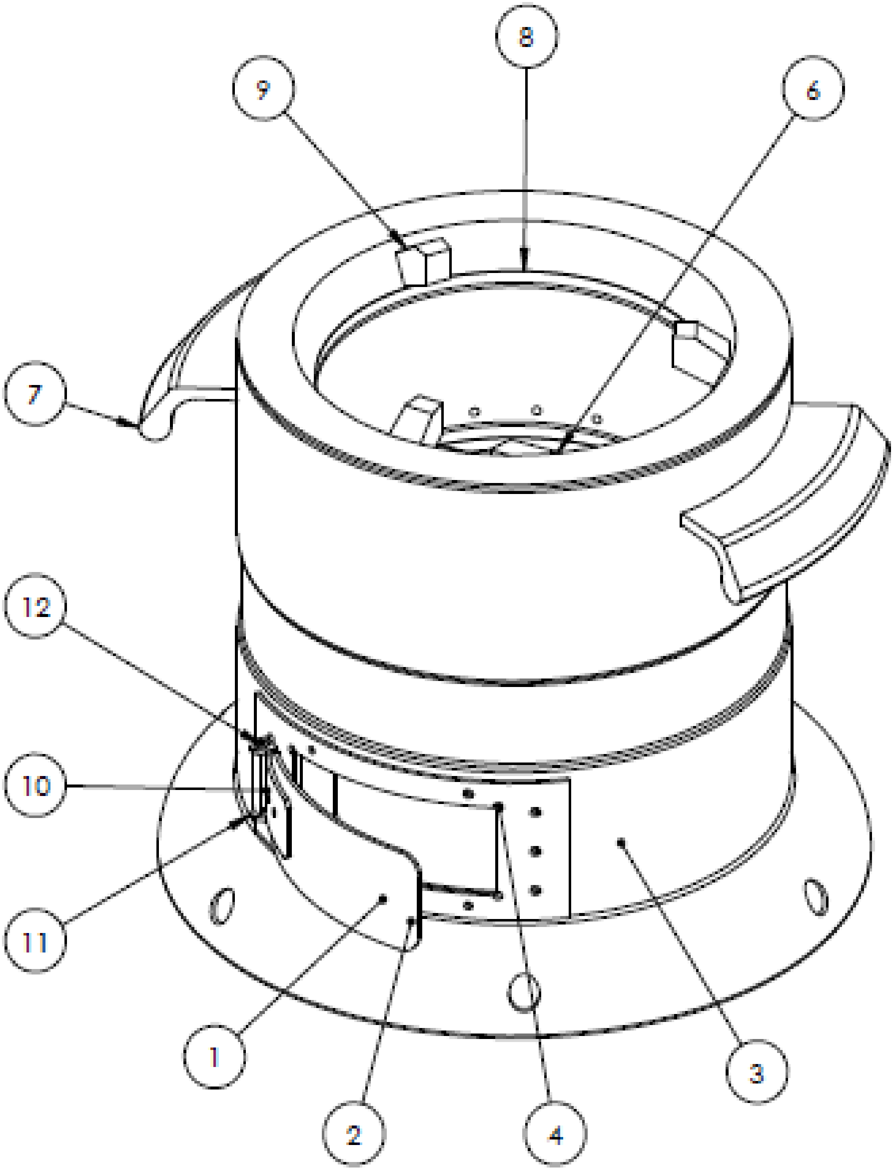


Figure 3-2: Full drawing of the new prototype

Figure 3-2: shows the major components of the new prototype stove. Most of the stove parts are made from sheet metal because of its availability on the local market. Clay was selected for the combustion chamber because it has low thermal conductivity and it is easily accessible. Aluminum foil was selected for the ash tray in order to reflect heat back to the grate holes and combustion chamber

Table 3-1: Part drawing names

Item no.	Part name	Material	Qty.
1	Door_Base_CS008SMXT2	Sheet metal	1
2	Door_CS009SMXT2	Sheet metal	1
3	Main_Case_CS001SMT1	Sheet metal	1
4	Bottom_Inner_Case_CS00 5T2	Aluminum foil	1
5	Bottom_Case_CS006T2	Sheet metal	1
6	Grate _CI003T15	Sheet metal	1
7	Handle_RB007T35	Wood	2
8	Inner_Case_CS003SMT2	Clay	1
9	Top_case_CS002SMT2	Sheet metal	1
10	Hinge_CS010T2	Carbon Steel	1
11	Vertical_Hinge_CS011T2	Carbon Steel	1
12	B18.3.4M - 3 x 0.5 x 3 SBHCS --	Sheet metal	2

3.1.1. Combustion chamber and Grate

The combustion chamber of the new prototype charcoal stove is made from clay mixed with predetermined amount of water and pressed into molds to form brick. The brick was allowed to dry, which took three weeks, and then it was fired at temperatures of 1050℃ .

Figure 3-3: Combustion chamber

Clay bricks are physically durable and to resist abrasion and breakage. The main function of the chamber is to hold the charcoal and to serve as a combustion area. The combustion chamber is 85 mm deep with 180 mm diameter and it is 30 mm thick. Clay properties are explained in chapter four of this research paper. Figure 3-3 shows the combustion chamber of the stove.

Steel was selected for the grate body because steel has less density than clay and it does not store huge amount of heat in its body. For this particular prototype the total numbers of holes are thirteen and are shown in figure 3-4 below. The holes are 12 mm diameter and 3 mm depth. It is 3 mm thick with 180 mm diameter.

Figure 3-4: Grate

First the diameter of the grate holes is determined from *Laketch* and *Merchaye* charcoal stoves. The diameter of the grate holes for *Laketch* and *Merchaye* charcoal stoves are 5 mm and 20 mm, respectively (Mamuye et al., 2017)

. The diameter of the new stove taken to be 12 mm in diameter because this is the optimum diameter. If it is less than this number enough air will not enter the combustion chamber and small pieces of charcoal can block the holes. But if it is greater than this number excess air will enter the chamber and small pieces of charcoal fuel will fall in the ash tray which diminishes the combustion process and thermal performance of the stove. The number of holes were determined using rotational angle with equal spacing method. One hole was drilled at the center and the other four holes were drilled using -90,180, -90- and -180-degree angles. The outer eight holes were drilled using 90, 45, 180, 135, -90, -135, -180- and -45-degree angles.

3.1.2. Auxilaries

Pot support is constructed on the top of the stove. Its basic function is to support the pot during boiling process of water, figure 3-5 shows the pot support of the prototype. It is 20 mm high with 200 mm inner diameter and 250mm outer diameter.

Figure 3-5: Pot support

In this particular study the ash tray of the charcoal stove is made up of aluminum foil and is used to collect ashes and small charcoal pieces during burning process. This reflecting aluminum foil placed in the ash tray is used to reflect radiant heat back to the combustion chamber. The ash tray is 2 mm thick and with 180 mm diameter. Figure 3-6 shows the ash tray of the new prototype stove.

Figure 3-6: Ash tray

The bottom casing is constructed on the bottom of the stove. It is made from sheet metal and its feet are constructed from woods. The woods are used for safety purposes, households can easily use them. It has 322 mm diameter at the bottom and 250 mm at the top.

Figure 3-7: Bottom casing

The bottom casing was manufactured to be aesthetically appealing to the end users. Users satisfaction is one of the essential requirements used to evaluate stove acceptability at community level. There are three feet which used are to prevent heat transfer from the stove to the ground. So, the prototype charcoal stove is easy to use everywhere. Figure 3-7 shows the bottom casing of the stove.

The main casing is used to hold the combustion chamber, the pot support, the grate and the ash tray. It is made from stainless steel and it is 180 mm high with 250 mm diameter. The main casing is shown in figure 3-8 below.

Figure 3-8: Main casing

Sheet metal was selected as a casing material because of; its availability on the local market, its resistance to corrosion in high temperatures, its minimum cost and it has longer service life time than most metals. Its material properties are described in chapter four table 4-5.

3.2. Design process

Designing of a stove consists of four steps: Define the functions, find ways to realize the constituent processes, define shape, materials, and dimensions as well as write specifications and manufacturing instructions (Verhaart, 1982). In order to design a device, one has to know what duties it is expected to accomplish. Other conditions also have to be met. There are organized design processes that can help designers and enterprises to find new ideas and opportunities as well as to create successful solutions that are more likely to meet their goals. The design process includes three phases and three stages. The three phases are: framing the problem, creating a solution and developing a product. Each phase includes three stages:

Collect information and opinions to gain a better understanding, brainstorm different ideas and select the best one, test, implement and verify prior to moving on to the next phase. Table 3-2 shows the essential requirements for cookstove design.

Table 3-2: The essential requirements for cook stove design (Global Alliance for Clean Cookstoves, 2014a)

Usability	Performance	Affordability
Attractiveness	Safety	Sale price
Maintenance & service	Health pollutants	Fuel consumption
Ease of ignition	Durability	Service life
Time saved	Time	Unit cost
Cleanliness	Energy efficiency	
Portability	Greenhouse emissions	
Weight		
User interface		

3.3. Methods

This section describes the method used to develop the improved charcoal stove from the beginning to the end. The method sections throughout this paper are as shown in Figure 3.9.

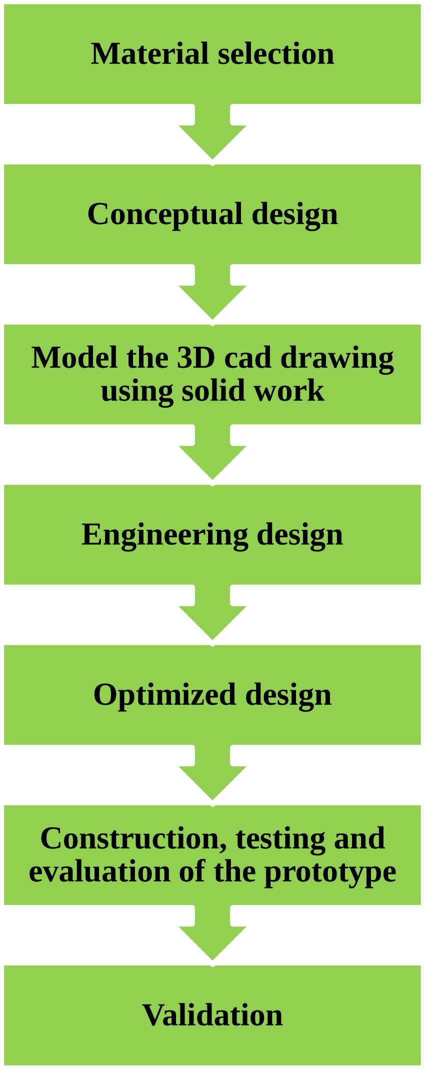


Figure 3-9: Methodology of the research

Material selection is the act of choosing material best suited to achieve the requirements of a given application. In this section the materials needed for the construction of the prototype are discussed. The materials for the combustion chamber, grate, ash tray and insulation sheets are selected. Conceptual design is an early stage of the design process which includes the design of experiences, processes, strategies and interactions. In the case of stoves this stage includes modification of popular stove designs, recombination of different stove designs, or full product design from scrap. Different scientific papers were reviewed in order to design the new prototype charcoal stove.

The 3D cad drawing model of the new prototype stove is drawn using solid work and dimensions are shown in Appendix A. After choosing the conceptual design fundamental and applied principles of engineering and science are applied to generate visible solution.

Modern engineering design tools such as CFD simulation, mathematical modeling of different physical phenomenon, dimensional analysis, numerical simulations and energy analysis are done at this stage. Simulation is the process of subjecting an individual stove component model to various operating and boundary conditions, to evaluate their behavioral characteristics.

Optimized design is the process of maximization or minimization of chosen variables related to quantities like heat transfer, specific fuel consumption, efficiency, emission and cost etc. The new prototype is made up of sheet metal, clay and aluminum foil. Water Boiling Test (WBT) was conducted in order to test stove. Different parameters such as wind speed, relative humidity, temperature etc. was taken during testing the stove. After the stove was manufactured and tested the test results were validated with other similar works.

3.4. Design parameters

When designing the stove, the following parameters were computed: area of the combustion chamber, circumference of the combustion chamber, the gap needed between the bottom of the pot and the top edge of the combustion chamber and. The gap needed between the bottom of the pot and the top edge of the combustion chamber can be very small for charcoal stoves when compared to wood burning stoves. The area of the pot exposed to the charcoal should be maximum when stove designs are done. Pot distance from the top of the fuel should be between 2-5 cm (Baldwin, 1987). For 18 cm diameter combustion chamber the pot diameter should be 30 cm. Area of the combustion chamber and circumference of the combustion chamber was computed based on the following formulas (Bryden et al., 2005).

$$A_c = \pi r^2 \qquad (3.1)$$

A_c is area of the combustion chamber, cm^2

r is radius of the combustion chamber, cm

π is 3.14

$$A = 3.14 \times 9^2$$

$$= 254 cm^2$$

$$C_c = 2\pi r \qquad (3.2)$$

$$C_c = 2 \times 3.14 \times 9$$

$$= 56.52\ cm$$

Where

C_c is Circumference of the combustion chamber, cm

$$A_s = 2\pi r^2 d + \pi r^2 \qquad (3.3)$$

$$A_s = 2(3.14 \times .09 \times 0.085) + (3.14 \times 0.09^2)$$

$$= 0.082\ m^2$$

As is surface area of the combustion chamber, m^2

d is depth of the combustion chamber

the gap needed between the bottom of the pot and the edge of the combustion chamber is given by;

$$N_G = \frac{A_c}{C_c} \qquad (3.4)$$

(Bryden et al., 2005)

3.5. Experimental Approach and Procedure

Charcoal stove prototype was built in the workshop. Charcoal fuels with known cross-sectional area were used for the experimentation. The height, diameter, upper surface area, combustion area, weight and depth of the stove were recorded. The mass of charcoal fuel required to boil water and the remaining charcoal was recorded. Different instruments were used for measurements. Thermal efficiency, time to boil and specific fuel consumption etc. were recorded.

3.5.1. Instruments used for the experimental procedure

The following instruments have been used for conducting testing of the charcoal stove.

a) **OHAUS Scale**

OHAUS Scale is used to measure different instruments like charcoal fuel, water, pot and remaining char etc. Table 3-4 shows the specifications of the scale.

Table 3-4: Specifications of the OHAUS scale

Temperature range	10℃ to 40 ℃
Maximum weight	32000 grams
Accuracy	0.4 milli gram to 0.4 milligram

b) **Wood moisture meter**

It was used to measure the approximate moisture content of the charcoal fuel. Table 3-5 shows the detail specifications of the wood moisture meter.

Table 3-5: Detailed specifications of wood moisture meter

Measurement Range	0 to 99.9% REL (relative reading) for wood;
Measurement Accuracy	±3%
Measurement Resolution	0.1%
Operating Temperature	0° to 50C) @<80%RH
Dimensions	146 x 66 x 22mm)

c) **5 in 1 Environmental meter**

The 5 in 1 environmental meter was used to measure many parameters like ambient temperature, humidity, light intensity, sound level and air velocity Table 3-6 shows the detail specifications temperature, relative humidity and air velocity of the environmental meter.

Table 3-6: Specifications of environmental meter

Measurement	unit	Range	Resolution	Accuracy
Temperature	℃	0 to 50 ℃	0.1℃	± 1.2°C
Air velocity	m/s	0.4 to 30.0m/s	0.1	≤20m/s: ± 3% F.S., > 20m/s: ± 4% F.S.
Humidity	%RH	10 to 95 %RH	0.1 %RH	< 70 %RH: ± 4 %RH ≧ 70 %RH: ± (4%rdg + 1.2 %RH)

d) **K-Thermocouple**

The temperature variation during boiling the water was recorded by thermocouple and they were placed inside the pot. Temperature specifications of the K-type thermocouple is shown in table 3-7 below.

Table 3-7: Thermocouple temperature range

Measurement	unit	Range	Resolution	Accuracy
Temperature	℃	-100 to 1300 °C	0.1℃	± (1% rdg + 1°C)

3.5.2. Water Boiling Test (WBT)

The water boiling test was conducted in Addis Ababa institute of Technology (AAiT) cook stove laboratory to determine the performance of the stove. The WBT test for efficiency can be accomplished with simple equipment all over the world. It is preferable than the other testing protocols because it has benefits such as; It delivers initial or laboratory assessments of stove performance in a controlled setting, Calculate stove modifications during improvements , Select the most hopeful products for field judgments, Confirm that fabricated stoves meet planned performance based on designs and Compare the effectiveness of different designs at accomplishing parallel tasks (Global Alliance for Clean Cookstoves, 2014b).

The water boiling test procedure is explained as follows; Determining the type, size and moisture content of the fuel used. General conditions such as room temperature, wind speed, relative humidity and local boiling of water was recorded, Pot was weighed empty and dry, then weight was recorded, The pot was filled with 2.5 litter water and its new weight was taken and recorded, Weight of charcoal and char containers were taken and recorded, Some quantity of charcoal fuel placed in charcoal container was weighted and recorded, Thermocouple was placed on top of the pot and water temperature was recorded at one-minute interval, The tests were done for 30 minutes. When 30 minute reaches all the remaining charcoal was removed from the stove, the weight of the remaining charcoal and the unused charcoal were weighted and recorded separately and the weight of the pot with the remaining water was taken and recorded.

3.5.3. Experimental test set-up description

An improved charcoal cook stove was used for conducting the experimental study. The experimental work mainly studies the transfer of energy from charcoal fuels to a pot placed in a charcoal stove. A stainless-steel pot of capacity 3.5 liter was used to contain water to conduct the cooking process. Thermocouples was inserted in the boiling water to measure the change in temperature and 5 in 1 environmental meter displays the temperature on its screen. The experimental tests on the new prototype improved charcoal stoves were carried out during the duration starting from August 04/08/2020-08/08/2020 between 08:00 am to 05:00 pm. The station is located at Addis Ababa institute of Technology where, longitude of 38.7 ^{0}E and latitude of 9.04 ^{0}N. figure 3-10 shows the actual test set-up with measuring instruments used.

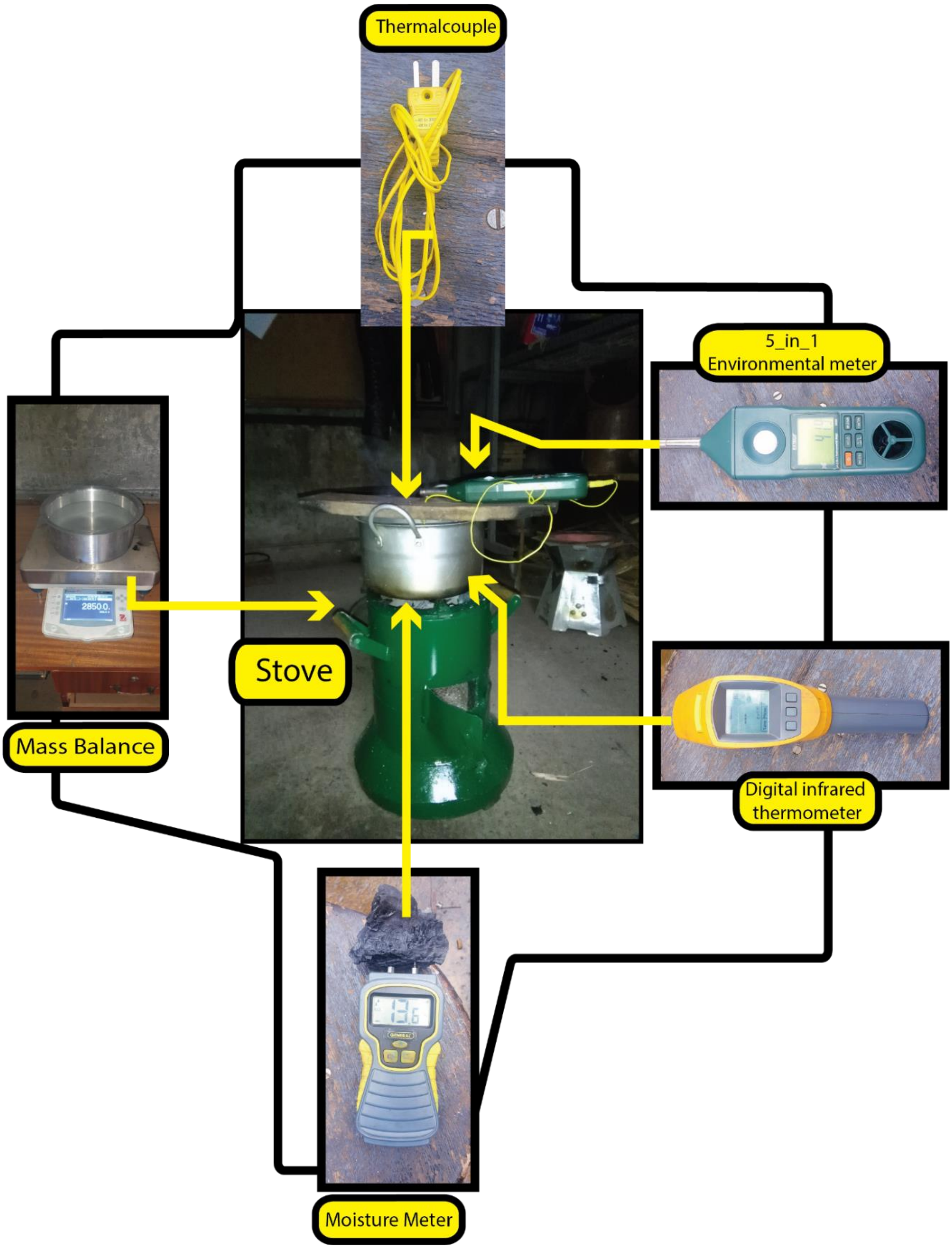


Figure 3-10: the actual test set-up with measuring instruments used

3.6. Performance evaluation methods

3.6.1. Useful energy delivered calculation

It is the amount of energy transferred to the ingredients of the cooking pot or space heating. It includes sensible heat energy and latent heat of vaporization (Ethiopian Standards Agency ,2018)

Useful energy delivered can be calculated using equation (3.5) as follows

$$\boldsymbol{U_i} = \boldsymbol{C_p} W_1 \,(T_2 - T_1) + \,(W_1 - W_2)\Psi \tag{3.5}$$

3.6.2. Cooking power calculation

It is the average rate of heat transferred to the contents of a cooking pot. It is expressed in kilo watts.

Cooking power can be calculated using equation (3.6) as follows;

$$P_{\boldsymbol{c}} = \frac{U_i}{(t_4 - t_1)} \tag{3.6}$$

3.6.3. Calculating cooking thermal efficiency without energy credit for remaining char

The Net Heating Value or Lower Heating Value is defined as the theoretical maximum amount of energy that can be extracted from the combustion of the moisture free fuel. If it is completely combusted and the combustion products are cooled to ambient temperature but the water produced by the reaction of the fuel burning hydrogen remains in the fluid or gas phase. It is calculated using equation (3.7) as follows;

$$\eta_{\boldsymbol{e}} = \frac{U_i}{L_{\boldsymbol{net.fA}}} \tag{3.7}$$

3.6.4. Calculating cooking thermal efficiency with energy credit for remaining char

Thermal efficiency increases when the energy credit for the remaining char is considered. This is calculated using equation (3.8) as follows

$$\varphi_{\boldsymbol{c}} = \frac{U_i}{AL_{\boldsymbol{net.f-JL_{net.c}}}} \tag{3.8}$$

(Ethiopian Standards Agency ,2018)

3.6.5. Calculating emission factor

The emission factor is calculated as follows

$$E_{\boldsymbol{F}} = \frac{X_{\boldsymbol{t}}}{U_i} \tag{3.9}$$

(Ethiopian Standards Agency ,2018)

3.6.6. Calculating emission rate

The emission rate is calculated as described below

$$E_{\boldsymbol{R}} = \frac{X_{\boldsymbol{t}}}{t_4 - t_1} \tag{3.10}$$

(Ethiopian Standards Agency ,2018)

3.6.7. Specific fuel consumption

The amount of charcoal consumed per unit mass of water boiled. It is calculated as follows

$$\boldsymbol{S}\mathrm{fC} = \frac{f\boldsymbol{c}}{WpW - \mathrm{P_t}} \tag{3.11}$$

Specific fuel consumption is a measure of the amount of the fuel needed to boil or simmer one liter of water. It is also described as any number of cooking tasks and should be considered the fuel needed to produce a unit output whether the output is boiled water, cooked foods or loaves of bread. In the case of the cold-start high-power WBT protocol, it is a measure of the amount of charcoal fuel required to produce one liter of boiling water beginning with cold stove.

CHAPTER FOUR

SIMULATION

4.1. Introduction to COMSOL Multiphysics and CFD

It is an influential communicating environment for modeling as well as for answering all types of engineering and scientific problems. COMSOL Multiphysics use the Recognized finite element method to solve models (Comsol AB, 2019). CFD models are capable of handling complex geometries, require simple assumptions, and can provide detailed information about heat transfer, combustion and fluid flow within the cook stove. There are three elements to every computational fluid dynamics (CFD) simulation process (Versteeg and Malalasekera, 2007): pre-processing, solution and post-processing. We describe each of them briefly below.

4.1.1. Pre-processing

It is done at the beginning of the simulation to build and analyze the fluid flow model. It includes building geometry of the model; generating and applying a proper computational mesh, choosing of fluid properties that need to be modeled and entering flow boundary conditions. The preciseness of the solution is defined by the number of cells in the mesh. Better accuracy is achieved by increasing the number of cells but this increases the computational time of the simulation. Finer mesh is needed at the point of interest.

4.1.2. Solution

At this step CFD solver is used to produce results by solving the discretized form of the governing equation. It needs clear understanding of the physics involved in the problem like phenomenon related to heat transfer, reacting flow, mass transfer, radiation, turbulence etc. there are different types of options in the CFD package to solve the governing equations. Flow parameters like velocity, viscosity, density, pressure concentration and temperature are calculated as a solution of all the governing equations at each grid point.

4.1.3. Post-processing

This is the final step in CFD analysis. At this stage the CFD analysis involve the coordination and explanation of the anticipated flow data and the yielding of CFD images and animations. In order to solve the problem different post-processing tools like counter plots, color plots and vector plots are used. The interpretation of these results plays important role in determining the performance of any system being used.

In this work, we develop a steady-state,2D axisymmetric CFD model to simulate heat transfer and fluid flow in charcoal cook stove. The objective of the model is to provide a link between (i) thermal performance of a stove (ii) stove physics (heat transfer, fluid flow) and stove design features. Stove design features include geometric parameters such as combustion chamber diameter and height, grate holes and primary air entrance.

4.2. Heat Transfer

Heat transfer is a method of energy transfer that is driven by temperature differences. Heat transfer occurs when a temperature difference exists in a medium or between media. There are three modes of heat transfer. These modes are; radiation, convection and conduction. In the charcoal stove, there is heat transfer by all the three modes mentioned above. We define each of them briefly below.

4.2.1. Radiation

Thermal radiation is the energy emitted by body that is at a nonzero temperature. It uses electromagnetic waves (photons) to transport the radiation field. Actually, radiation transfer occurs most efficiently in a space. Radiation heat transfer is the principal mode of energy transfer in charcoal stoves. There are five principal areas through which radiative heat transfer should occur in charcoal stoves; from the fire bed and flames to the frying pan, From the hot gases to the charcoal to sustain combustion, from the flames and fire bed to the stove wall, from the stove body to the pot and from the stove body to the surrounding (Usman, 2011) .

The rate at which energy is released per unit area is termed as the surface emissive power and it is governed by Stefan Boltzmann law which can be expressed as

$$E = \varepsilon\sigma T^4 S \qquad (4.1)$$

ε= emissivity, whose values lie in between 0 and 1 (1 for an ideal radiator or black body)

The rate at which radiation is incident upon the surface per unit surface area is called irradiation, G (W/m^2). This irradiation can be transmitted, reflected or absorbed (Bergman et al., 2011). That is;

$$irradiation = transmitted + reflected + absorbed$$

$$\rho + \alpha + \tau = 1 \qquad \mathbf{(4.2)}$$

Radiosity (J) is the rate at which radiation leaves a surface per unit area. For an opaque surface itis described by

$$J = E + \rho G \qquad (4.3)$$

4.2.2. Convection

Convection heat transfer is a mode of energy transfer between a solid surface and a moving fluid due to bulk fluid motion and random motion of fluid molecules. To understand convection heat transfer between a surface and flowing fluid the concept of boundary layer is necessary. The rate of convective heat transfer can be expressed as

$$\mathbf{Q_{conv}} = \mathrm{hA}(\mathrm{T}_{\mathbf{sur}} - \mathrm{T_f}) \qquad (4.4)$$

4.2.3. Conduction

Conduction is mode of energy transfer between two solid surfaces. In charcoal stoves there are two principal areas which conductive heat transfer should be expected; conduction heat transfer through the stove walls and conduction heat transfer through the pan to the product to be boiled, fried and baked (Usman, 2011). The conductive heat transfer is given by the Fourier's relation

$$\boldsymbol{q}_{\boldsymbol{cond}=-\boldsymbol{KA}\frac{\partial \boldsymbol{T}}{\partial \boldsymbol{y}}} \qquad (4.5)$$

The minus sign in the above formula is inserted to satisfy the second principle of thermodynamics i.e. energy transfers from high temperature region to low temperature region (Holman, 2010).

4.3. Fluid flow Governing Equations

There are three fundamental conservation laws governing the fluid flow behavior in biomass cook stoves. Each of them is briefly described below.

4.3.1. Conservation of mass

Conservation of mass simply means that the time rate of change mass of a system must be zero. In differential form it is expressed as

If density of fluid is dependent of time the mass conservation equation is expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 \qquad (4.6)$$

For stationary analysis

$$\nabla \cdot (\rho u) = 0 \tag{4.7}$$

(McDonough, 2009)

4.3.2. Conservation of Momentum

Fluids are not consisting of point masses, so, it is not proper to apply Newton's second law of motion in the usual form$F_{r=ma}$. Instead, we will use a more universal form expressed in words as time rate of change of momentum of a fluid element = sum of forces acting on the fluid element. The general statement of the Newton's second law is given by

$$\mathrm{F}_{\boldsymbol{r}} = \frac{\mathrm{d(mu)}}{\mathrm{dt}} \tag{4.8}$$

Where

F_r is the resultant of all forces acting on the fluid element.

If we consider a fixed mass m of a fluid contained in an arbitrary region R(t), there are two main types of forces acting on a fluid element. These are categorized into body forces and surface forces.

Body forces acting on the entire region R(t), denoted

$$\int_{\mathrm{R}(\mathbf{t})} \boldsymbol{F_B}\, \mathrm{dV} \tag{4.9}$$

Surface forces acting only on the surface S (t) of R (t). Denoted by.

$$\int_{\boldsymbol{s}(\boldsymbol{t})} \boldsymbol{F_s}\, \mathrm{dA} \tag{4.10}$$

This is not suitable for practical use or engineering calculations. So, the momentum conservation equation for a single-phase fluid flow interfaces are based on the Navier-stokes equations, which in their most general form read as

$$\rho \frac{\partial \mathrm{v}}{\partial \mathrm{t}} + \rho(v.\nabla)v = \nabla.[-\mathrm{pI} + \tau] + F_v \tag{4.11}$$

The viscous stress tensor is given by

$$\tau = 2\mu S_{r-}\frac{2}{3}\mu(\nabla.\mathrm{v})\mathrm{I} \tag{4.12}$$

$$S_r = \frac{\mathbf{1}}{2}(\nabla v + (\nabla v)\mathrm{T}) \tag{4.13}$$

On rearranging equations (4.10) and (4.11) the momentum conservation equation for incompressible as well as for compressible fluid flow with viscosity and density variations are given by (Zienkiewicz et al., 2000)

$$\rho\frac{\partial v}{\partial t} + \rho v.\nabla v = -\nabla p + \nabla.\left(\mu(\nabla v + (\nabla v)square) - \frac{2}{3}\mu(\nabla.v)I\right) + F_v \tag{4.14}$$

For a stationary analysis, the equation reduces to

$$\rho v.\nabla v = -\nabla p + \nabla.\left(\mu(\nabla v + (\nabla v)square) - \frac{2}{3}\mu(\nabla.v)I\right) + F_v \tag{4.15}$$

For incompressible fluid flow where ρ is constant or nearly constant i.e., the case for gases at low velocities and for all liquids under normal conditions the momentum conservation equation reduces to;

$$\rho\frac{\partial v}{\partial t} + \rho(v.\nabla)v = \nabla.\left(-pI + \mu(\nabla v + (\nabla v)square\ T)\right) + F_v \tag{4.16}$$

For a stationary analysis, the equation reduces to

$$\rho(v.\nabla)v = \nabla.\left(-pI + \mu(\nabla v + (\nabla v)square\ T)\right) + F_v \tag{4.17}$$

4.3.3. Conservation of Energy

The first law of thermodynamics states that energy is always conserved. It cannot be created or destroyed. This means that the amount of energy entering a system must be equal to the amount of energy leaving a system. For single-phase fluid flow interfaces are based on the Navier-stokes equations which in their most general form read as;

$$\rho C_p\left(\frac{\partial T}{\partial t} + (v.\nabla)\mathrm{T}\right) = -(\nabla.\mathrm{q}) + \tau{:}\,S_r - \frac{T}{\rho}\frac{\partial\rho}{\partial T}\left(\frac{\partial p}{\partial t} + (v.\nabla)\mathrm{p}\right) + \mathrm{Q} \tag{4.18}$$

4.4. Materials

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

i. Combustion chamber

The combustion chamber is made of fired clay which can withstand high temperatures. Some important properties of fired clay are given in table 4-1.

Table 4-1: Material properties of the fired clay

Property	value
Specific heat capacity	880J/kg. k
Thermal conductivity	1.3 K [W/ (m. K)]
Density	1460kg/m^3

ii. Sheet metal

Sheet metal is the material needed for the seal, grate and vessel. The most important properties of the material used are stated in Table 4-2.

Table 4-2: Material properties of sheet metal

property	value
Heat capacity at constant pressure	475 J/Kg.
Density	7850 Kg/m^3
Thermal conductivity	44 K (W/m. K)

iii. Air

The material specified for the fluid phase occurring in the domain is air. The properties of air available from the COMSOL Multiphysics material library are used. Table 4-3 shows air properties

Table 4-3: Air properties from COMSOL Multiphysics

No	Property	Value
1	Thermal conductivity	0.0242 k$[w/(m.k)]$
2	Density	1.225 kg/m^3
3	Viscosity	1.789*10^{-5}kg/m-s
4	Specific heat capacity	1006.43 J/kg. k

4.5. Boundary conditions

Figure 4-7 shows the different boundary conditions used in the domain.

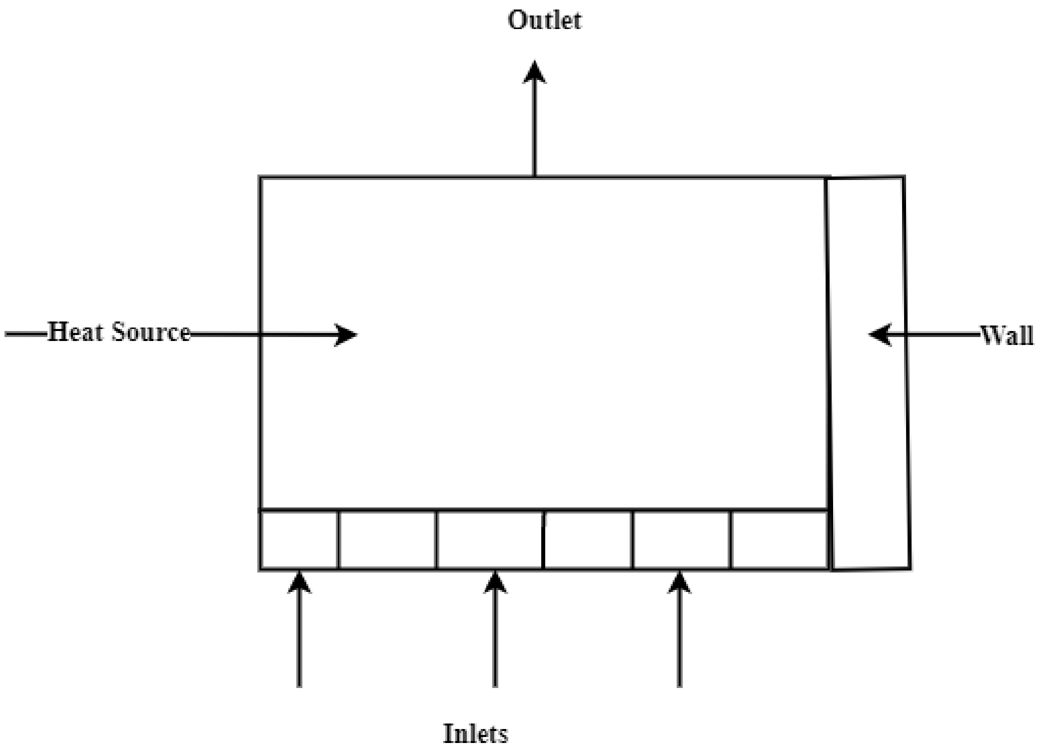


Figure 4-1: Model boundary conditions

Some of the major assumptions made in defining the geometry are:

- In this simulation process only the combustion chamber of the stove is modeled.
- The model is developed for a case when there is not a vessel placed on the top of the stove.
- To reduce computational effort detailed design of the insulation sheets has not been included.

- The flow is steady state flow where fluid variables become independent of time
- The fluid is assumed to be incompressible
- To reduce computational time and resource on 2D-axisymmetric model is developed

There are four types of boundary conditions in the domain. A brief overview of the different boundary conditions is provided in the following section.

4.5.1. Inlet

It is the part where air enters the ash chamber. The air at this position is entered by natural convection. The flow properties of the entering air are calculated from experimental results. The fluid velocity measured at the inlet is

$$F_R = VA \tag{4.19}$$

The mass flow rate of air through the stove is

$$\mathrm{w} = \mathrm{V}\rho \tag{4.20}$$

The area of each grate holes, G_A is given by

$$G_A = \pi r^2 \tag{4.21}$$

After calculating the grate hole areas and with the flow rates available a rough estimation of the Reynolds number can be obtained. Since there are three grate holes, the flow from the ash chamber is divided almost equally among the three holes. The flow rate through each of the grate holes was calculated using equation 4.22;

$$V_g = AV \tag{4.22}$$

Velocity at the grate hole is calculated by

$$\mathrm{U_g} = \left(\frac{\mathrm{V_g}}{\mathrm{G_A}}\right) \tag{4.23}$$

The air gets heated as it rises up the grate. The average air temperature at the inlet of the grate holes which is found from experimental measurement is 500K .

4.5.2. Stove walls

The inside stove wall is made up of clay material and the boundary conditions at the walls are; Temperature, radiation heat transfer, convective heat transfer but at the solid wall the temperature specified is the ambient temperature which is 293K. There is conduction and radiation heat loss to the base of the combustion chamber. No slip conditions.

4.5.3. Heat source

This node describes heat generation within the combustion chamber. The combustion chamber is modeled using a source term with uniform heat generation. Heating is expressed with a positive value and cooling is expressed with a negative value. The average heat source in the new prototype charcoal obtained from experimental measurements is about 1,715 kW.

4.5.4. Outlet

This boundary condition is specified as the outlet pressure and pressure value was taken as ambient pressure. The ambient pressure of Addis Ababa is 76 kPa. This value is taken for the simulation.

4.6. Laminar flow model

Laminar flow model is used to compute the velocity and pressure fields for the flow of a single-phase fluid in the laminar flow regime. A fully developed flow condition is described by a dimensionless Reynolds number. The Reynolds number is the ratio of the inertial force to the viscous force of the flow. The fluid flow in geometries like cook stoves having Reynolds number less than 2000 is called laminar flow (Ismail and Adewoye, 2012). At low Reynolds number viscous forces dominate which leads to laminar flow. Laminar flow is characterized by flows in parallel layers with no disruption between the layers, low velocities, no lateral mixing, and adjacent layers slide past one another.

A flow will remain laminar as long as the Reynolds number is below a certain critical value. The equations solved by the laminar flow interface are the Navier-stokes equations for conservation of momentum and the continuity equation for the conservation of mass. The laminar flow interface can be used for stationery and time-dependent analysis. Note that for high Reynolds number, a flow becomes inherently time-dependent and three dimensional, and time dependent studies have to be used. We can use the Reynolds number, as a simple mathematical expression, used to predict whether the flow via geometry will be laminar or turbulent. Laminar flow heat transfer in tube geometries like cook stoves is encountered in a wide variety of engineering and science applications. The following examples describe laminar heat transfer in tubes (Hong, 1974); heat of the circulating fluid in solar collectors, heat transfer in compact exchangers, heat transfer in biomass cook stoves, cooling of space suits and warming and cooling of blood during surgical operations. Laminar flow heat transfer is dependent on many variables including tube geometry, flow inlet velocity profile, fluid properties, tube orientation, tube wall properties and heat flux boundary conditions. The Reynolds number can be calculated using equation (4.23) (Uruba, 2018)

$$\mathrm{Re} = \frac{\rho U_g d}{\mu} = \frac{U_g d}{\nu} = \frac{Q_r d}{\nu A} \quad (4.24)$$

4.7. Simulation workflow

Figure 4-3 shows the simulation work flow of the research. When one opens the COMSOL Multiphysics software the model environment open first and select the model wizard. The next step is to space dimension window and the 2D-axisymetric dimension was selected. After selecting the space dimension, the physics would follow and from this the heat transfer in fluids and laminar flow from heat transfer and fluid flow modules was selected, respectively, which are found in the CFD package of the software. Stationery and time dependent studies are available with the heat transfer in fluids interface. Stationary study is selected because temperature field is independent of time at each point. Stationary type of study is selected because the flow is at steady state and the temperature is independent of time. This study type is also used for optimum problems that are constrained with stationary PDE. In heat transfer, it is used to compute the temperature field at thermal equilibrium.

In the COMSOL Multiphysics software desktop different types of windows are found such as model builder window settings window and graphics window etc. So first making a tour in the desktop window is necessary. Before creating a geometry creating definitions like parameters, variables and functions were done. The 2D-axisymmetric geometry was done in the software first by creating 3D drawing of the object and second by making a partition of the object in four parts. After creating the geometry material was selected from the material library which is found in the software.

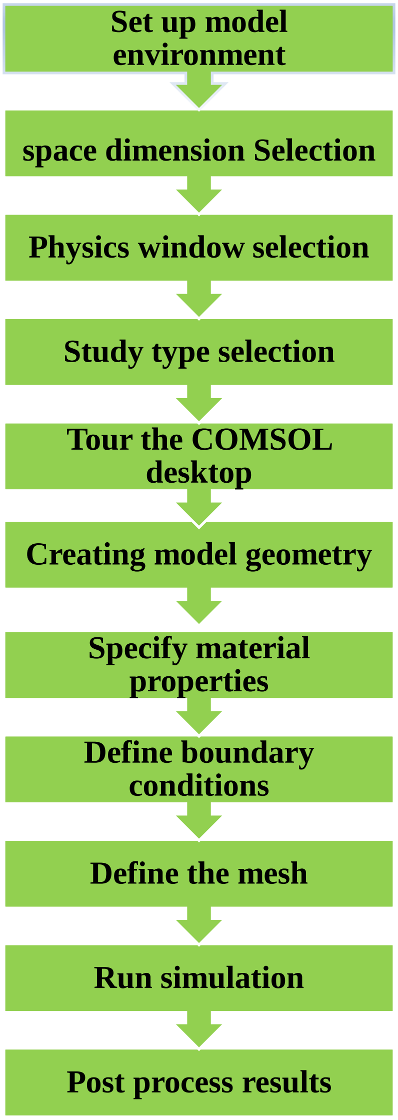


Figure 4-2: The simulation work flow

In the material browser section, there are a lot of materials to be selected. In this model air, clay and stainless steel were selected and added in the material properties window. There are four types of boundary conditions in this simulation; inlet, clay wall, heat source and outlet. After doing the above procedures the mesh was done and normal mesh was selected for clay wall and extra fine mesh for grate inlets and the fluid section. Lastly, running the simulation and interpreting the results were done.

CHAPTER FIVE
RESULTS AND DISCUSSION

In this chapter, the results obtained from the experiment and simulation model are discussed. The chapter is divided into two sections. The first section discusses the results obtained from the experimental testing and in the second section the CFD simulation results are discussed and compared with the experimental ones.

5.1. Thermal performance of the stove

Thermal performance indicators including thermal efficiency, specific fuel consumption, fire power, water boiling rate, and fuel use reduction were used to calculate the performance of the designed stove. Data used in the calculation (Table 5-1) were produced by WBT protocol. In order to know the thermal performance of the stove five tests were conducted. The test results are summarized in Table 5-1 below. From the table the two main performance indicators i.e., thermal efficiency and specific fuel consumption are discussed in detail. The other performance parameters are briefly discussed below;

Time to Boil; The time it took to boil pot 1 from initial temperature to final temperature.

Temp-corrected time to boil Pot # 1; it is an important parameter which is used to determine the speed of the stove at high power. It is time it took for pot #1 to reach boiling temperature, corrected to reflect a temperature rise of 75 deg C from start to boil.

Burning rate**;** The rate of fuel consumption during which the water gets boiled. It is calculated by dividing the equivalent dry fuel consumed by the time of the test.

Temp-corrected specific fuel consumption; This is the specific fuel consumption measure, also corrected as if the temperature rises from start to boil was 75 ℃, in order to easily compare different tests that may have had different beginning or boiling temperature. It is best to usually look at the corrected temperature.

Temp-corrected specific energy consumption; This is the same measure as the temperature-corrected specific fuel consumption, but reported as kilojoules per liter. This is used to compare different fuels, such as various types of wood, charcoal, dung etc.

Temp-corrected specific energy consumption; This is the same measure as the temperature-corrected specific fuel consumption, but reported as kilojoules per liter. This is used to compare different fuels, such as various types of wood, charcoal, dung etc.

Table 5-1: Summary of results on thermal performance of the stove

No	Performance index	Unit of measure	high power test (cold start) charcoal stove						Three -stone fir (Adem andAmbie, 2017)
			Test -1	Test-2	Test-3	Test-4	Test-5	Avg.	test-1
1	Thermal efficiency	%	31	32	33	35	32	32.6	14
2	Time to boil Pot # 1	min	30	30	30	30	30	30	24
3	Temp-corr time to boil Pot # 1	min	30	31	30	30	31	30	27
4	Burning rate	g/min	3.3	3.1	3.5	3.9	3.4	3	35
5	Specific fuel consumption	g/liter boiled	60	59	56	53	52	56	187
6	Temp-corr sp consumption	g/liter	61	60	57	53	54	57	213
7	Temp-corr sp energy consumption	kJ/liter	1819	1798	1700	1591	1613	1704	4013
8	Firepower	watts	1674	1555	1674	1949	1723	1715	10913

Fire power; this is the fuel energy consumed to boil the water divided by the time to boil. It tells the average power output of the stove in watts during the high-power test. It is affected by both the stove i.e., size of fuel and combustion chamber and user operation i.e., rate of fuel feeding. It is an indicator of how consistently the operator ran the stove over multiple tests. A higher or lower value is not necessarily preferable, but rather is an indicator of the size of the stove.

5.1.1. Thermal efficiency

Thermal efficiency is the most commonly used indicator for reporting stove performance. Thermal efficiency is the percentage of input energy transferred to the water in a vessel placed on the stove. The new prototype charcoal stove was compared with the previous works in terms of its thermal efficiency. The average thermal efficiency obtained is 32.6%.

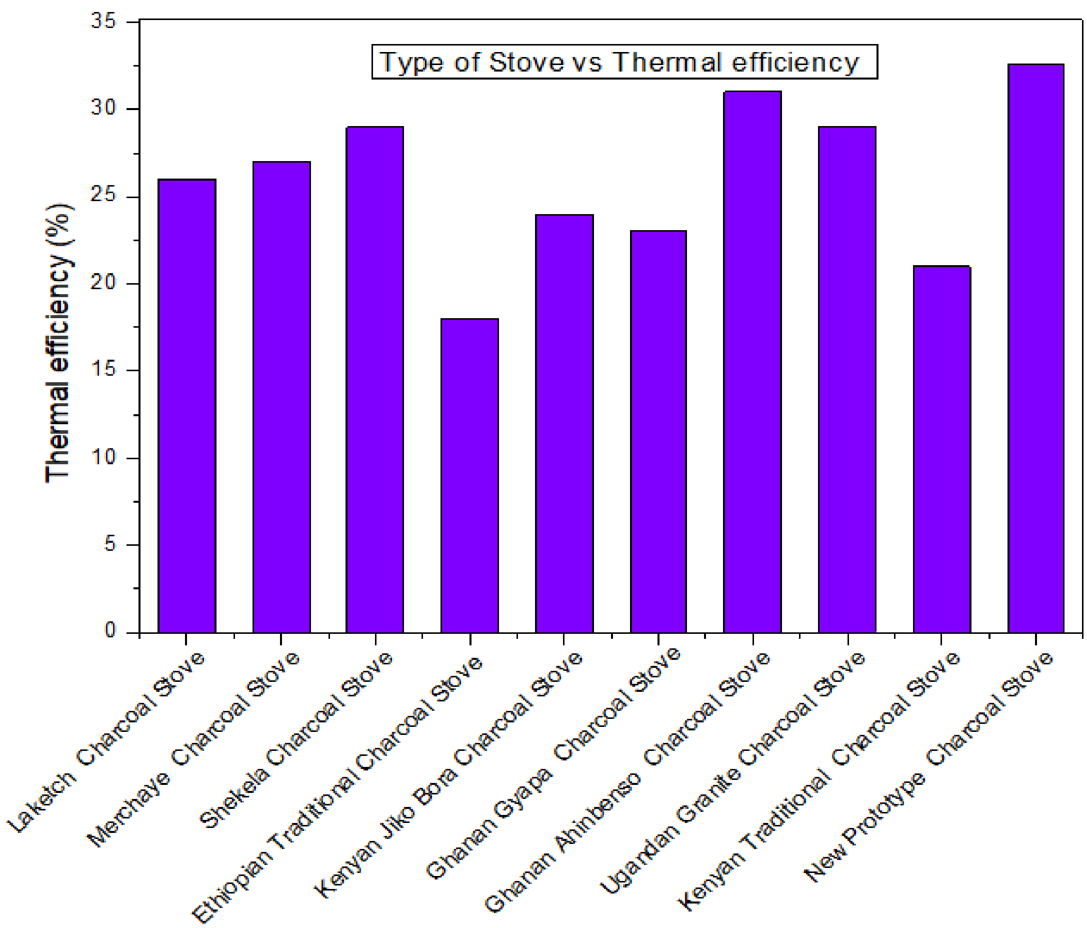


Figure 5-1: Comparisons between thermal efficiencies % of different stoves

The thermal efficiency of the new prototype stove is increased because of the grate and the ash tray are made from sheet metal and aluminum, respectively. Sheet metal does not store and absorb huge amount of heat in its body. Aluminum foil in ash tray is used to reflect radiant heat back to the combustion chamber. The thermal efficiency of a granite charcoal stove is 29% (Bantu et al., 2018) . The thermal efficiencies of shekel, *Lakech*, *Merchaye* and traditional charcoal stoves are 29%, 26%, 27%, and 18%, respectively (Mequaninte et al., 2013) . the Tanzanian traditional charcoal stove and Jiko Bora charcoal stove have a thermal efficiency of 21% and 24%, respectively (Grimsby et al., 2016). The thermal efficiency of Gyapa and Ahinbenso charcoal stoves which are found in Ghana are 23% and 31.3 %, respectively (Boafo-Mensah et al., 2013). In Fig 5-1 Comparisons was made with locally and globally existing stoves. The designed, simulated and manufactured new prototype charcoal stove achieves tier 2 in the IWA tiers of performance which shows substantial improvement over the baseline traditional 3-stone fire.

5.1.2. Specific fuel consumption

Specific fuel consumption is defined as the amount of fuel consumed per liter of water boiled. The specific fuel consumption of the new prototype charcoal is compared to that of the traditional stove to measure the fuel saving between the two. The specific fuel consumption of the new prototype charcoal stove shows 63% improvement compared to the traditional charcoal stove. Figure 5-3 shows the specific fuel consumption of the different stoves.

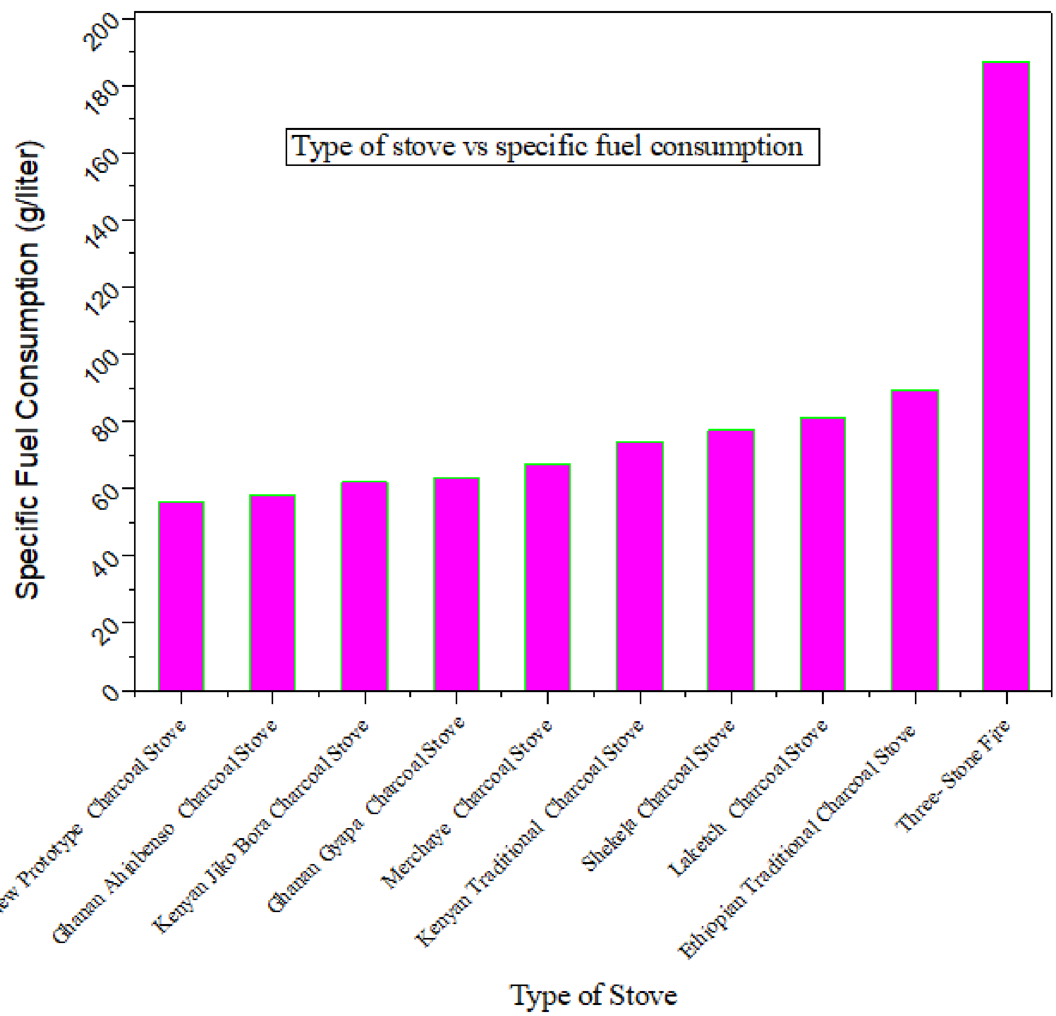
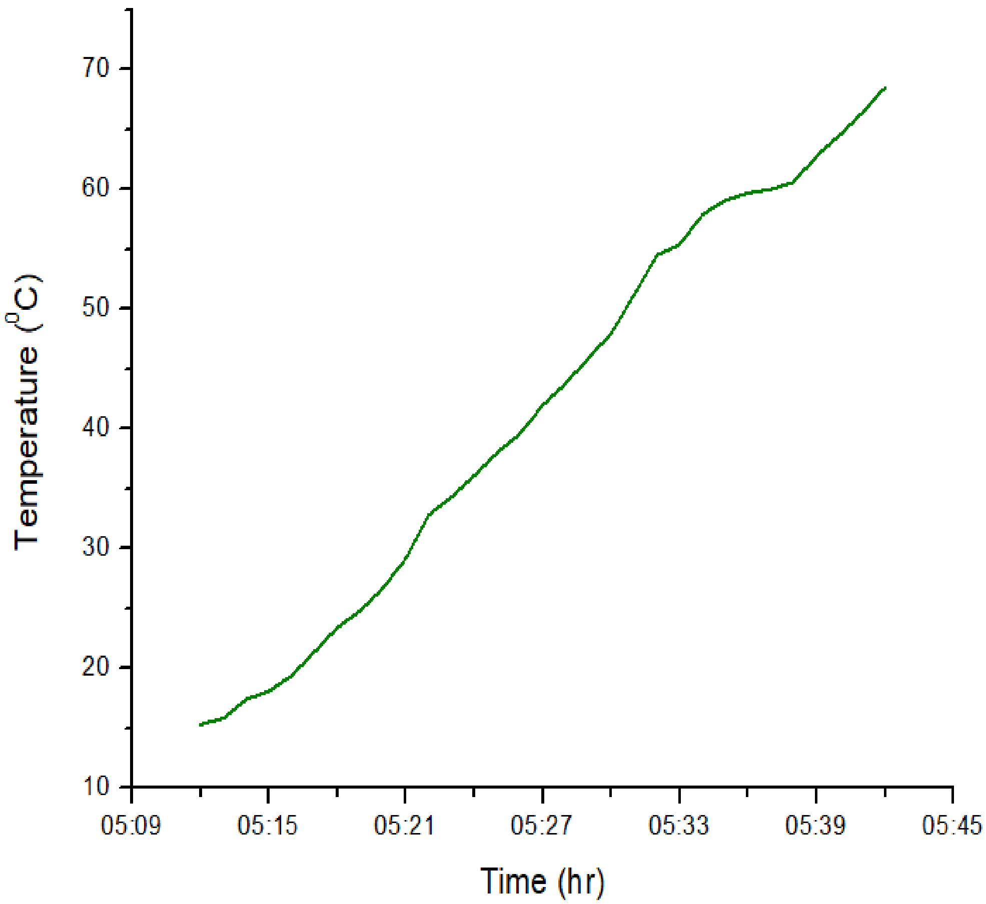


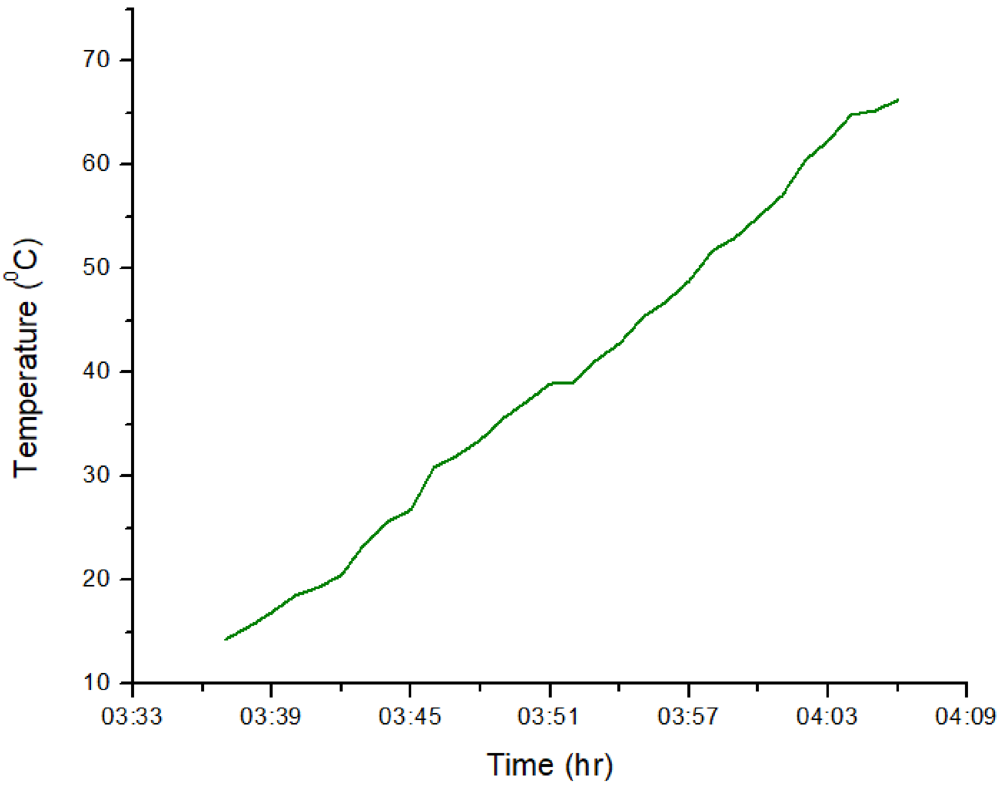
Figure 5-2: Comparisons between specific fuel consumptions g/liter of different stoves

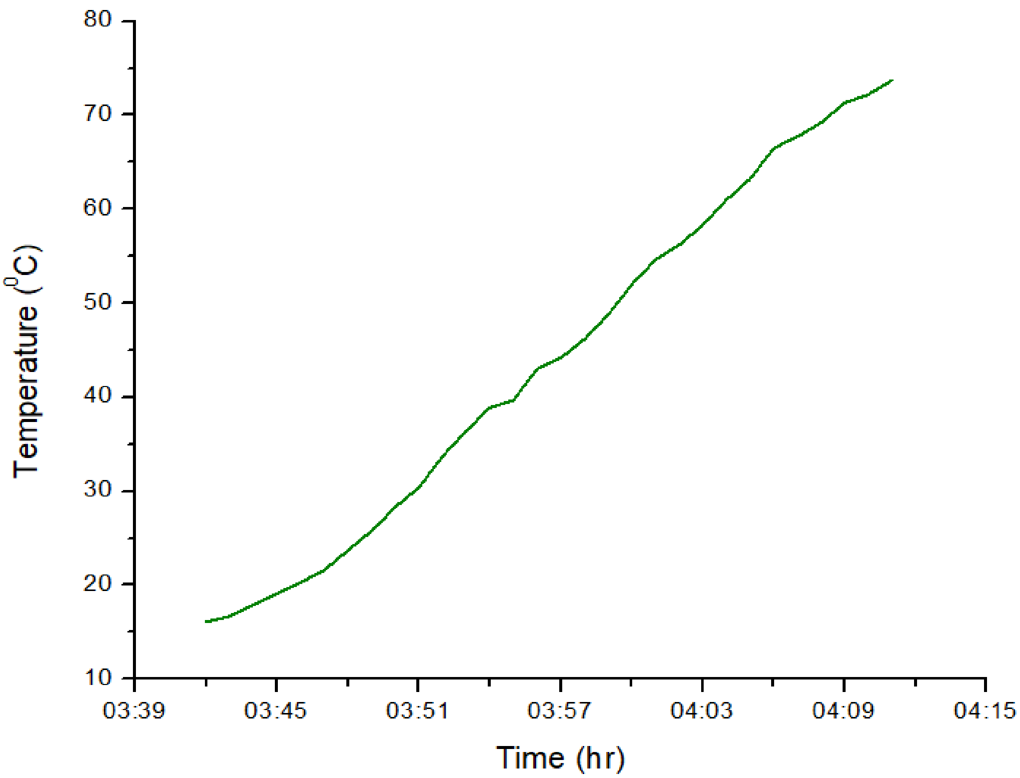
From figure 5-2 the new prototype charcoal consumes less fuel than the other charcoal stoves. If a stove can save a fuel up to 25% over a traditional stove it is called an improved cook stove (Ethiopian Environmental Protection Authority, 2004). In Africa, especially sub-Saharan Africa, charcoal and wood fuel accounts for 75% of total wood harvest, which contributes for high deforestation in countries like Ethiopia (Jagger and Jumbe, 2016). Thus, designing and manufacturing improved cook stoves have great implications concerning forest degradation since the use of such stoves can reduce deforestation and climate changes.

5.2. Time vs. temperature variation for the tests

The variation of temperature with time for the five tests was shown in table 5-2. The test was conducted for duration of 30 minutes.




Temperature (0C)
70
60
50
40
30
20
10
03:33
03:39
03:45
03:51
03:57
04:03
04:09
Time (hr)


Temperature (0C)
80
70
60
50
40
30
20
10
03:39
03:45
03:51
03:57
04:03
04:09
04:15
Time (hr)

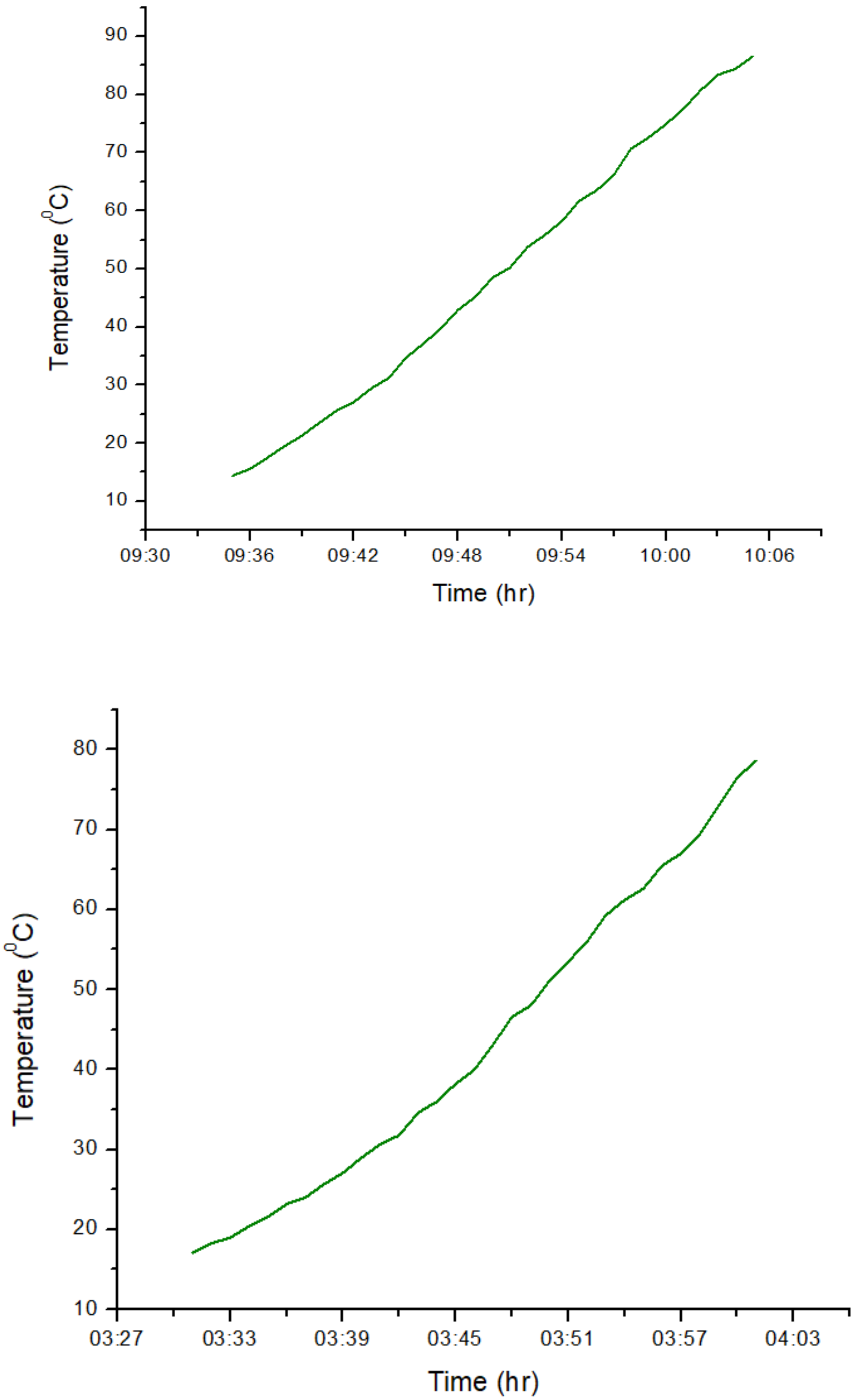


Figure 5-3: Temperature of water during boiling process

The WBT protocol specifies that the stove to tested at three phases i.e., high-power cold start phase, high power hot start phase and low power (simmer phase). All the tests began with the stove at ambient conditions and this is called the high-power cold phase. During high power phase the stove operated at high power to heat water in the pot. As the WBT protocol the tests were conducted inside cook stoves lab. In all the tests conducted temperature increases from the starting time to the end of the test. Five tests were conducted on the manufactured stove principally to access the thermal performance of the stove such as thermal efficiency, specific fuel consumption time to boil, fire power etc. At the same time, the result indicates the accuracy level of the test results. The tests were conducted at different times day morning and day afternoon. At both times the tests show similar trends because the tests were conducted at rainy season. For all the tests there was a gradual decrease in mass of water with increasing temperature over time. During the first test mass of water with pot decreases from 2850.4 grams to 2680.5 grams and water temperature increases from 15.3 ℃ to 68.5 ℃. The weight of fuel consumed was 120 grams and the time was day-morning. For test two weight of pot with water decreases from 2850 grams to 2685.7 gram and water temperature increases from 16.3℃ to 66.2 ℃. The amount of fuel consumed was 110 grams and the time was day morning. For the third test the weight of pot with water decreases from 2848 grams to 2678 grams and water temperature increases 16.1℃ to 73.1 ℃. In this test the amount of fuel consumed was 118 grams and the time was day-morning. During the fourth test weight of pot with water decreases from 2850 grams to 2640 grams and water temperature increases from 14.4℃ to 86.5 ℃. The amount of fuel 157 grams and the time was day-afternoon. For the last test weight of pot with water decreases from 2848 grams to 2690 grams and temperature increases from 17.1 ℃ to 78.6 ℃ . The amount of fuel consumed was 120 grams.

5.3. CFD Simulation result analysis

5.3.1. Mesh statistics

When building the mesh there are several factors that should be taken in to consideration. All of which can be addressed using various features and functionalities available in the software. These includes; choosing a mesh sequence type either it is physics controlled or user controlled, meshing sequence order, element type, element size and distribution, element order being used and mesh quality. In discretizing a given problem there are three considerations; how to divide the geometry (element type used), Shape used to divide the geometry, how the solution is interpolated between the nodes. The generated mesh was dominantly composed of mostly triangular elements is used for the simulations. Table 5-2 shows some details of the mesh used.

Table 5-2: Some details of the mesh used

Description	Value
Minimum element quality	0.1355
Average element quality	0.9296
Triangle	9548
Quad	344
Edge element	536
Vertex element	18

Discretization of the geometry in to small elements of simple shapes is called mesh. The mesh quality is defined as an indication of the length to width ratio of the elements. Minimum element quality measures the regularity of the mesh elements shapes which leads to inverted mesh elements. From the above table the geometry is divided by element type. The element type used is the shape which is used to divided of the geometry. The mesh element quality is a dimensionless quantity between 0 and 1, where 0 represents a degenerated element and 1 represents a perfectly regular element in the choosen quantity measure. Low element quality cuases poor convergence for iterative solvers and makes the problem ill- conditioned in general. Inverted mesh element is defined that a mesh element is wrapped inside-out or has zero area in 2D or zero volume in 3D. Triangular and quadirilateral shapes are used to divide 2D model geometry. Tetrahedron, hexahedron,pyramid and prism shapes are used to divide the 3D-model geometry. The number, size and distribution of elements are controlled using size and distribution nodes.

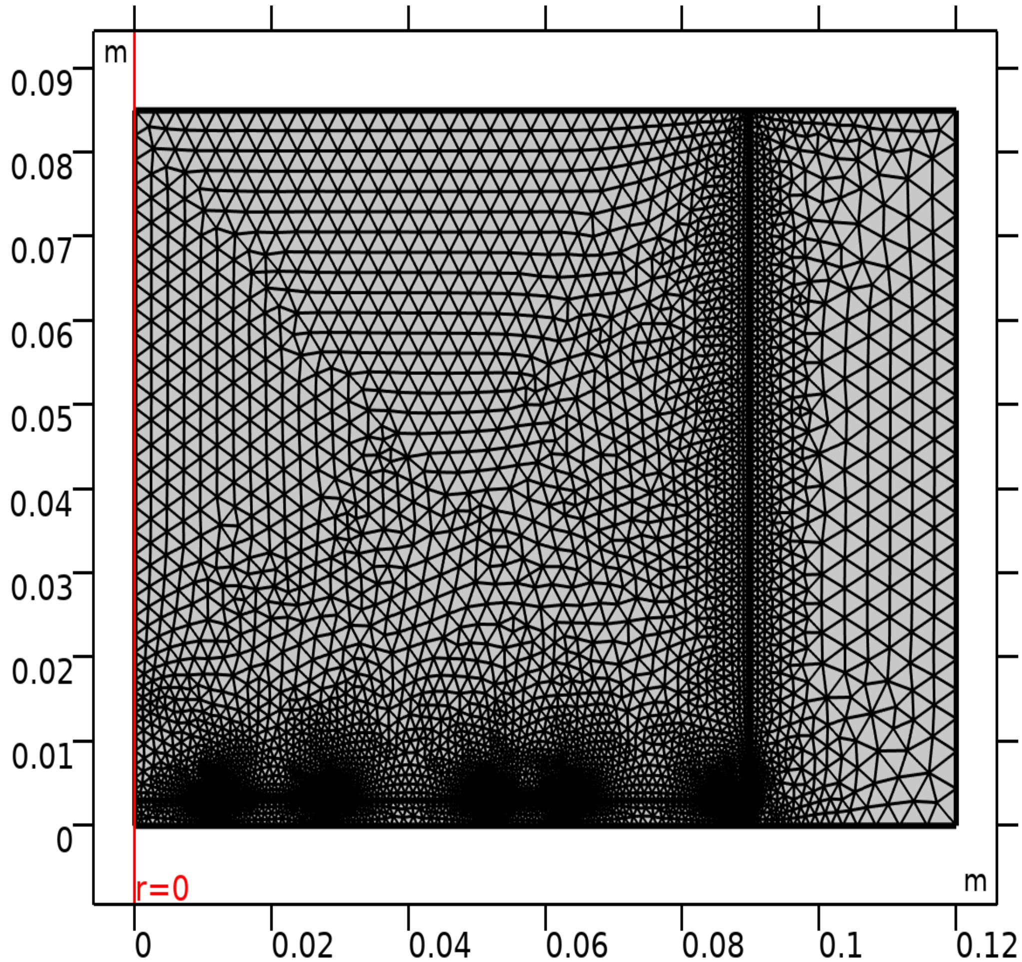


Figure 5-4: The generated mesh

There is very finer mesh at the shared boundary and this is to accommodate the material effects on both sides. In order to get real solution, the number of edge elements must be increased. When the number of edge element increases the mesh becomes very finer and this leads to high average element quality. Very finer mesh near at the walls is required to produce a smooth solution.

5.3.2. Mesh independence test

Mesh independence test is done to determine the level of enhancement needed. The results of the mesh independence test are given in table 5-3 below.

Table 5-3: Mesh independence test

Mesh	Degree of freedom	Solution time(minutes)
Coarse	5350	20
Normal	6170	27
Fine	8181	46
Finer	18020	61
Extra fine	41911	89
Extremely fine	65951	122

When the number of elements increases the degree of freedom also increases. The memory requirement and the solution time are directly related to the number of degrees of freedom in the simulation. The variation in temperature is studied for all the mesh sizes. There is temperature variation from extremely coarse mesh to the finer mesh. Reducing the mesh size further beyond the finer size did not give any great difference in the temperature. Figure 5-5 shows generated mesh independence test of the simulation.

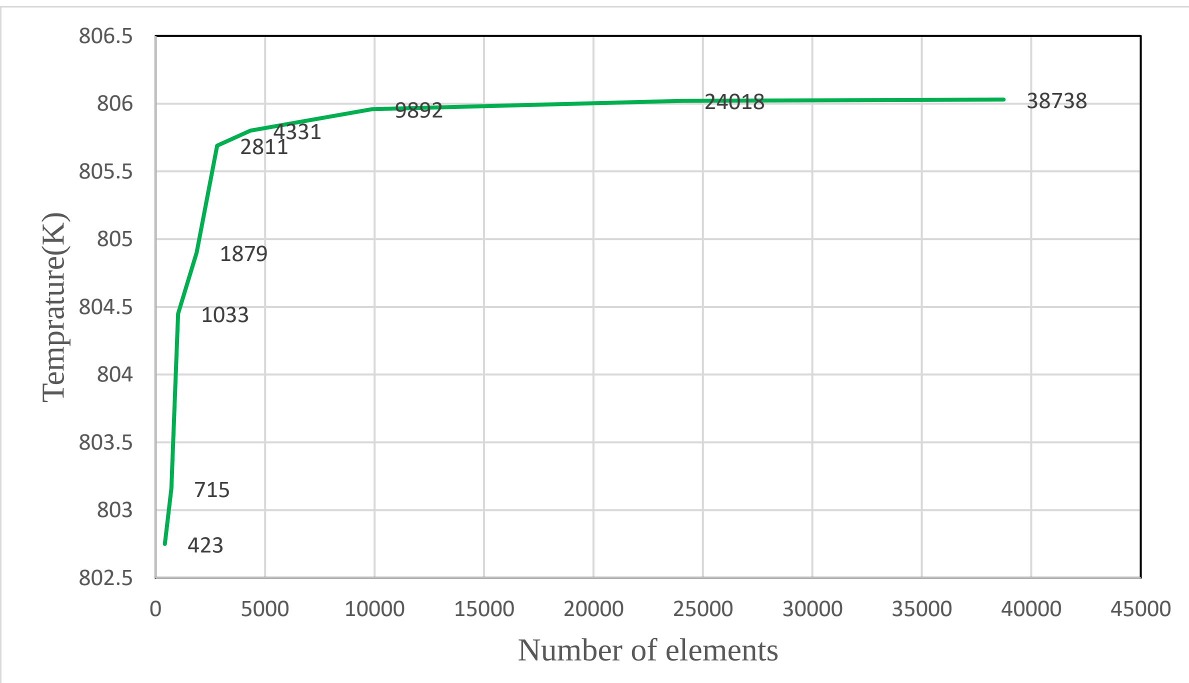


Figure 5-5: Mesh independence test graph

From figure 5-5 when the number of elements increases temperature increases. When the number of elements reaches 9892 there is no great temperature variation. If we further increase the number elements the temperature remains almost the same.

5.3.3. Velocity distribution

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 grate holes and gradual decreases along the height of the combustion chamber. From the velocity magnitude, the Reynolds number of the air calculated from equation 4.23 is 323.

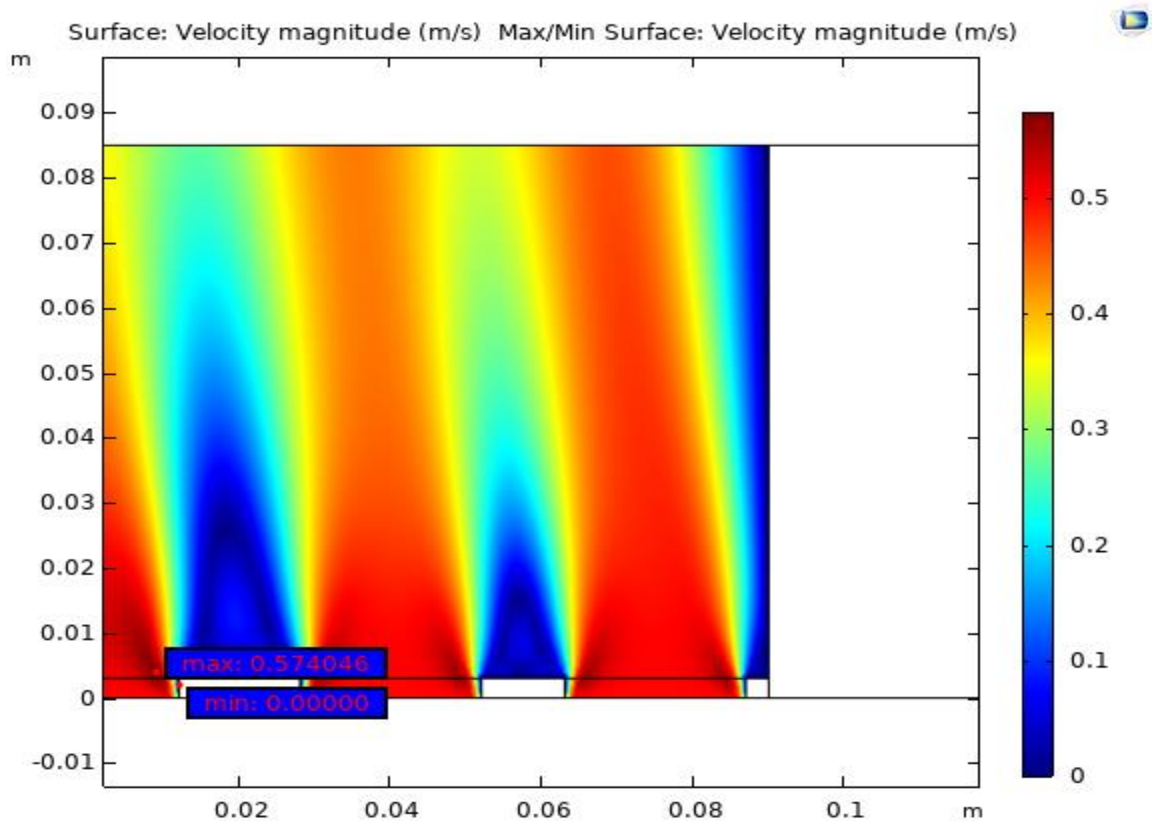


Figure 5-6: Velocity distribution in the grate holes and combustion chamber

There exists a zero-velocity region in the combustion chamber. This to the blocked region where there is limited fluid flow. This is due to non-detailed design which means specific detail designs have not been included in the model to reduce computational time and resource. But this is in contrast to the actual operating conditions. Therefore, the Reynolds number of the air flow at the grate holes is around 323. The Reynolds number along the grate holes is lower than the critical value of 2300 for flow in circular channels (Cengel and Cimbala, 2006). The flow in the grate holes remains laminar. From the counter plot shown in figure 5-6 there is high velocity at the center of the grate holes and it is surrounded by relatively lower velocity layers near the wall of the grate holes, this was also hypothesized by (Asranna, 2015).

5.3.4. Pressure distribution

The pressure is high at the inlet of the combustion chamber and it is gradually decreasing from the bottom of the chamber to the top. At the outlet the pressure is the ambient pressure.

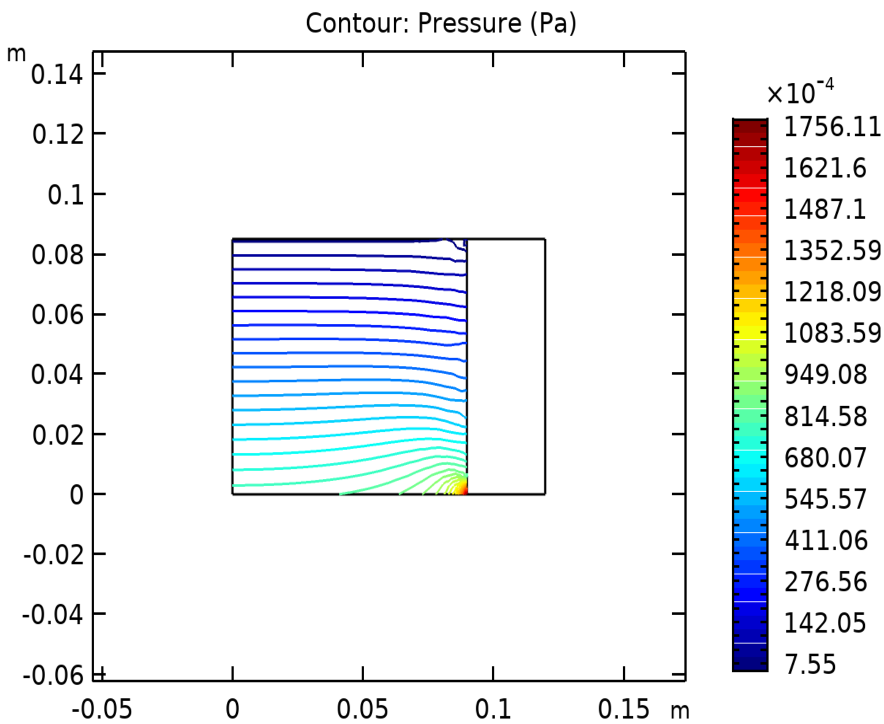


Figure 5-7: Pressure distribution in the combustion chamber

Due to the overloading of charcoal fuels there is pressure gradient in the stove combustion chamber (Klayborworn and Pakdee, 2019). There is also horizontal pressure gradient in the combustion region chamber this is due to horizontal pressure gradient force is directed from higher pressure towards lower pressure of the stove.

5.3.5. Temperature versus fire power

We use the model to examine the relationship between temperature and fire power. Figure 5-6 shows a plot of the computed fire power as a function of temperature.

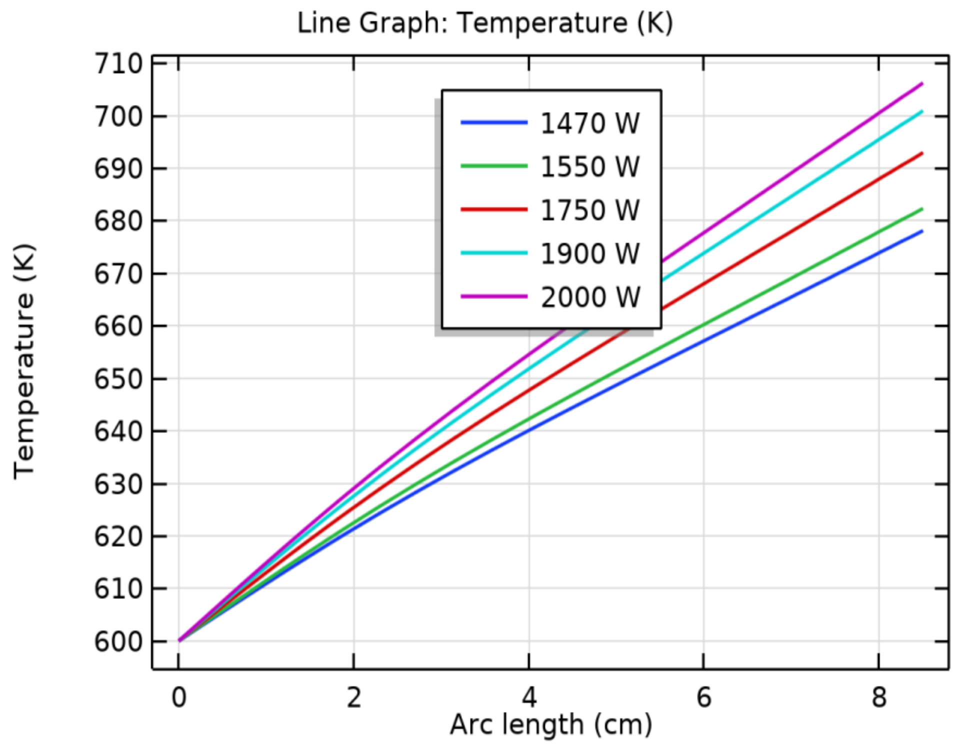


Figure 5-8: Temperature versus firepower in the combustion chamber

Temperature and firepower have direct relationship. As the height of the chamber increases both temperature and fire power increases. As the gas temperature increases density of the gas decreases resulting in increasing volumetric flow rates. Increase in fuel consumption results in greater buoyant force in the combustion chamber, which results in higher gas temperatures. At firepower 1470 W the temperature varies from 600-670 K and at fire power of 2000W the temperature varies from 600-705 K. This indicates that when the firepower increases the amount of heat transferred from the stove to the pot increases. This is also true in the case of experimental test done in the cook stoves laboratory. Thermal performance of the stove such as thermal efficiency increases as temperature increases (Pundle et al., 2019)

5.3.6. Temperature profile

Temperature is highest at the outlet of the combustion chamber. Figure 5-9 shows the temperature distribution in the combustion chamber which varies from 500 K at the inlet of the grate holes and around 1126.91 K at the outlet of the chamber.

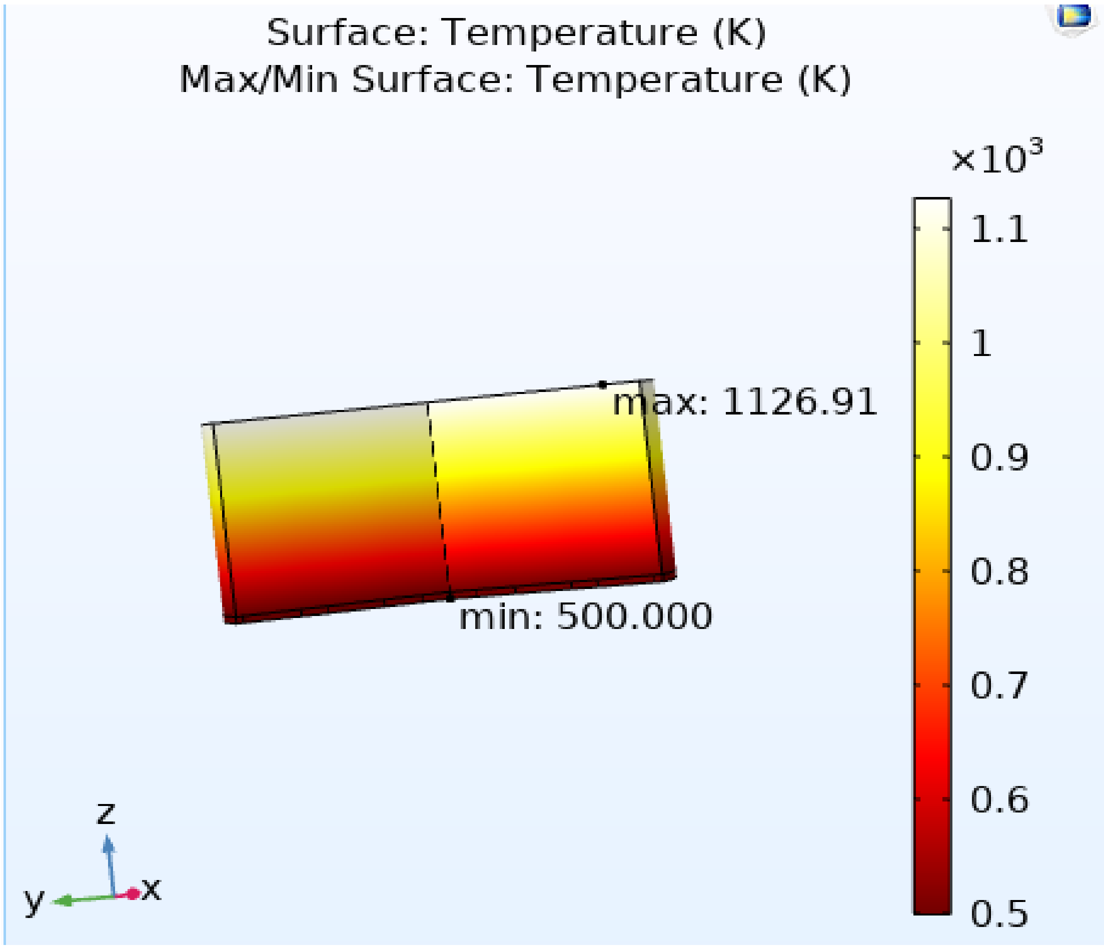


Figure 5-9: Temperature distribution in the fluid region

Cold air is seen at the sides of the combustion zone, which diminishes the combustion process of the fuels and this leads to a reduction in the thermal performance of the stove. The temperature distribution decreases from the top of the fluid domain to the bottom of the fluid domain because at the bottom of the fluid domain there is cold air entering the stove and this decreases the combustion process, which leads to lower temperature at the bottom of the fluid domain. But this is the same to the actual operating conditions where higher temperatures are expected towards the outlet of the stove. Therefore, the temperature field is in realistic approximation of the actual conditions. The highest temperature occurs at the center of the combustion chamber and this is true for all temperature distributions (Klayborworn and Pakdee, 2019).

5.3.7. Thermal efficiency

In this COMSOL Multiphysics software analysis of charcoal cook stove, the model used to simulate the system is energy model and fluid flow model and this is used to compute heat transfer rate in the domain. If heat transfer rate at the outlet of the stove is the same as heat utilized by the system, then thermal efficiency of the stove is calculated as

$$Thermal\ efficiency\ (\eta)\ =\ \frac{net\ heat\ transfer\ to\ the\ pot}{energy_{in\ fuel}} \tag{5.1}$$

From the simulation heat transfer rate at the outlet of the stove is found to be 951.34 W and the total heat flux at this region is 74809 W/m^2. Heat loss by radiation, convection and conduction at the height of the pot support is obtained by simulation i.e. 273 W. So, the net heat transfer to the pot will be; 951.34-273= 678.34

$$Energy\ _{in\ fuel}\ = \frac{LHV * M_{charcoal}}{T_B} \tag{5.2}$$

$$\frac{29800kJ/Kg * 0.118kg}{1800\ s} = 1.9536kW$$

$$Thermal\ efficiency = \frac{678.34}{1953.6} * 100\% = 34.7\%$$

5.4. Experimental versus simulation validation

5.4.1. Thermal efficiency

The experimental procedure and simulation conducted on the prototype charcoal stove was used to distiniguish the thermal performance of the stove i.e. thermal efficiency, specific fuel consumption, fire power etc. the average thermal efficiecy obtained from experimental test and simulation were 32.6% and 34.7% respectively. The simulation analysis result doesn"t consider the ambient conditions such as; humidity, moisture content of the biomass fuel, daily temperature condition and daily wind speed. Therefore by considering those factors the thermal efficiency result acquired from simulation will decrease from 2% to 10%. The relative error is 6% and this value is very close to the tested data.

5.4.2. Temperature

Temprature values of simulation and experimental data at different regions of the stove were validated. Table 5-4 provides a comparison of the simulation and experimental values.

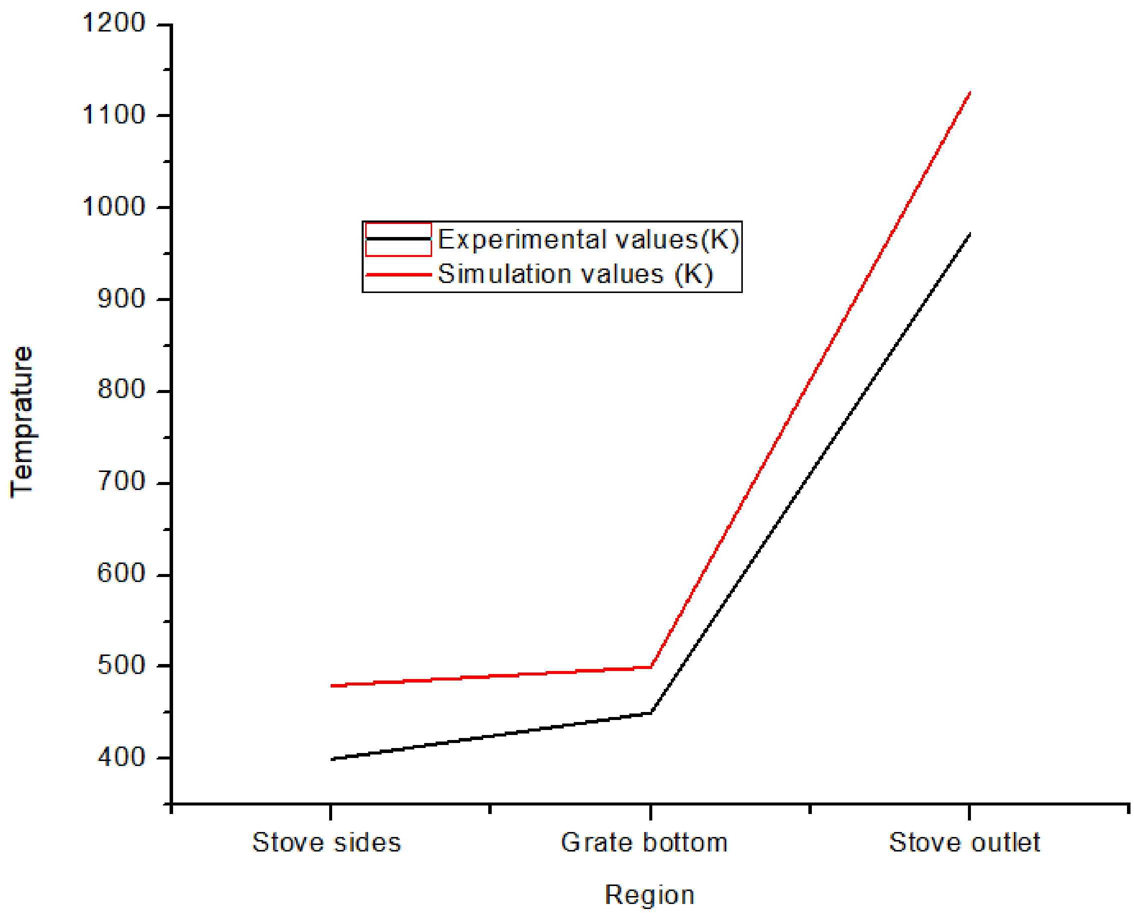


Figure 5-10: comparison between simulation and experimental temperature values

There are slight differences between experimental and simulation values . the values are comparable only at the grate bottom. Simulation values at the outlet of the stove are significantly higher than experimental results. This is due to the absence of detailed design. Detailed designes have not been included in the model partly to reduce the computational time and resource. A specific detailed design will lead to more suitable results.

CHAPTER- SIX

CONCLUSION AND RECOMMENDATION

This chapter contains a summary of the necessary information of the research and recommendations for future work are also included.

6.1. Conclusion

This paper examines the performance of an improved charcoal stove through experimental and numerical simulation. The relationship between thermal efficiency and temperature was analyzed. Considering the design principles that were followed, there was a successful design construction and simulation of the improved charcoal stove. The aim of manufacturing thermally efficient easy to use and aesthetically pleasing stove was achieved successfully. The stove was designed using a solid work and it was manufactured in the university workshop. The performance of the stove was accessed using a WBT protocol and the simulation was done using CFD package which is found in COMSOL Multiphysics. For the sake of computational efficiency, only the combustion chamber was modeled.

CFD model is developed to investigate the fluid flow and heat transfer in the combustion chamber for steady state operation of the charcoal stove. The simulation model is only expected to aid the experimental design. Combustion is modeled using uniform heat source in the combustion chamber. The computational domain is done using 2D-axisymmetric geometry. From the simulation velocity distribution, temperature profile, pressure distribution, thermal efficiency, Reynolds number as well as the relationship between temperature and fire power is analyzed. The temperature field inside combustion chamber increases as the height of the combustion chamber increases. The Reynolds number inside the grate holes 318 and the flow is laminar flow.

Thermal efficiency obtained from experimental and simulation results are compared. According to this thermal efficiency obtained from experiment is 32.6% and from simulation it is 34.7% and the relative error is 6% and this value very close to the tested data. This difference is because of simulation is done at steady state condition, while experimental procedures are not. Based on our study, the new prototype charcoal stove is worth promoting than other improved charcoal stoves and traditional charcoal stoves which are found in

Ethiopia and in other countries. Disseminating this new prototype charcoal stove will result in reduced fuel charcoal use in urban and semi-urban areas of Ethiopia where local people widely use traditional charcoal stoves for household cooking and coffee ceremony.

6.2. Recommendation

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.

- In this thesis secondary air entrance has not been included in the stove thus it is recommended to use secondary air has been demonstrated to improve combustion and thermal performance of the stove.
- The combustion chamber is made from clay material. Very low thermal conductivity materials like perlite or volcanic glass in the combustion chamber has been demonstrated to increase the thermal performance of the stove.
- Only the combustion chamber of the stove is modeled. It is suggested to model the different parts of the stove like modeling thermal efficiency as a function of pot support height and modeling thermal efficiency as a function of thickness of the clay wall etc.
- Temperature distribution at the grate holes and combustion chamber are not modeled in detail thus it is recommended for future researchers.

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APPENDIX A

WBT test results

WATER BOILING TEST - VERSION 4.2.4 - TEST #1

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Lemma Kahsay	gray: efficiency
Test Number	1	blue: emissions
Date	4/8/2020	pink: error, missing input
Location	AAiT	
Stove type/model	charcoal stove	
Type of fuel	eculptus	

Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	12.0	°C		Dry weight of Pot # 1 (grams)	345	g	P1
Wind conditions	No wind			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	35*30*20			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	-	kJ/kg	HHV	Weight of container for char (grams)	315	g	k
Net calorific value (dry fuel)	30,000	kJ/kg	LHV	Local boiling point	90.0	°C	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	25,112	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	-	kJ/kg		PM		ug/m3	PM,b

TEST #1 1		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	5:12	t_{ci}	5:42	t_{cf}
Weight of fuel	g	320	f_{ci}	200	f_{cf}
Water temperature, Pot # 1	°C	15.3	$T1_{ci}$	68.5	$T1_{cf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	2850.4	$P1_{ci}$	2680.5	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	---				
Weight of charcoal+container	g			924.1	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm				CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	°C				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g				$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

Calculations/Results	Units	COLD START data	label
Fuel consumed (moist)	g	120	f_{cm}
Net change in char during test	g	609	Δc_c
Equivalent dry fuel consumed	g	100	f_{cd}
Water vaporized from all pots	g	170	w_{cv}
Effective mass of water boiled	g	1,663	w_{cr}
Time to boil Pot # 1	min	30	Δt_c
Temp-corr time to boil Pot # 1	min	30	Δt^T_c
Thermal efficiency	%	31%	h_c
Burning rate	g/min	3.3	r_{cb}
Specific fuel consumption	g/liter boiled	60	SC_c
Temp-corr sp consumption	g/liter	60.64480937	SC^T_c
Temp-corr sp energy consumpt.	kJ/liter	1,819	SE^T_c
Firepower	watts	1674	FP_c

WATER BOILING TEST - VERSION 4.2.4 - TEST #2

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Lemma Kahsay	gray: efficiency
Test Number	2	blue: emissions
Date	5/8/2020	pink: error, missing input
Location	AAiT	
Stove type/model	Charcoal stove	
Type of fuel	eculptus	

Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	12.0	°C		Dry weight of Pot # 1 (grams)	346	g	P1
Wind conditions	No wind			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	30*23*28			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	14%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	-	kJ/kg	HHV	Weight of container for char (grams)		g	k
Net calorific value (dry fuel)	30,000	kJ/kg	LHV	Local boiling point	90.0	°C	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	25,438	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	-	kJ/kg		PM		ug/m3	PM,b

TEST #2 2		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	3:37	t_{ci}	4:07	t_{cf}
Weight of fuel	g	305	f_{ci}	195	f_{cf}
Water temperature, Pot # 1	°C	16.3	$T1_{ci}$	66.2	$T1_{cf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	2850	$P1_{ci}$	2685.7	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1085	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm				CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	°C				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g				$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START	
Calculations/Results	Units	data	label
Fuel consumed (moist)	g	110	f_{cm}
Net change in char during test	g	1,085	Δc_c
Equivalent dry fuel consumed	g	93	f_{cd}
Water vaporized from all pots	g	164	w_{cv}
Effective mass of water boiled	g	1,584	w_{cr}
Time to boil Pot # 1	min	30	Δt_c
Temp-corr time to boil Pot # 1	min	31	Δt^T_c
Thermal efficiency	%	32%	h_c
Burning rate	g/min	3.1	r_{cb}
Specific fuel consumption	g/liter boiled	59	SC_c
Temp-corr sp consumption	g/liter	59.92864575	SC^T_c
Temp-corr sp energy consumpt.	kJ/liter	1,798	SE^T_c
Firepower	watts	1555	FP_c

WATER BOILING TEST - VERSION 4.2.4 - TEST #3

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Lemma Kahsay	gray: efficiency
Test Number	3	blue: emissions
Date	8/8/2020	pink: error, missing input
Location	AAiT	
Stove type/model	Charcoal stove	
Type of fuel	eculpthus	

Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	18.5	°C		Dry weight of Pot # 1 (grams)	346	g	P1
Wind conditions	No wind			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	30*26*40			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	14%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	-	kJ/kg	HHV	Weight of container for char (grams)	419	g	k
Net calorific value (dry fuel)	30,000	kJ/kg	LHV	Local boiling point	90.0	°C	T_b
Effective calorific value (accounting for fuel moisture)	25,539	kJ/kg	EHV	Background concentrations: CO2		ppm	CO2,b
				CO		ppm	CO,b
Char calorific value	-	kJ/kg		PM		ug/m3	PM,b

TEST #3 3		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	3:42	t_{ci}	4:12	t_{cf}
Weight of fuel	g	315	f_{ci}	197	f_{cf}
Water temperature, Pot # 1	°C	16.1	$T1_{ci}$	73.1	$T1_{cf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	2848	$P1_{ci}$	2678	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1030	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm				CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	°C				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g				$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START	
Calculations/Results	Units	data	label
Fuel consumed (moist)	g	118	f_{cm}
Net change in char during test	g	611	Δc_c
Equivalent dry fuel consumed	g	100	f_{cd}
Water vaporized from all pots	g	170	w_{cv}
Effective mass of water boiled	g	1,799	w_{cr}
Time to boil Pot # 1	min	30	Δt_c
Temp-corr time to boil Pot # 1	min	30	Δt^T_c
Thermal efficiency	%	33%	h_c
Burning rate	g/min	3.3	r_{cb}
Specific fuel consumption	g/liter boiled	56	SC_c
Temp-corr sp consumption	g/liter	56.67349808	SC^T_c
Temp-corr sp energy consumpt.	kJ/liter	1,700	SE^T_c
Firepower	watts	1674	FP_c

WATER BOILING TEST - VERSION 4.2.4 - TEST #4

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Lemma Kahsay		gray: efficiency
Test Number	4		blue: emissions
Date	10/08/20202		pink: error, missing input
Location	AAiT		
Stove type/model	Charcoal stove		
Type of fuel	ceculpthus		

Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	12.2	°C		Dry weight of Pot # 1 (grams)	347	g	P1
Wind conditions	No wind			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	22*35*33			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	14%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	-	kJ/kg	HHV	Weight of container for char (grams)		g	k
Net calorific value (dry fuel)	30,000	kJ/kg	LHV	Local boiling point	90.0	°C	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	25,601	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	-	kJ/kg		PM		ug/m3	PM,b

TEST #4 4		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	9:35	t_{ci}	10:05	t_{cf}
Weight of fuel	g	368	f_{ci}	231	f_{cf}
Water temperature, Pot # 1	°C	14.4	$T1_{ci}$	86.5	$T1_{cf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	2850	$P1_{ci}$	2640	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1241	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm				CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	°C				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g				$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

		COLD START	
Calculations/Results	Units	data	label
Fuel consumed (moist)	g	137	f_{cm}
Net change in char during test	g	1,241	Δc_c
Equivalent dry fuel consumed	g	117	f_{cd}
Water vaporized from all pots	g	210	w_{cv}
Effective mass of water boiled	g	2,187	w_{cr}
Time to boil Pot # 1	min	30	Δt_c
Temp-corr time to boil Pot # 1	min	30	Δt^T_c
Thermal efficiency	%	35%	h_c
Burning rate	g/min	3.9	r_{cb}
Specific fuel consumption	g/liter boiled	53.46424235	SC_c
Temp-corr sp consumption	g/liter	53.03992297	SC^T_c
Temp-corr sp energy consumpt.	kJ/liter	1,591	SE^T_c
Firepower	watts	1949	FP_c

Test- five

WATER BOILING TEST - VERSION 4.2.4 - TEST #5

DATA AND CALCULATION FORM (for one to four pots)*

Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	Lemma Kahsay		gray: efficiency
Test Number	5		blue: emissions
Date	10/8/2020		pink: error, missing input
Location	AAiT		
Stove type/model	charcoal stove		
Type of fuel	eculpthus		

Initial Test Conditions

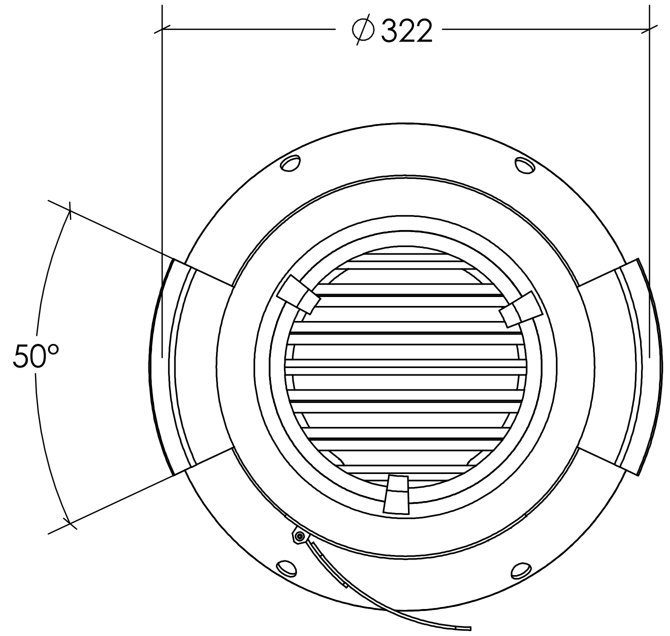
Data	value	units	label	Data	value	units	label
Air temperature	16.4	°C		Dry weight of Pot # 1 (grams)	345	g	P1
Wind conditions	No wind			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	27*30*32			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	-	kJ/kg	HHV	Weight of container for char (grams)	310	g	k
Net calorific value (dry fuel)	30,000	kJ/kg	LHV	Local boiling point	90.0	°C	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	25,017	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	-	kJ/kg		PM		ug/m3	PM,b

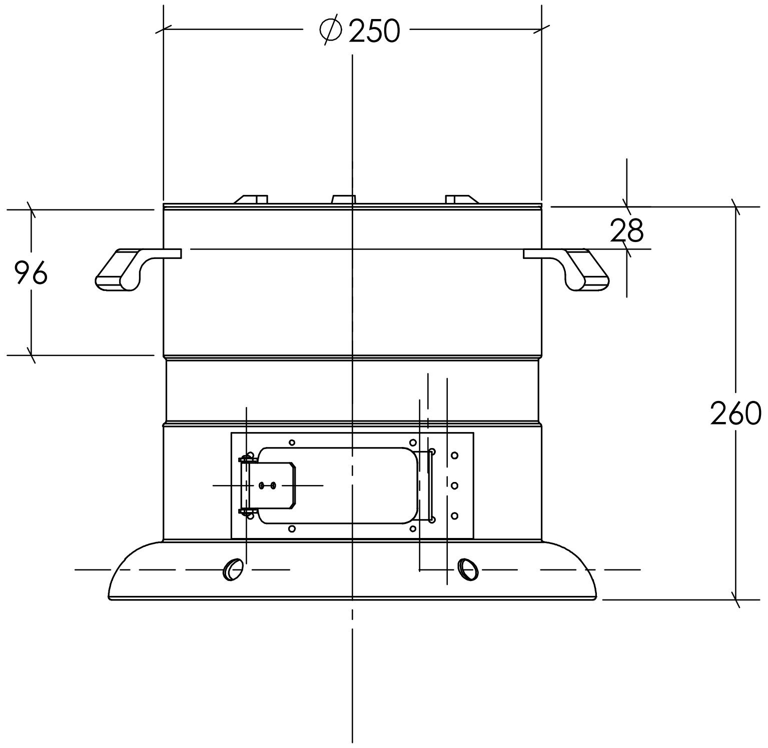
TEST #5 5		COLD START HIGH POWER			
		Start		Finish: when Pot #1 boils	
Measurements	Units	data	label	data	label
Time (in 24 hour form)	hr:min	3:31	t_{ci}	4:01	t_{cf}
Weight of fuel	g	304	f_{ci}	180	f_{cf}
Water temperature, Pot # 1	°C	17.1	$T1_{ci}$	78.6	$T1_{cf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$
Weight of Pot # 1 with water	g	2848	$P1_{ci}$	2690	$P1_{cf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$
Fire-starting materials (if any)	--				
Weight of charcoal+container	g			1098	c_c
Average CO2	ppm				$CO2_c$
Average CO	ppm				CO_c
Average PM	ug/m3				PM_c
Average Duct Temperature	°C				T_{cd}
Total CO2 (if available)	g				$m_{CO2,c}$
Total CO (if available)	g				$m_{CO,c}$
Total PM (if available)	g				$m_{PM,c}$

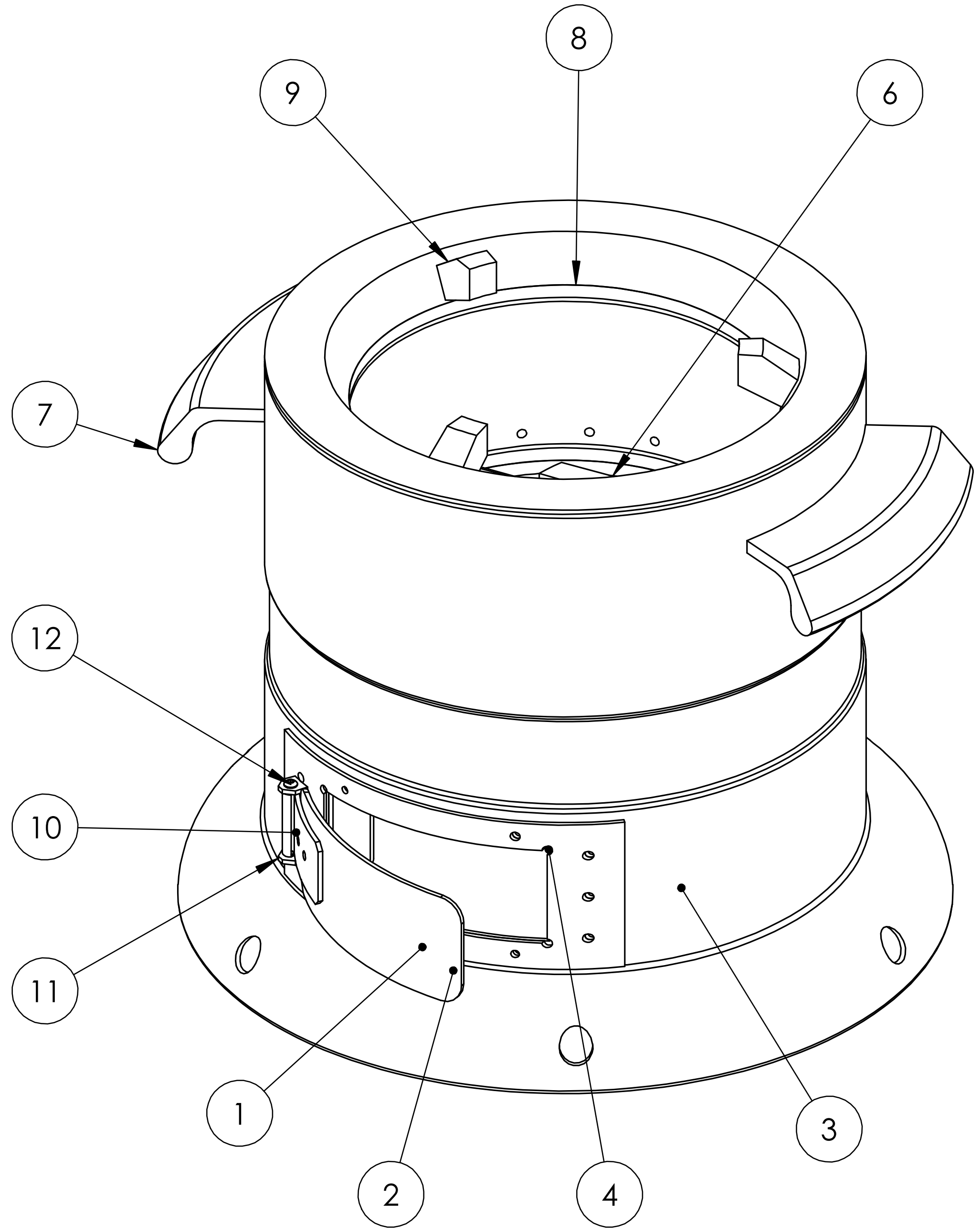
		COLD START	
Calculations/Results	Units	data	label
Fuel consumed (moist)	g	124	f_{cm}
Net change in char during test	g	788	Δc_c
Equivalent dry fuel consumed	g	103	f_{cd}
Water vaporized from all pots	g	158	w_{cv}
Effective mass of water boiled	g	1,978	w_{cr}
Time to boil Pot # 1	min	30	Δt_c
Temp-corr time to boil Pot # 1	min	31	$\Delta t^T{}_c$
Thermal efficiency	%	32%	h_c
Burning rate	g/min	3.4	r_{cb}
Specific fuel consumption	g/liter boiled	52.27471368	SC_c
Temp-corr sp consumption	g/liter	53.78056963	$SC^T{}_c$
Temp-corr sp energy consumpt.	kJ/liter	1,613	$SE^T{}_C$
Firepower	watts	1723	FP_c

APPENDIX B

part drawing





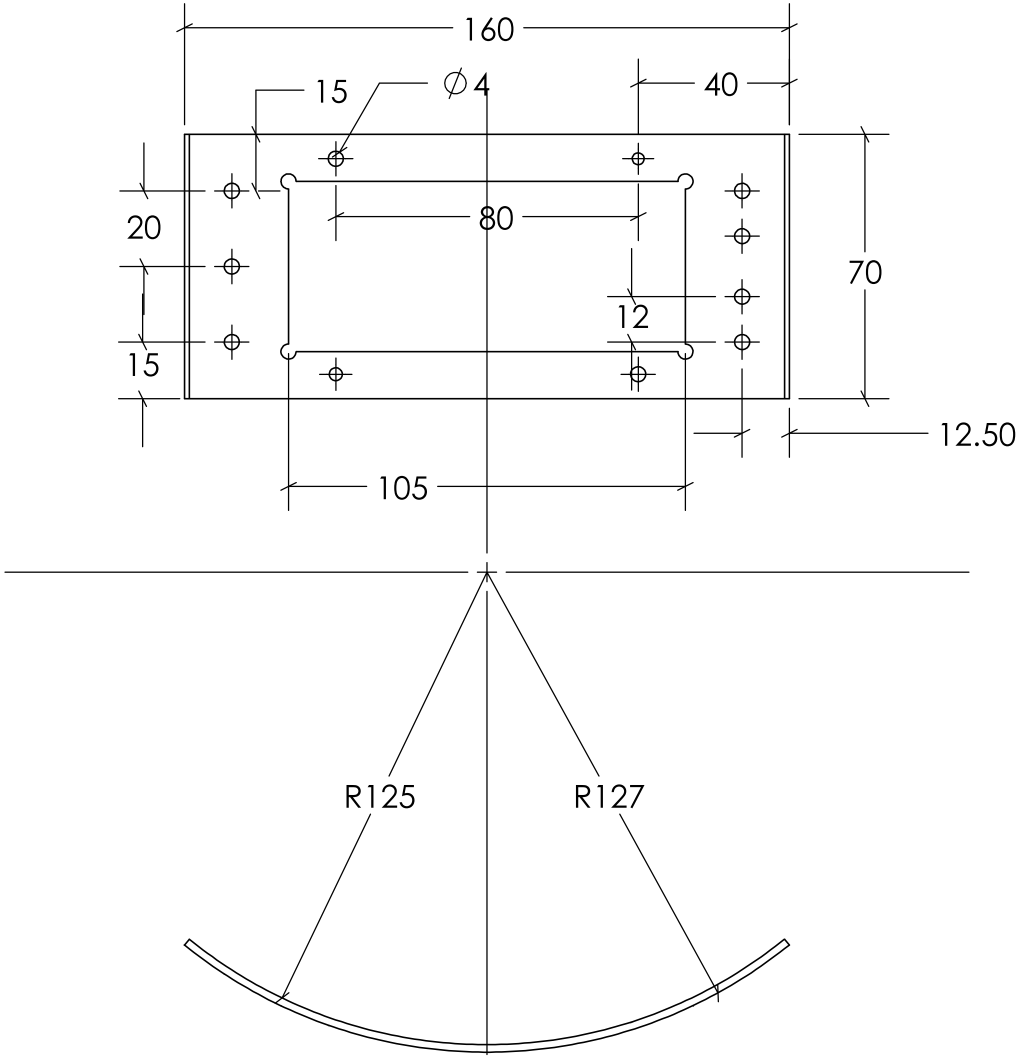


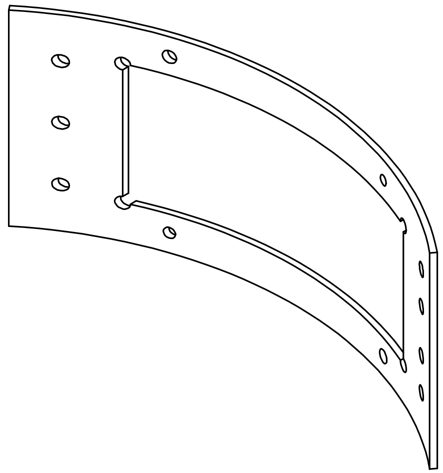
ITEM NO.	PART NAME	MATERIAL	QTY.
1	Door_Base_CS008SMXT2	Sheet Metal	1
2	Door_CS009SMXT2	Sheet Metal	1
3	Main_Case_CS001SMT1	Sheet Metal	1
4	Bottom_Inner_Case_CS005T2	Sheet Metal	1
5	Bottom_Case_CS006T2	Sheet Metal	1
6	Grid_CI003T15	Cast Iron	1
7	Handle_RB007T35	plastic	2
8	Inner_Case_CS003SMT2	Clay	1
9	Top_case_CS002SMT2	Sheet Metal	1
10	Hinge_CS010T2	Carbon Steel	1
11	Vertical_Hinge_CS011T2	Carbon Steel	1
12	B18.3.4M - 3 x 0.5 x 3 SBHCS --N	Stainless Steel	2

AAiT
Center of Eneryg Technology

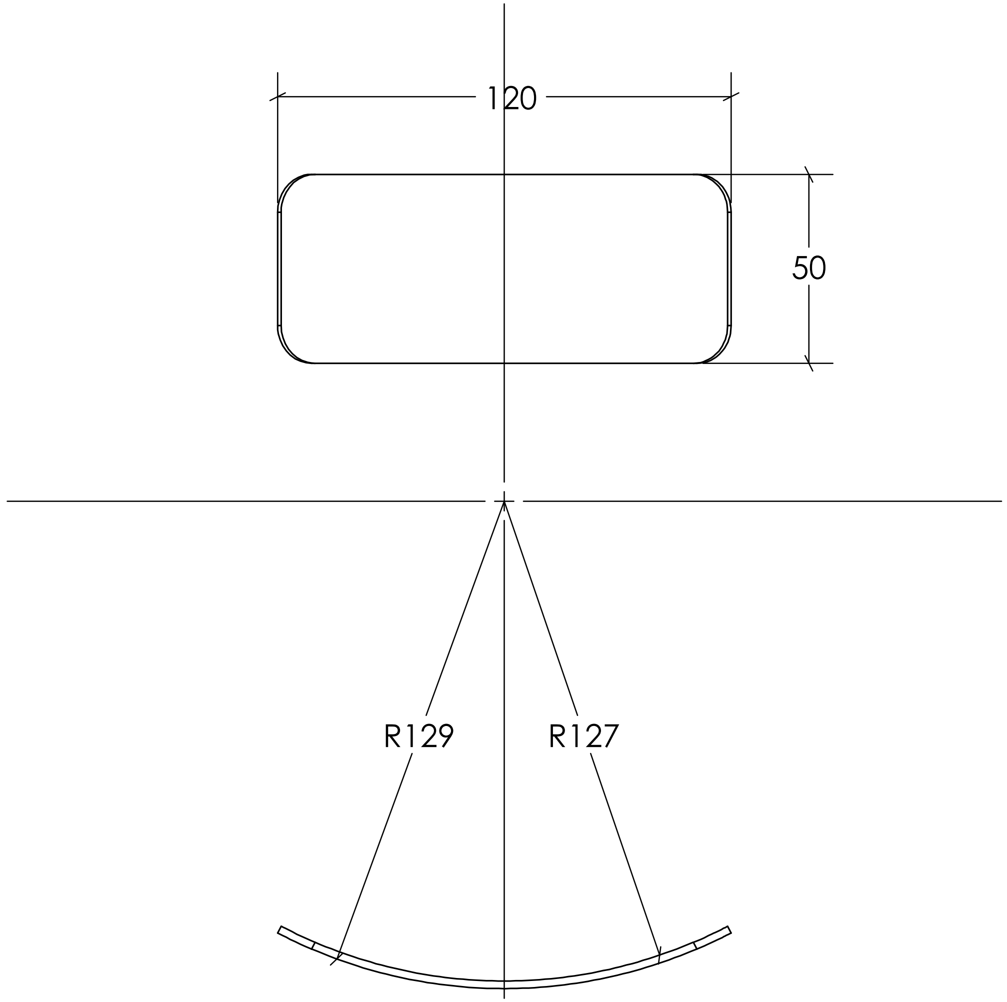
DESIGNING SIMULATING AND MANUFACTURING IMPROVED CHARCOAL STOVE

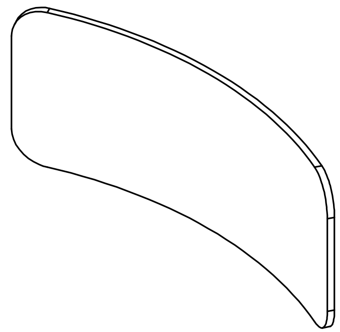
DRAWN	LEMMA KAHSAY	MAY,2020	**DWG NO._001/2020**
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE: 1:3 — SHEET 1OF 12



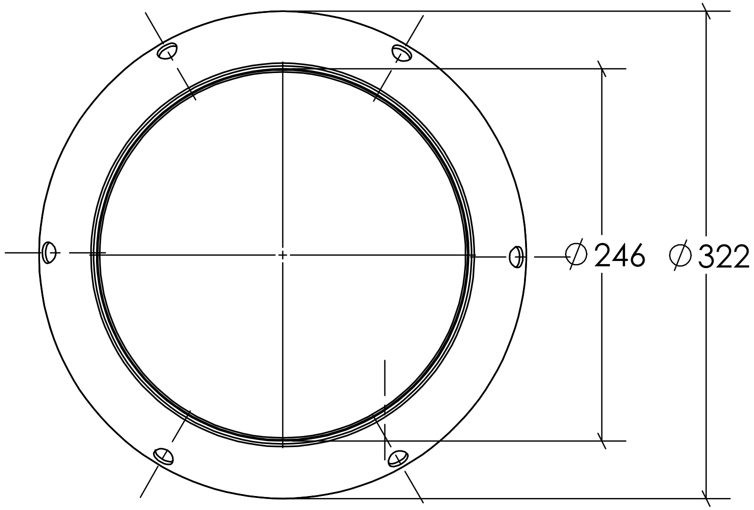


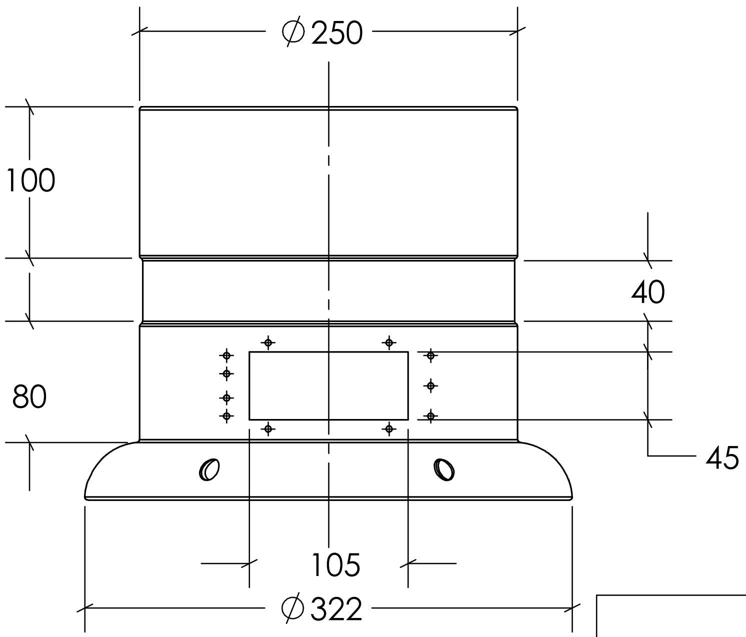
AAiT **Center of Eneryg Technology**			All dimensions are in mm Door_Base_CS008SMXT2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-008T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:2	SHEET 8 OF 12

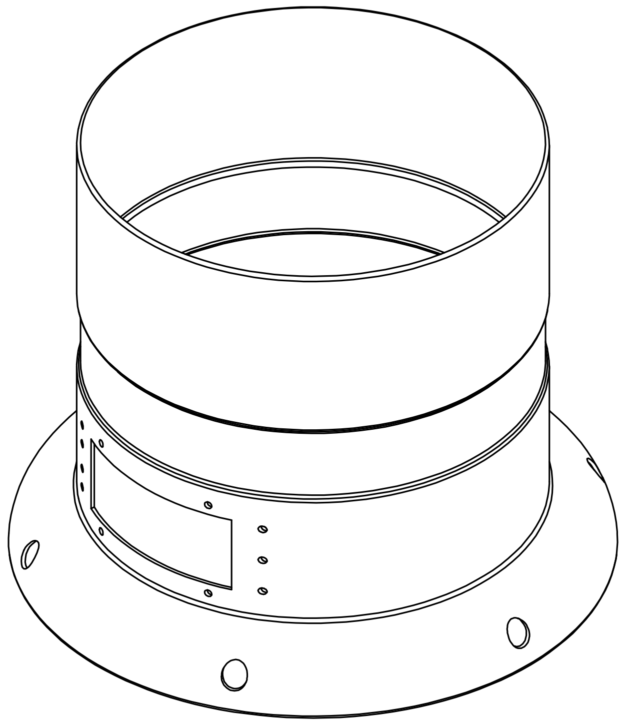




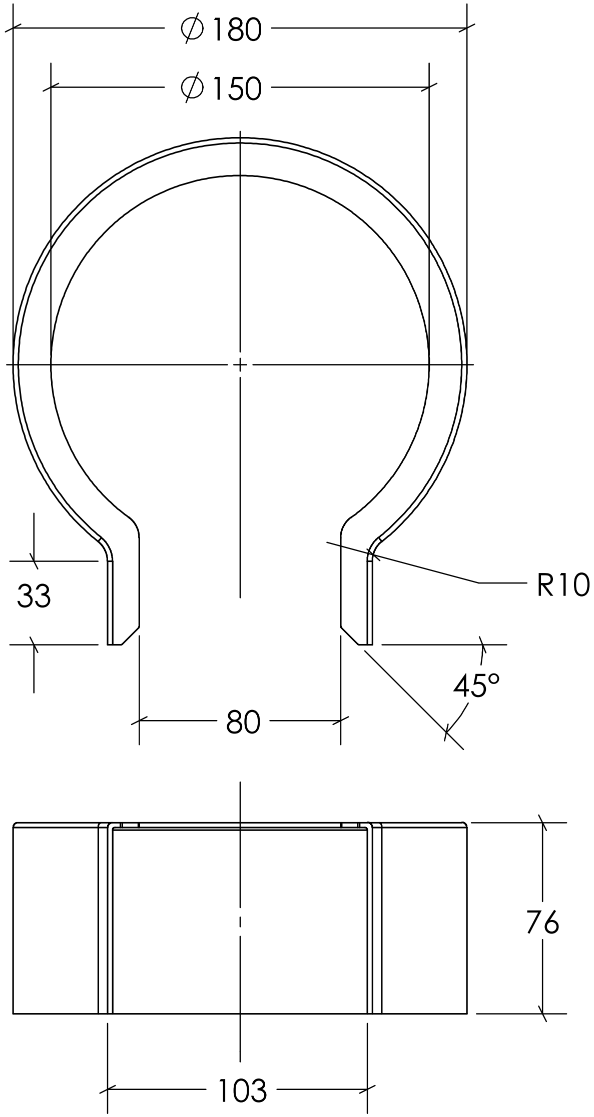
AAiT **Center of Eneryg Technology**			All dimensions are in mm Door_CS009SMXT2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-009T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE: 1:2	SHEEET 09 OF 12

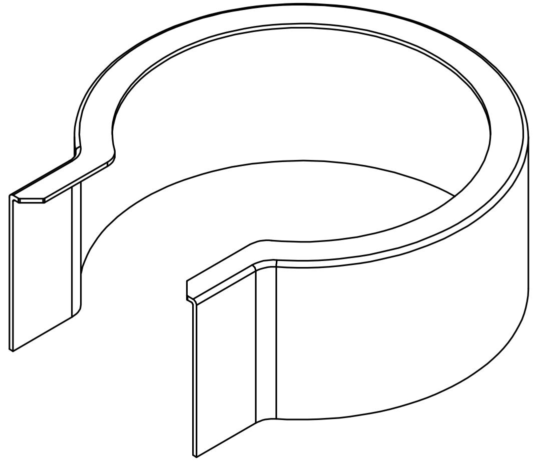




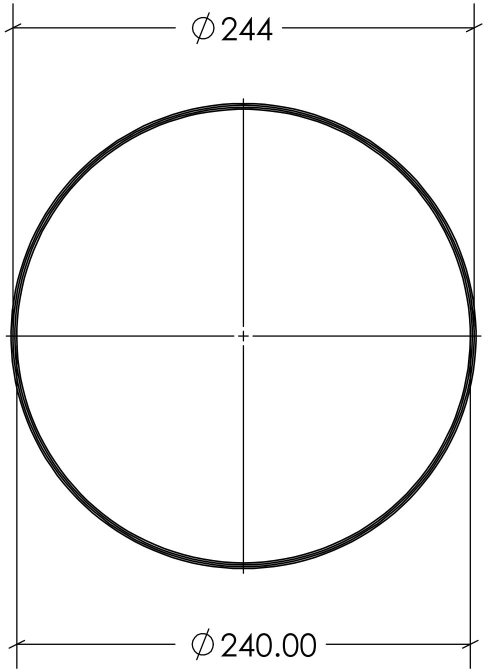


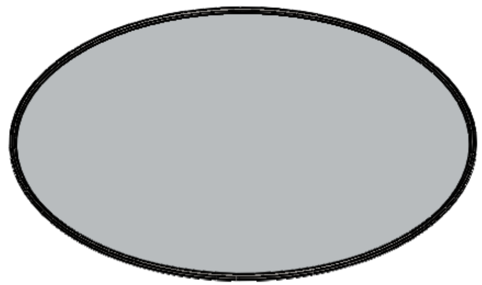
AAiT Center of Eneryg Technology			All dimensions are in mm Main_Case_CS001SMT1
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-001T2
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:4 / SHEET 1 OF 12





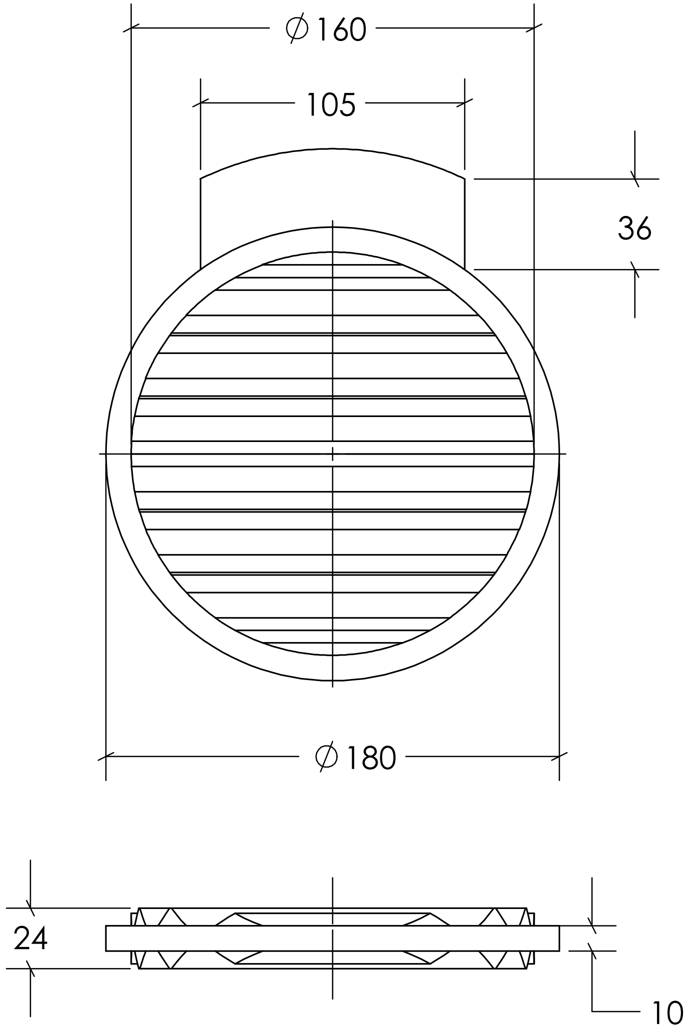
AAiT **Center of Eneryg Technology**			All dimensions are in mm Inner Bottom_Case_CS005T2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-005T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:2	SHEET 5 OF 12

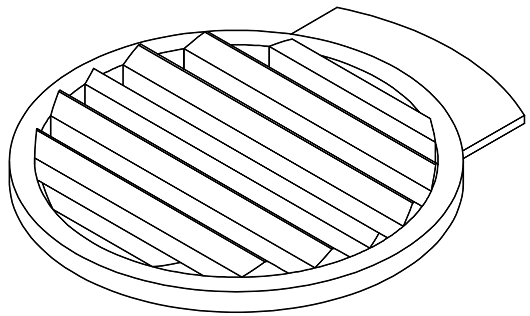




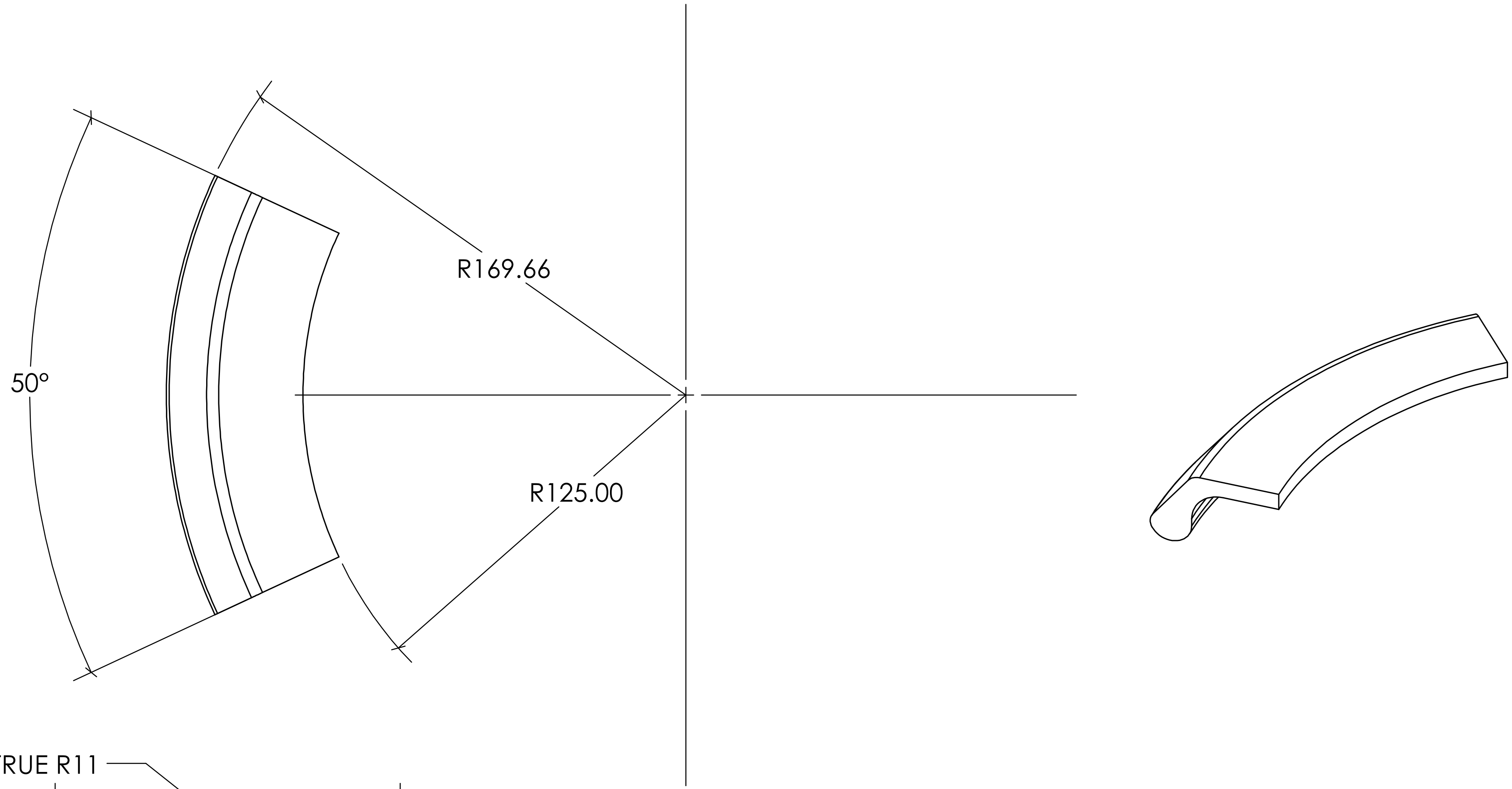
Thickness: 4mm

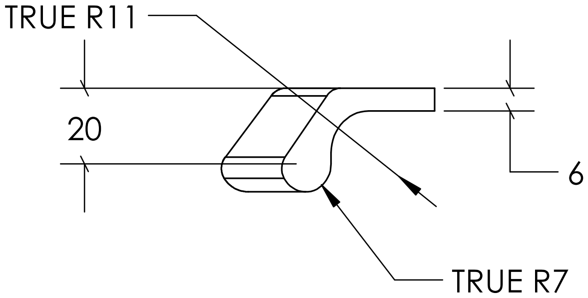
AAiT Center of Eneryg Technology			All dimensions are in mm	
			Bottom_Case_CS006T2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-006T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:4	SHEET 06 OF 12



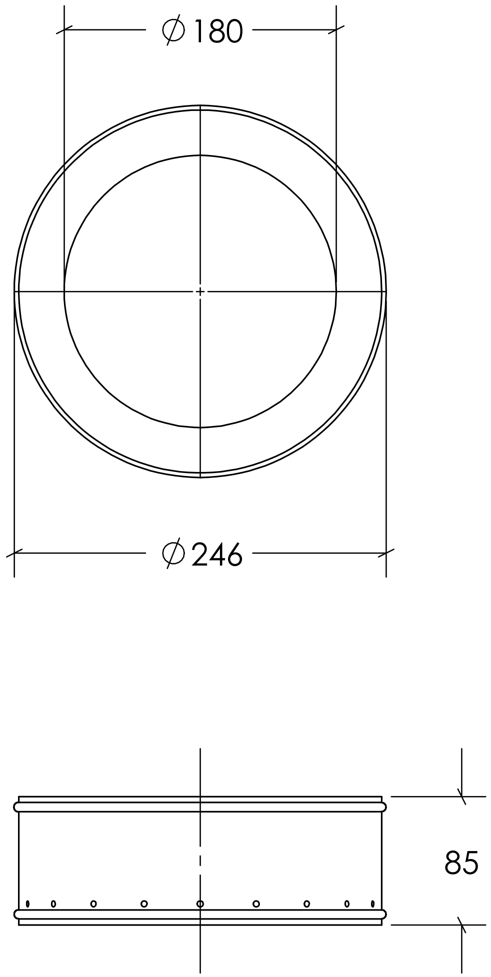


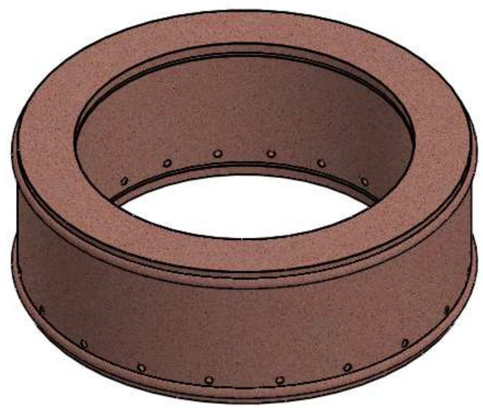
AAiT **Center of Eneryg Technology**			All dimensions are in mm Grid_CI003T15	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-003T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:3	SHEET 03OF12



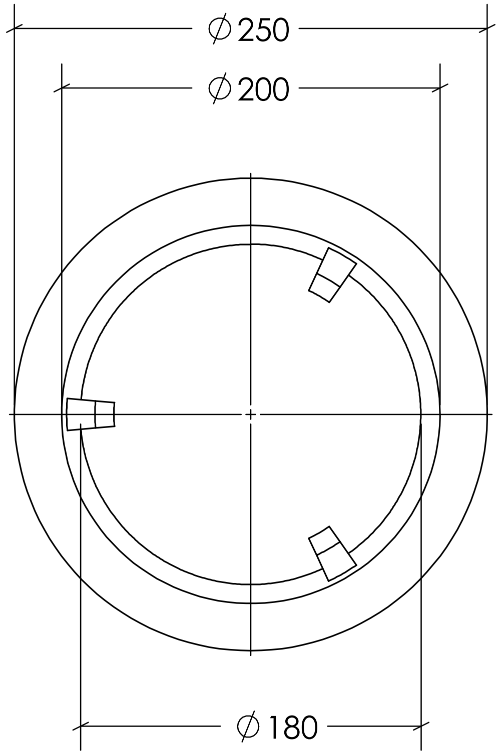


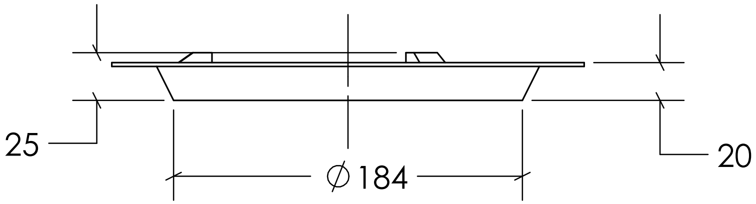
AAiT **Center of Eneryg Technology**			All dimensions are in mm Handle_RB007T35	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-007T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:2	SHEEET 07OF12

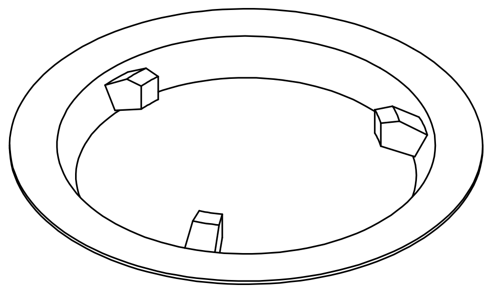




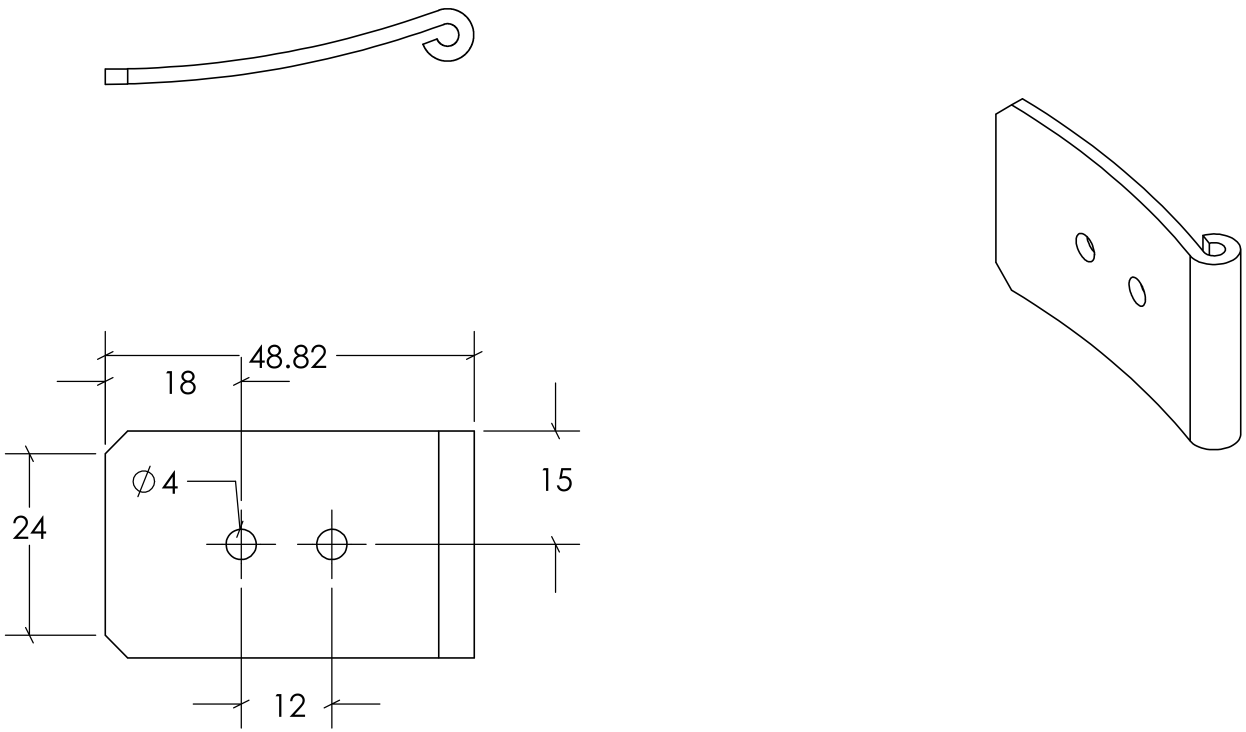
AAiT **Center of Eneryg Technology**			All dimensions are in mm Inner_Case_Clay CS003SMT2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-003T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:5	SHEET 3 OF 12



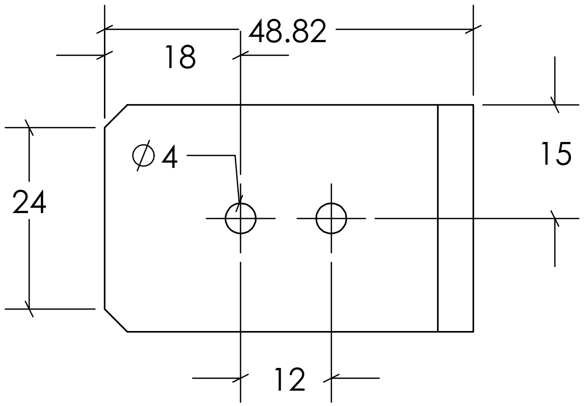


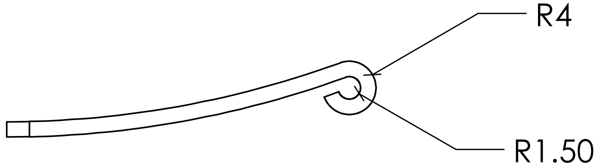


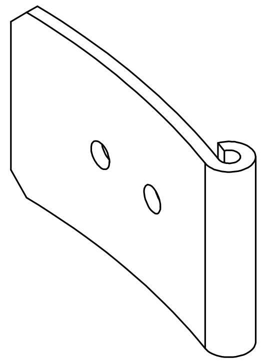
AAiT Center of Eneryg Technology			All dimensions are in mm Top_case_CS002SMT2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-002T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:4	SHEET 2 OF 12



AAiT Center of Eneryg Technology			All dimensions are in mm Hinge_CS010T2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-010T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:2	SHEET 10 OF 13

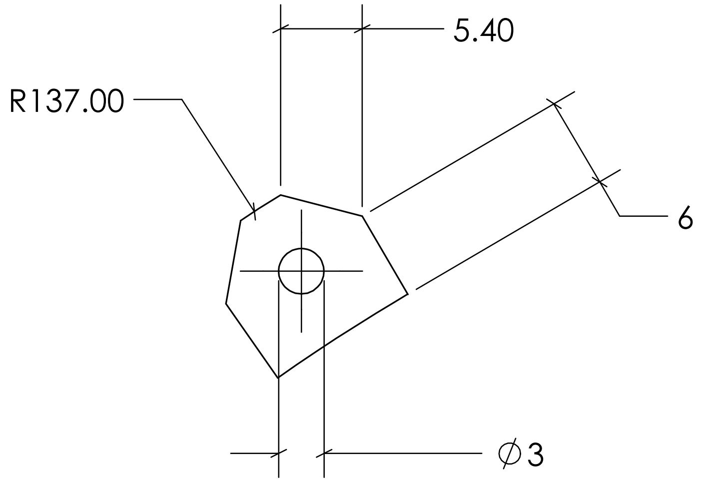


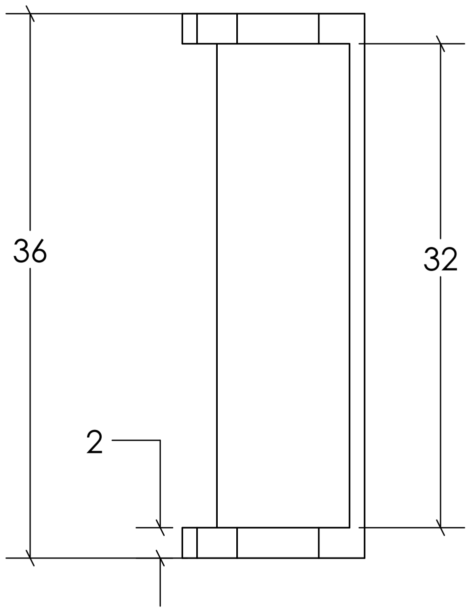


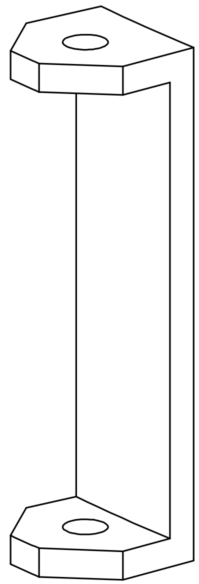


Thickness: 2mm

AAiT **Center of Eneryg Technology**			All dimensions are in mm Hinge_CS010T2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-010T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:2	SHEET 10 OF 12







AAiT **Center of Eneryg Technology**			All dimensions are in mm Hinge_CS011T2	
DRAWN	LEMMA KAHSAY	MAY,2020	DRG NO.-011T2	
CHK'D	Dr.KAMIL DINO ADEM	JUNE,2020	SCALE:1:1	SHEET 11 OF 12