JIMMA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

SUSTAINABLE ENERGY ENGINEERING

PRODUCT DEVELOPMENT USING CFD SIMULATION AND PERFORMANCE EVALUATION OF ENERGY EFFICIENT INSTITUTIONAL BIO-CHAR ROCKET STOVE

A Research thesis Submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirement for the Degree of Masters of Science in Sustainable Energy Engineering

By

Getachew Hailu

April 04, 2018
Jimma, Ethiopia

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By

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April 04, 2018

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Declaration

I undersigned, declare that this thesis entitled “product development using CFD simulation and performance evaluation of energy efficient institutional bio-char rocket stove” is my original work, and has not been presented by any other person for an award of a degree in this or any other university.

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Nomenclatures

Acronyms

ICS	Improved cooking stoves
CDM	Clean Development Mechanism
UNFCCC	United Nation Framework Convention on Climate Change
LPG	Liquid Pressured Gas
TLUD	Top-Lit Up-Draft
EU	European Union
PPM	Parts Per Million
WHO	World Health Organization
MOWE	Ministry of Water & Energy
SFC	Specific Fuel Consumption
FDRE	Federal Democratic Republic of Ethiopia
USD	United State Dollar
CFD	computational fluid dynamic
MC	moisture content
WBT	Water boiling test
Δcc	Change in char during test
fcd	Equivalent dry wood consumed
wcv	Water vaporized
wcr	Effective mass of water boiled
Δtc	Time to boil
hc	Thermal efficiency (%)
r_{cb}	Burning rate
SFC	Specific fuel consumption
FPc	Firepower
LHV	Lower heating value
ρ	Density
Wt_w	Weihgt of water
Wtv	Weight of vessel

Wt_{chip}	Weight of wood chip
h	Convection coefficient
Nu	Nussuilt number
Re	Reynolds number
Pr	Prandtl Number
T_{amb}	Ambient temperature
IOT_s	Inter-Operability Testing
GIZ	German International Zusammenarbeit

Executive Summary

Globally, biomass accounts for ten percent of energy production, two-thirds of which is used for cooking and heating purposes in developing countries. Environmental degradation and natural resource depletion are also serious issues as a result of cutting trees to serve as fuel wood; biomass will govern household energy of the countries in the near future and increased afforestation, reforestation, and forest management to increase carbon sequestration in forests and woodlands. This study was product development using CFD simulation, evaluate developed prototype of modified rocket stove, the performance of the stove for institutional cooking and evaluate the stove co-product (bio-char production) for soil amendment. The stove design was selected for both the computational fluid dynamic (CFD) simulation, and experimental measurements. ANSYS fluent work bench was used for CFD simulation the wood combustion and pyrolysis of woodchip to form multi-face exhaust holes syngas flow to stove combustion chamber. Gasses start to come out from the pyrolysis chamber through the exhaust outlet after 8 minutes of pyrolysis, and pressurized the gasses come out at this time, it start burn in combustion chamber. After 20 minutes the water boiling was completed, the biochar had 4.634 pH value. At 60 minutes pressurize Syngas was stop and gives low combustion. The char was tested and found to be rich in carbon with a pH of 7.235 and 1.35kg(30.17%)yield when syngas burn up to 60minutes. The results of experiment show that the fuel consumption 8.75kg, and overall thermal efficiency 45.67% of stove and the biochar produced is good for amendment of soil

Key words*: stove, CFD, combustion, pyrolysis, Syngas, biochar, biochar rocket stove*

Chapter 1

1. Introduction

1.1. Background

Alternatives to fuel-wood as cooking fuel are generally expensive and hardly available in Sub-Saharan Africa. As a result, the demand for fuel-wood in rural communities remains inelastic as long as the resource continues to be available to these communities [1]. Investments in direct fuel saving solutions are thus needed to combat the unsustainable use of fuel-wood. An important strategy is the distribution of improved cooking stoves (ICS) [1,2,3] that allow for significant savings of fuel-wood without the need to introduce energy is expected to be used in domestic cooking activities with no alternative substitute to fire wood [4]. Meanwhile, ICS are increasingly used in fuel-wood-based countries [4, 5, 6], often supported by carbon funding [7, 8]. Under the Clean Development Mechanism (CDM), there is an increasing number of projects and programs distributing ICS Sophisticated technologies or to change cooking habits.

Based on an evaluation of the United Nation Framework Convention on Climate Change (UNFCCC) registry [9], CDM cooking stove projects generally claim emissions reductions between one and five tons per ICS, depending on stove efficiencies, baseline fuel consumption and interpretations of the applicable CDM methodologies. There are however still few CDM credits issued for ICS projects, while more credits have been issued for ICS projects through the voluntary market with approximately 5.8 Mt·CO2 in 2012,[10].

In order to reduce pressure on forests, and agricultural productivity, mitigate the adverse impact of indoor air pollution and gender related issues in bio-fuel collection, the government has devised a number of strategies on biomass fuel use. The green economy strategy (2013-2030) has prioritized two programs that could help to develop sustainable forestry and reduce fuel-wood demand: Reduce demand for fuel-wood via the dissemination and usage of fuel-efficient stoves and/or alternative-fuel cooking and baking techniques (such as electric, LPG, or biogas stoves) leading to reduced forest degradation. Biomass will govern household energy of the country in the near future and increased afforestation, reforestation, and forest management to increase carbon sequestration in forests and woodlands. In recently developed bio-energy policy; enhancement of bio energy supply and increase bio energy use efficiency is prioritized. One of the specific objectives of the strategy is ensuring the availability of efficient and effective end-use devices.

Why bio-char stove?

Health: Bio-char-producing stoves are potentially much cleaner, with lower emissions of carbon monoxide, hydrocarbons, and fine particles.

Climate: Bio-char-producing stoves have lower greenhouse gas (carbon dioxide and methane) and black carbon emissions, create bio-char that can be used to sequester carbon in soils, and reduce the use of fossil-fuel based fertilizers.

Deforestation: Bio-char-producing stoves use less fuel, can use a wider variety of fuels, and can replace inefficient charcoal production technologies.

Soils: Bio-char-producing stoves create bio-char that sequesters carbon in soils, may be in some cases reduce emissions of nitrous oxide (a powerful greenhouse gas) from soils, improves fertility, and increases productivity in degraded soils.

Income Generation: Bio-char-producing stoves can accommodate many forms of agricultural residues some without further treatment. Collecting this residue is another income generating opportunity not presently available for most other stoves since they cannot utilize that type of fuel.

Rocket stove

Rocket stove is a portable stove made up of galvanized sheet metal with internal lining with heat resistance insulation material used for cooking. The stove can potentially save up to 70% of fuel compared to the three-stone open fire with a thermal efficiency of 40-50%. In Ethiopia, it is developed and promoted for large-scale institutional cooking purpose. And it is the only ICS registered under carbon credit projects in the country.

Anila stove

Anila-type stoves use two concentric cylinders of different diameters. Biomass fuel is placed between the two cylinders and a fire is ignited in the center. Heat from the central fire pyrolysis the concentric ring of fuel. The gasses escape to the center where they add to the cooking flame as the ring of biomass turns to char. The center combustion chamber can be configured as either a rocket stove design (with a side opening door) or as a TLUD with primary combustion air entering from the bottom.

Hybridization of Rocket and Anila Stove

The principles of biochar cook stoves can be applied to developed countries as well as developing countries. This would help us to reduce our ecological footprint, sequester CO2 and produce a greater proportion of our food locally. More suited to domestic use in developed countries than are the anila or tlud. A rocket stove as hybridized with an anila stove by replacing the insulation of a rocket stove with biomass to be pyrolysis. The inner elbow becomes the combustion chamber and the outer chamber (insulation chamber in a rocket stove) is now a retort. Holes need to be cut in the bottom of the combustion elbow in order that the wood gases can pass from the retort into the

Combustion elbow. Like anila stoves, the only place for the wood gases produced in the retort to go is through the holes in the bottom of the combustion chamber where they then combust, adding to the heat being produced

How the hybridized Stove Works

Work on the principle of having a combustion chamber inside a retort. An outer chamber (the retort) is filled with biomass for turning to bio-char. An inner chamber (the combustion chamber) is then filled with biomass (sticks) which is lit from the top. The heat in the combustion chamber passes through to the retort initiating pyrolysis of the biomass in the retort. The wood gases pass through holes into the bottom of the combustion chamber, where they combust

1.2. Statement of Problem

The pressure on forests, and agricultural productivity, the adverse impact of indoor air pollution and gender related issues in bio-fuel collection, are the challenges issues in our country. In

Ethiopia, the forest cover has been reduced from an initial estimate of 40% a century ago to less 3% .This bring environmental degradation, natural resource depletion and air pollution as well as associated health risks become serious issues as a result of cutting trees to serve as fuel wood. The influence of particulate matter (PM) by burning of biomass fuel has effect on the air quality, ecosystems and human health for cooking food.

The persisting reliance on solid fuels, high and rising fuel prices will be a major demand driver for fuel-efficient biomass ICS and clean-fuel alternatives. At recent time period, in nominal terms, LPG prices have risen 8% annually for key Africa LPG markets (11% globally); kerosene prices have grown 9% annually; electricity costs have grown more slowly, but vastly exceed the cost of other cooking fuels in most markets; and the price of ethanol, a potential alternative cooking fuel, has remained above that of kerosene. Because of increasing demand and growing biomass scarcity, however, charcoal prices have grown even faster more than tripling in a decade (>11% annual growth). The other thing, across much of the world, the traditional method of cooking is over a three-stone fire. The three-stone fire is inefficient in transforming solid fuels to energy and, although its performance varies greatly dependent on the cook. Traditional cook stoves, locally made from mud or metal, are slightly more fuel-efficient than the three-stone fire, yielding as much as 15 percent fuel savings. As well as stove which has not heat resistant material rise in high temperatures of stove body, the body of the stove or of the earth robs heat from the fire which lowers combustion temperatures, decrease efficiency and increase smoke (gas emission).Therefore a rocket stove can be modified to increase efficiency and produce co-product by replacing the insulation of a rocket stove combustion chamber with biomass such as woodchip, coffee husk, saw dust etc.

1.3. Objective of the Study

1.3.1. General Objective

To produce modified rocket stove type that is more efficient in using energy, improving environmental degradation, natural resource depletion, economic, health and gender problems as well as to reduce greenhouse gas emission to environment

1.3.2. Specific Objective

- To simulate modified institutional bio-char rocket stove using CFD
- To develop the prototype of bio-char rocket stove
- To evaluate the performance of the stove for institutional cooking
- To analysis co- product (bio-char) of the stove

1. 3.3. Scope and Limitations of the Study

This research considers simulation of institutional sized bio-char rocket stove using CFD, design, produce prototype and evaluate the performance of the stove for institutional cooking stove as well as bio-char production as co-product that available for recover fertility of soil. The main aim of this thesis produce efficient modified (bio-char rocket) stove for institutional energy consumption as well as co-product (bio-char) to environment soil condition.

Chapter 2

2. Literature Review

2.1. Environmental Protection

Globally, biomass accounts for ten percent of energy production, two-thirds of which is used for cooking and heating purposes in developing countries. It's about 2.4 billion people rely on solid fuels like biomass and Coal for their energy needs burning million tons of biomass each day, and this has implications for environmental and human health. According to Ethiopian Rural Development and Promotion Center [4] 77% of total energy consumption is covered by fire wood and charcoal and the other 15% is from agricultural residue, and the other 6% was met by modern electricity and kerosene [12]. The influence of particulate matter (PM) on the air quality, ecosystems, human health, and climate changes, it is necessary to be aware of its chemical composition and size distribution. As humans are the most important recipients of environmental pollutants, differences in relationships between specific PM fractions (their concentrations) and morbidity and mortality of the human population must be taken into consideration [13]. Bond estimated that cooking with traditional biomass contributes to 18% of current global greenhouse gases emission.

Table 2.1: Percent of national burden of disease due to solid fuel burning in selected countries [3]

Country	Percent of burden of disease due to solid fuel burning
Ethiopia	4.9%
Kenya	2.9%
Malawi	5.2%
Rwanda	5.8%
Uganda	4.9%

Table 2.2: Maximum mean exposure limit to $PM_{2.5}$ for 24 hours and annual (WHP, 2006)

Duration	PM2.5
24-hour mean	25µg/m^3 (or 0.025mg/m^3)
Annual mean	10µg/m^3 (or 0.01mg/m^3)

Table 2.3: Maximum Time Weighted Average Carbon Monoxide Exposure Limits (WHO)

Duration of exposure	Maximum Exposure limit	
	Parts per million (ppm)	gm/m^3
15 minutes	87	100
30 minutes	52	60
1 hour	26	30
8 hours	9	10
24 hours	4	-

Environmental degradation and natural resource depletion are also serious issues as a result of cutting trees to serve as fuel wood. Many countries in Sub-Saharan Africa have witnessed alarming rates of deforestation and the depletion of more than three quarters of their forest cover. In Ethiopia, the forest cover has been reduced from an initial estimate of 40% a century ago to less than 3%.

Hence, there is an urgent need for integrated initiatives addressing interrelated problem like deforestation, land degradation, climate change, inefficient biomass burning and associated health risks. Improved cooking stoves address at least five of the eight United Nations' Millennium Development Goals:-ending poverty and hunger, gender equity, child health, maternal health and environmental sustainability [8, 9].

The vast majority of improved cook stoves, built today are for domestic cooking, often used by single families or households. However, there are also universities, colleges, hospitals, prisons, factories and large temporary settlements such as refugee camps or sites of religious festivals where a large number of people may need to be fed. In such places conventional domestic stoves would not be suitable [2], even if several of them were used together they would be just too small to meet the demand. Stoves to supply larger groups of people, known as institutional stoves, are distinguished from domestic stoves mainly by their larger size and more sturdy construction.

The impact on fuel wood use of institutional stoves in a particular country may be quite significant. For example, some time ago, it was estimated that Kenya had 5,000 institutional kitchens that were using 10% of all the fuel wood used for cooking in the country. As institutions buy fuel from outside contractors, rather than gather it for free themselves, as users of domestic stoves sometimes do, they have a strong incentive to keep down fuel costs by using efficient stoves.

The most commonly used fuel in large stoves is wood. Even where gas or electricity is available, supplies can be unreliable and wood is often cheaper. Alternatively, a wood burning stove may be held in reserve when using electricity, oil or gas burning stoves in case the fuel supply fails

Studies conducted in Malawi reveal that savings in fire wood consumption by institutional cook stoves, dependent on several variables, can be as high as 70%. In Ethiopia, MOWE through GIZ installed pilot Rocket type stoves in IOTs but not being used due to slow cooking and longer warm up time.

Edwin Atkins conducted an assessment of rocket type institutional stoves in Kenya for Millennium Villages Project and found that they affected a reduction in SFC ranging from 15-48% compared to three stone stove [3]. In Ethiopia, no comparative assessment of Institutional stoves have been conducted using traditional dishes despite their significant environmental damage potential and hence the present study is an attempt in this regard; the FDRE government has prioritized plans to deploy 9 million more efficient stoves. This would have a massive impact.

1. On top of decreasing greenhouse gas emissions from forest degradation,
2. it would save USD 270 million in opportunity costs for fuel wood,
3. Increasing rural household income by 10%.
4. Would also create many more jobs in making stoves.

The principal concerns about improving thermo-chemical performance of wood-burning stoves are related to indoor pollution and excessive wood consumption for a given cooking task. The first concern is dealt with by designing smokeless stoves in which smoke is driven out of the kitchen by providing a chimney. The second concern is dealt with by designing a stove in which thermal and combustion efficiencies are improved by suitable dimensioning and by controlling combustion, [11, 14].

2.2. Pyrolysis

Almost any form of organic material can be pyrolysis; however both energy conversion efficiency and the quality of the bio-oil, biochar and Syngas co-products are dependent on the nature of the feedstock. In order to reduce energy loss, pyrolysis reactors should be fed materials with low moisture content (<10 percent moisture by mass) [40]. Among thermal treatment products, char has attracted considerable interest as an additive to improve the water retention and productivity of poor agricultural soils, in which context it is known as biochar.

Char production, i.e. the relatively mild thermal processing of large biomass particles, generally known as “slow pyrolysis” or “conventional pyrolysis” (peak temperatures≤ 600°C, heating rates ≤ 50°C/min, particle size 1 cm [16].Biomass conversion under these conditions is typically characterized by a small to moderate pyrolysis number (*Py*), indicating that the conversion process is either heat transfer- limited, or influenced by both heat transfer rates and kinetics.

The majority of studies indicate that temperature, mass, and/or particle size as functions of time during pyrolysis. The mass of the biomass reduced as the pyrolysis temperature increased, i.e., at 500 °C more bio-char yield produced as compared to 600°C and 700°C. At higher temperatures, biochar produced are relatively alkaline in nature [17].The stove geometry, fuel controlling during operation, heating time and type of biomass are the governing parameters in changing the quality of biochar. The effect of the biomass type and the type of stove design were less in changing the bio-char yield. Biochar significantly affected by the type of biomass ,heating time and stove type (9.52 mean for normal Anila and 8.01 mean for Anila continuous feeding flange less). In fact, the type of biomass significantly affects the bulk density and surface area of bio-char [18].

Table2. 4: The normal mixture of gases in the synthesis gas

Mixture of gases in the synthesis gas	volume%
CO2 (carbon dioxide)	9 to 55
CO (carbon monoxide)	16 to 51
H2 (hydrogen gas)	2 to 43
CH4 (methane)	4 to 11
N2 (Nitrous gas)	Low amount
other hydrocarbons	Low amount

The properties of the synthesis gas vary depending on which process is being used. They also depend on the distribution between the different gases. However, it can be mentioned that the gas is flammable and contains carbon monoxide, which is a health hazard. CO2 and N2 have no heating value when combusted and therefore they affect the synthesis gas energy content negatively.

2.3. Production of Biochar

Biochar has the potential to be the possible solution of soil fertility amendment and atmospheric carbon sequestration. Biochar is the solid product remaining after biomass is heated to temperatures typically between 300^{o}C and 700^{o}C under oxygen-deprived conditions, a process known as “pyrolysis”. Because of its physical, chemical, biological properties and its interaction with soil and soil microbes, it has many agricultural and environmental benefits. It increases crop yields, sometimes substantially if the soil is in poor condition. It helps to prevent fertilizer run off and leeching allowing the use of less fertilizers and diminishing agricultural pollution to the surrounding environment [16, 17].The external temperature is a factor determining the char yield. Small particles give less char than large particles: at 400^{o}c, the char yield, which is 20 % for particles of 5-7mg rises to 30 % for particles of 600-800mg. The effect of the particle size is more important at low temperature. Above 600 ^{o}c, the difference between small and large particles is almost negligible [22, 26]. The particle size influence on the char yield is explained by the heating rate, and the residential time of the volatiles, which react with the char layer when flowing out the particle to form char. It takes longer time for the volatiles to leave a large particle than a small. At high temperature, the rate of pyrolysis is sufficiently high to decrease considerably the residential time of the volatiles, even for large particles [23, 25]. Therefore the difference in char yields be-come less important between small and large particles at high temperatures.

The most influential design-specific parameters on the pyrolysis process are peak temperature and residence time [23]. However, process parameters like heating rate, gas retention/sweep gas scenarios, feeding rate and pressure, as well as feedstock/pre-treatment parameters (e.g. particle size and water content) can also have significant additional influence on the process [24]. To get the right quality of the end products char and pyrolysis gas, the operating parameters can be adjusted. The operating parameters affecting the pyrolysis process are temperature, mass flow, particle size, pressure and moisture content.

Most stoves are designed specifically to produce a clean flame suitable for cooking and not necessarily to maximize biochar production, but they can produce between 25 and 30% biochar weight from the initial feedstock weight [21, 22]. The suitability of each biomass type as a potential source for biochar is dependent on a number of chemical, physical, environmental, as well as economic and logistical factors. In future Pyrolysis is considered to be one of the sustainable solutions that may be economically profitable in large scales and minimize. Environmental concerns especially in terms of Waste minimization, Carbon sequestration, soil amendment, energy/heat supply Value added chemicals, and development of rural areas.

2.4. Computational Fluid Dynamics (CFD)

Computational fluid dynamics (CFD) has become a well-known aiding tool in these regards as to characterize the conversion process, optimize the design, visualize the f low fields in the reacting flow environment, and to improve the operating efficiency as a whole. Thermo-chemical conversion of biomass offers an efficient and economically process to provide gaseous, liquid and solid fuels and prepare chemicals derived from biomass. Computational fluid dynamic (CFD) modeling applications on biomass thermo-chemical processes help to optimize the design and operation of thermo-chemical reactors. Simulations on stove design, pyrolysis process, and combustion systems particle deposit and pollutant release have been performed with CFD packages. Design of biomass stoves using CFD for high thermal efficiency and low emissions of toxic gases and particulate matter requires detailed understanding of various fundamental physical phenomena, namely, heat transfer, fluid flow, pyrolysis and combustion, and the complex interaction among them. All these phenomena are so intimately coupled with one another that a realistic prediction of performance of a biomass stove needs detailed modeling of each of the above phenomena and their coupling.

Design of a biomass stove basically involves the choice of the various geometric dimensions of the stove for achieving a desired range of operating conditions of the stove with the best possible thermal efficiency and the minimum possible harmful emissions. The complete statement of the design problem needs the mathematical expression of the functional relationship between the geometric parameters and the performance parameters such as the thermal efficiency, power and emission factors. These functions need to be obtained for different stove configurations for a given fuel. It should also be noted that these functions would be different for different fuels used in the same stove configuration [14].

In naturally aspirated wood-burning stoves, the air-flow is driven by buoyancy forces which overcome the flow resistances inside the stove. This air flow, in turn, determines the wood burning rate as well as the overall thermal and combustion efficiencies. The flow and associated heat/mass transfer and combustion phenomena are 3-dimensional and time dependent [14, 15].

ANSYS fluent is capable of modeling heat transfer and combustion for various fluid flow regimes (laminar and different turbulence models). Its post processor provides color graphics and important flow parameters (mass flow rate, temperature, etc.) by a click of a few buttons. Those capabilities make fluent a very valuable tool to analyze the flow and temperature within the cook stove, as well as estimating the performance of the prototypes [17]. The principles of biochar rocket stoves can be applied to increase cooking efficiency of stove as well as this will help us to reduce our ecological footprint, sequester CO2 and produce a greater proportion of our food locally.

Chapter 3

3. Materials and Method

3.1. Experimental Site Description

The experiment was conducted at Jimma Agricultural Engineering Research Center (JAERC), Oromia Agricultural Research Institute (OARI). The center is located at 07 41' 43.973"N latitudes and 36 48'.52446"Elongitudes, having an elevation of 1772 meters above sea level (masl).

3.2. Institutional Bio-Char Rocket Stove Design and Development

3.2.1. Design Consideration

Institutional bio-char rocket stove was designed and developed based on the CFD simulated result for the cost-effectiveness of carrying out multiple parametric studies with greater accuracy allows the production prototype of new system design of high thermal efficiency and low emissions of toxic gases and particulate matter requires detailed understanding of various fundamental physical phenomena, namely, heat transfer, fluid flow, pyrolysis and combustion.

The parameters consider designing stove were:

- Non-smokiness
- Safety hygiene
- Ergonomics stability
- Ease of lighting
- Time taken to start fire
- Fire wood consumption
- Speed of cooking
- Socio-cultural fit
- Size
- Cleaning requirements

- Ease of adding more fuel

Detail design of institutional bio-char rocket stove considers the vessel (dist) size and capacity (amount) to hold for purpose it perform. The other thing was the availability of materials locally to reduce cost of production, and maintenance; the materials for the construction of the various component parts were selected on the basis of weight stove as well as the force that would be acting on them, the performance it is expected to perform and the environmental condition in which they would function. As well as by identifying position pyrolysis chamber to modified with rocket stove for achieving a desired range of operating conditions of the stove with the best possible thermal efficiency.

3.2.2. Description of Stove

The configuration this stove in its original form as received from the institutional rocket stove. The stove was medium (60liter), and equipped with a chimney. The stove body is111cm in over-all height, weighed 47kg institutional bio-char rocket stove was constructed from sheet metal of 1.5mm thicknesses.The stove has three sections (figure3:1), vessel holder, pyrolysis and combustion chambers.This prototype has very similar features to that of rocket stove models. The cook stove consists of two concentric cylinders. A rectangle cut was connected to the inner cylinder to draw the air (primary flow) and inlet of biomass fuel into the cook stove. The inner cylinder is the combustion chamber, where the product of wood combustion and pyrolysis gas mix. The pyrolysis chamber is slightly higher than that of combustion chamber and this was designed to create a gap between the combustion and the pyrolysis chamber. This gap allows the pyrolysis gas to enter the combustion chamber and mixes with the wood combustion products.

The major components of the combustion chamber with inlet of biomass fuel at bottom, pyrolysis chamber at top inlet of biomass(such as wood-chip ,coffee husk, saw-dust etc.) also at bottom outlet of bio char and vessel(Dist) holding chamber as well as chimney at middle holding chamber of vessel. Figure 3:1 gives details of Stove designed, constructed and used in the experiment. The biomass enters a through inlet into combustion chamber section.The second section, where pyrolysis is taking place. The volatiles, some Syngas, flue gas are taken out of the pyrolysis chamber through exhaust to combustion chamber wall. The steam, the flue gas and any air exhausts out the top of the stove chimney.

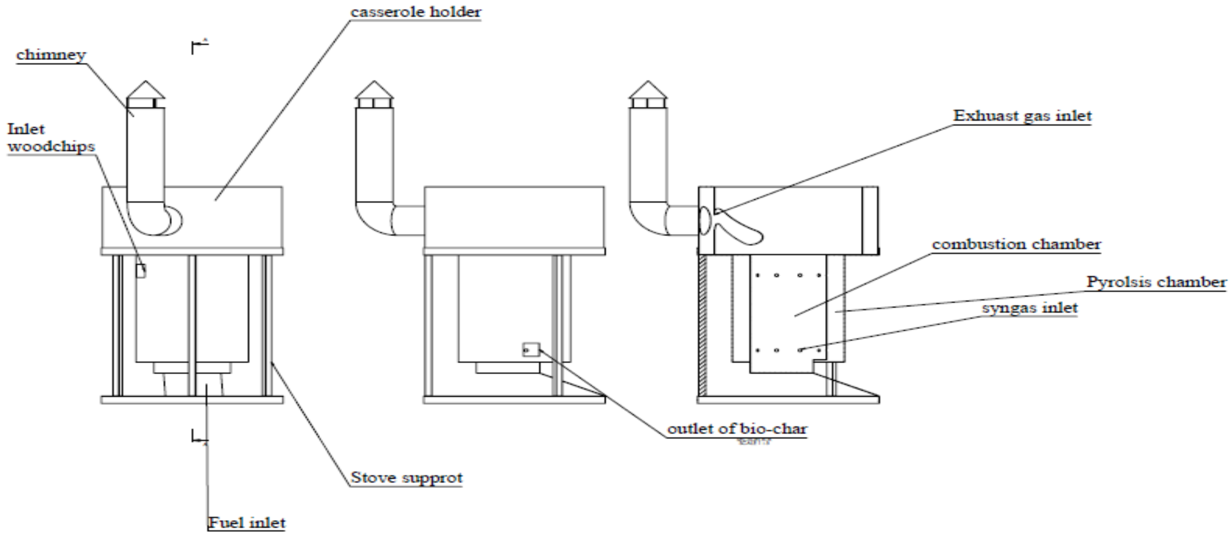

Figure 3.1: Details of the stove

Table 3.1:Pertinent dimensions of component parts of stove

Component	Dimensions
Overall size (length × width × height)	(75 x 75 x 111) cm
Vessel(Dist) holding chamber (width × length)	(62x 62) cm
Vessel (Dist) holding chamber inner (diameter)	62cm
Vessel (Dist) holding chamber outer (diameter)	75cm
Combustion chamber (diameter)	32cm
Pyrolsis chamber(diameter)	47cm
Area of combustion chamber ($2\pi r^2 + 2\pi rh$)	7937.92cm^2
(Area of pyrolsis chamber) – (Area of combustion chamber)	3841.79 cm^2
(volume of pyrolsis chamber ($\pi r^2 h$)) – (volume of combustion chamber ($\pi r^2 h$))	4735.95cm^3
Stove standing(Length x Height)	(75 x75) cm

3.3. Numerical Simulation

ANSYS fluent work bench was used for simulation of wood combustion and wood chips pyrolysis the stove. Geometry model was designed using ANSYS fluent and model gets transferred to mesh. The geometry was imported into ANSYS mesher, where the model would be meshed. Body sizing was the primary tool used to create the desired mesh [42]. The mesh in the combustion and pyrolysis chamber was given a finer mesh to fully capture the behavior of the fluid flow. In meshing section parameters of geometry part was defined for better thermal efficiency and gas flow analysis ,under mesh sizing, fining was selected to discrete flow into many elements and updated to recognize the input. Modeling, the bio-char rocket stove system was divided into three zones: the solid phase packed bed zone, the gas phase combustion or flame zone, and the heat transfer zone.

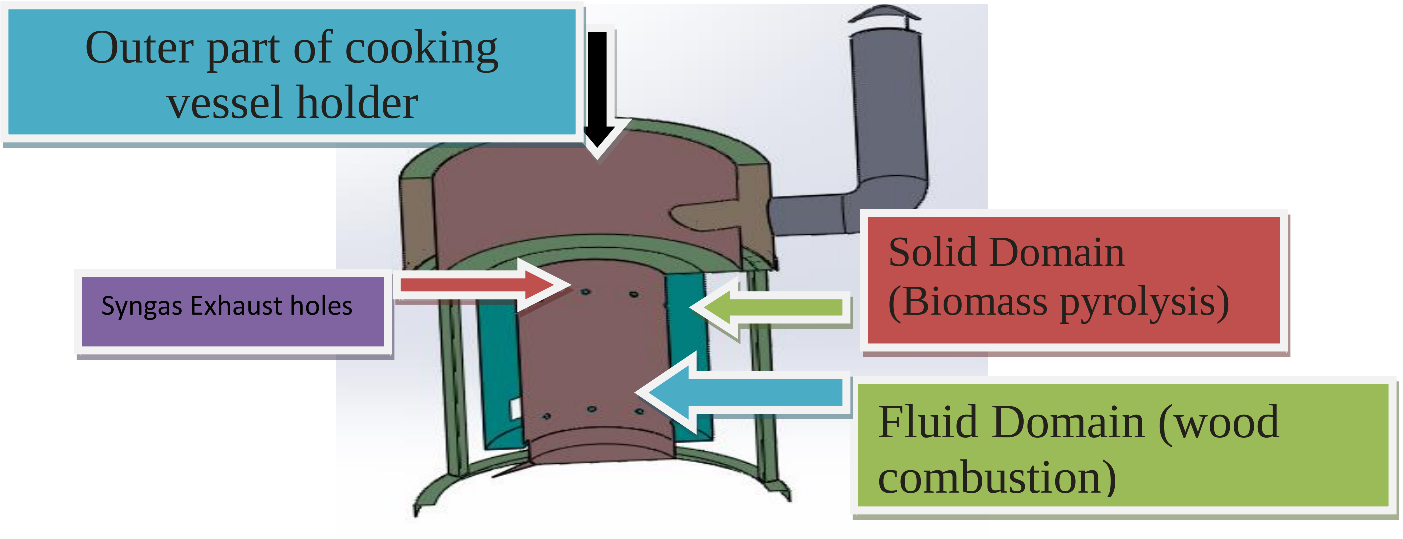

Figure 3.2: Sectional view of stove

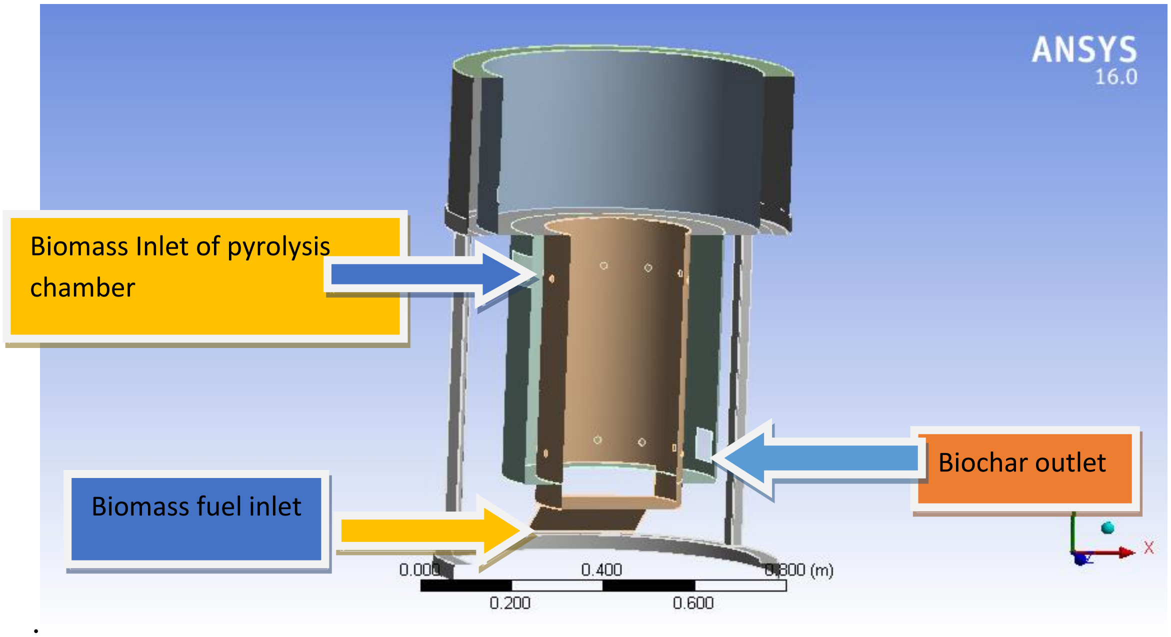

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Figure 3.3: 3D Sectional view

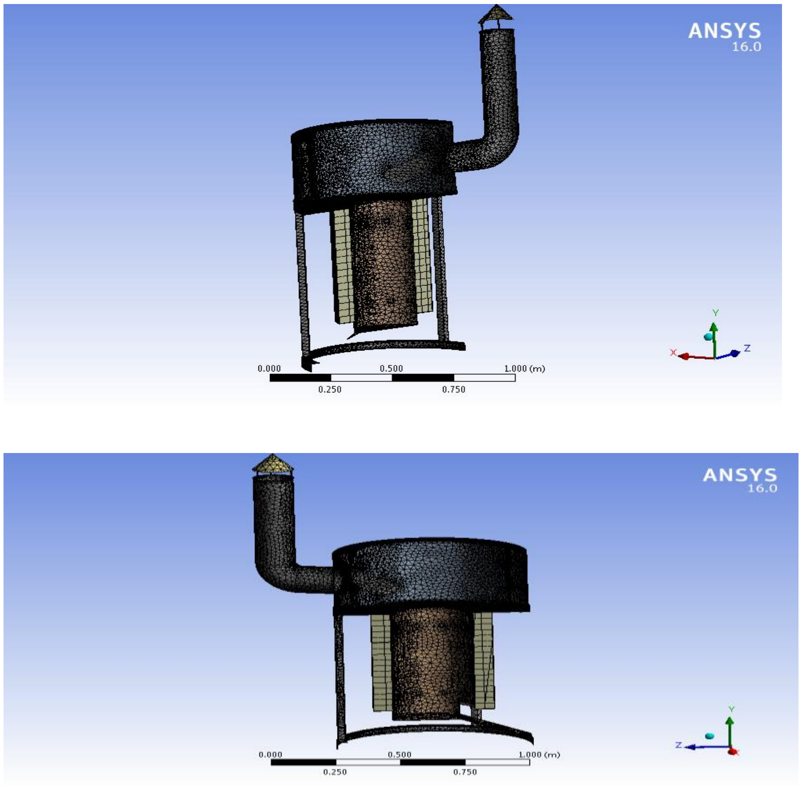


Figure 3.4: 3D model section view with mesh grid

Similar model was designed, prototype manufactured and assembled for the experimental test**.** The models tested should be able to simulate the pyrolysis of the wood chip and combustion biomass fuel in a general case in order to have a scientific value. Therefore no change of key properties of the wood should be used to improve the agreement between experimental and simulated results.

3.3.1. Boundary Conditions

The fluent model was used six of boundary conditions to simulate stove but Syngas outlet from pyrolysis is twenty holes. Those boundary conditions were temperature, Wood volatile velocity, syngas flow, pressure inlet, wall surface and Pressure outlet.
The procedures that was used to quantify Boundary condition:

The convection coefficient of the outer wall of the stove was assumed to be the greater of the natural convection correlation for a heated cylinder [42].

$h_{wall,\ ext}=1.42((T_{ext}-T_{amb})/\ (H_{stove}))$

$h_{wall,\ ext}$- convection coefficient of the external wall of the stove

H_{stove}- over all Height of stove

$T_{ext}=873k$, $T_{amb}=300k$, $H_{stove}=1.11m$

$h_{wall\ ext}=7.41w/m^2k$ (outer surface of the stove and surface around of the vessel)

- Biomass fuel used: 6kg
- Wt_w (Weihgt of water) = 60kg
- Wtv (Weight of vessel)=7kg
- Wt_{chip}(weight of wood chip)=5kg

Combustion chamber

- Average burning rate:(6kg/60min)=0.1kg/min
  =6kg/hr
- Bulk flow of gases=Average burning rate(Wtv +Wt_w)/(biomass fuel used)
  =6(7+60)/(6)=67kg/hr

Density: $\rho = (353.09)/\ (T)kg/m^3$Gas Properties [43]

$T=873k$, $\rho=0.41kg/m^3$

- Volumetric flow of gases=(Bulk flow of gases)/(ρ)
  =(67kg/hr)/0.41kg/m^3= 163.4m^3/hr
- Velocity of gases= (Volumetric flow of gases)/(area)
- Area of combustion chamber=0.794m^2
- Velocity of wood-volatile =(163.4m^3/hr)/(0.794m^2)
  =205.8m/hr=0.057m/s

Pyrolysis Chamber

- Average pyrolysis rate of wood chip =(5kg/60min) =0.083kg/min=4.98kg/hr
- Weight of Vessel(Wt_v)=7kg
- Weight of water(Wt_w)=60kg
- Bulk flow of syngas=Average pyrolysis rate (Wtv +Wt_w)/(wood chip used)=(4.98kg/hr(7kg +60kg))/(4.98)=66.732kg/hr
- At temperature 723k of pyrolysis chamber, ρ=0.41kg/m^3
- Volumetric flow of syngas =(Bulk flow of syngas)/(ρ) =(66.732kg/hr)/(0.41)=162.8m3/hr
- Area of pyrolysis chamber==0.384m^2
- Velocity of syngas = (Volumetric flow of syngas) /(Area of pyrolysis chamber)=0.118m/s
- Re=Vavg(D)/(viscosty), Diameter syngas exhuast holes=0.007m,visco=7.395*10-4, V=3m/s that flow through exehuest hole to combustion chamber

Re=(3m/s*0.007m)/(7,395*10-4)

- Re=7299 ,therefore from this flow was turbulent flow.
- Nu=(hD)/k= 0.023$Re^{0.8pr0.4}$,turbulent flow(Incropera et. al.,2007)

=180.6

- K= 26.2w/km,of sheet metal [43]

Table 3.2: List of boundary conditions

Boundary Name	Boundary Type	Boundary condition
Case wall	Surface	$H_{wall\ ext}$=7.41 w/m^2k Ambient T=300k
Wood-volatile gas velocity inlet	Wood-volatile velocity inlet	V=0.04m/sand T=873k
Syngas(from exhaust hole to combustion chamber through 20 holes)	syngas velocity inlet	V=3m/s and T=723k

Model assumptions

The following assumptions were made:

- The operation is transient state.
- Combustion is assumed to be complete (Ragland et al, 2011).
- There is ax- symmetric, one-dimensional, vertical airflow within the combustion chamber.
- The radiation temperature is neglect.

Governing Equations

The Navier – Stokes equations describe the motion of viscous fluids [15]. For a single-phase flow they are composed by the continuity equation and the momentum equation.

Governing Equations for Reactions

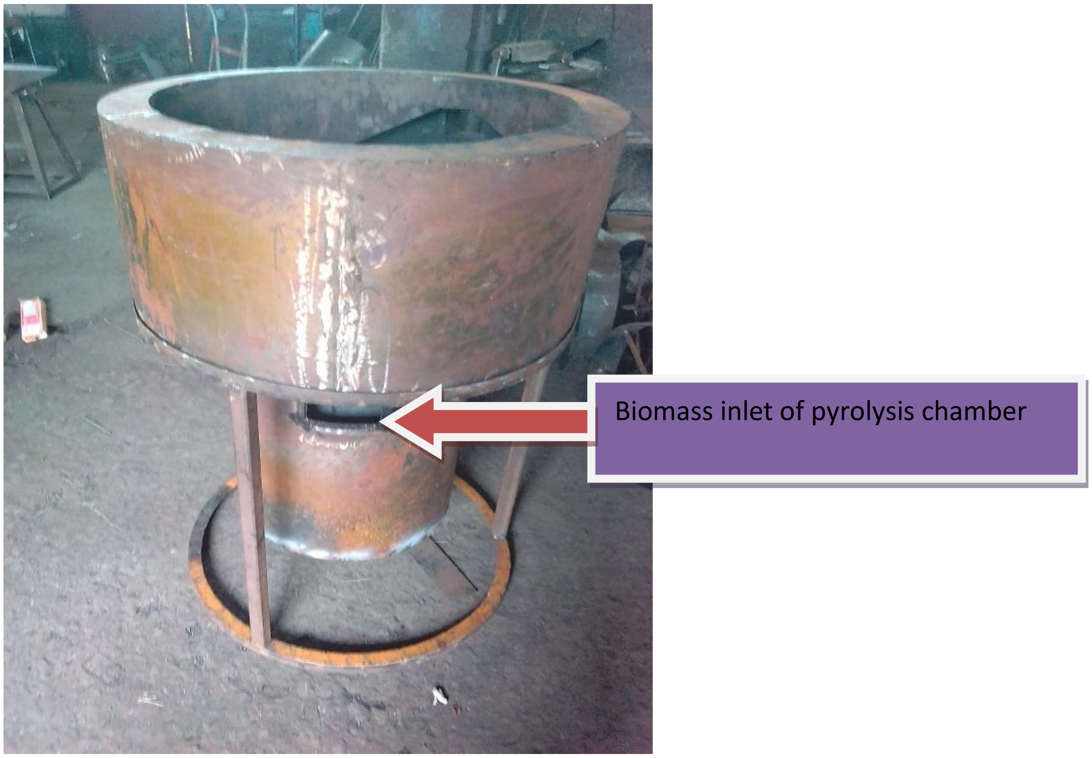
- Conservation of mass
- Conservation of momentum
- Conservation of energy
- species transport equation

3.4. Prototype Production of Stove

Figure 3.5: a) Cylinders rolling by machine b) Combustion and Vessel holder

Figure 3.6: a) Pyrolysis Cylinder b) Bottom vessel holder plate

Figure 3.7: a) Up-side down vessel holder   b) Assembled vessel holder and combustion cylinder



Biomass inlet of pyrolysis chamber

Figure 3.8: Prototype of stove

Figure 3. 9: Bio-char rocket stove in the experimental investigation

3.5. Measuring Devices and Instruments

The remote thermometer was used for measuring surface temperature such as pyrolysis cylinder, vessel (Dist) holder and chimney to analysis heat loss on those main parts. The outer surface temperature of the stove was measured using infrared temperature (remote thermometer) measuring device by selecting a similar region on each surface of the stoves per 5 min interval for all testing condition. Hygrometer was also used for measuring humidity of surrounding environment during collection data of stove. An electrical oven, made in USA (Dry oven max 105C^{o}) was used for measuring the moisture content sample of wood fuel and woodchips. Model - CT digital balance and spring-scale were used to measure weights of samples woodchips before and after stove performing as well as bio-char weights. As well as big digital balance was used to measure weight samples wood fuel before and after stove performing. Thermocouple was used for measuring of the temperature that occurs inner body of stove by inserted into the process and also using multi-meter thermometer reading temperature result from instrument. To measure the temperature within the biomass bed, point was marked on the outer surface of the stove from ground and drilled to insert type E thermocouple wire up to the center. Then the drilled part of the outer surface of the stove was sealed using epoxy.

Figure 3.10: Stove temperature test instruments

Figure 3.11: Humidity and wind speed measuring instrument

3.6. Experimental Analysis

3.6.1. Experiment Set-Up

Cooking on stoves that need to be fed fuel wood continuously, is like feeding a baby. It requires immense patience. One has to start the fire with the thinner sticks and then move to the ones with larger diameters [35]. Tests were conducted in a biomass fuel Juniperus procera (Tside) with a 1 cm *2.5 cm cross section and a height of 137 cm. Real-time temperature data were acquired by type E thermocouples installed at various distance on stove. The temperature measurements included combustion temperature, surface and pyrolysis temperature. Temperatures were also recorded at various locations in the fuel chamber and on the outside of the stove body. An additional type E thermocouple or Mercury thermometer submerged in the vessel of water measured the water temperature, and recorded the starting and ending time for each test. The test includes measurement of fuel-wood consumed and water boiling time for each phase pre-weighed quantities of the same size in average of fuel-wood, each phase boiled on a bio-char rocket stove. Quantity, quality fuel-wood were measured before and after boiling. A batch of firewood was set aside and weighed before cooking for each phase of WBT. The remaining wood was weighed after cooking and the amount consumed was computed by difference. The weight of char-coal remaining in the stove after boiling each quantity of water was estimated by weighed. The test used for Water Boiling Test, version 4.2.3. Water Boiling Test [18, 21] was calculated using version 4.2.3. The WBT consists of three phases that immediately follow each other.

- cold-start high-power phase
- hot-start high-power phase
- simmer phase

Experimental Procedure

The WBT (The Water Boiling Test: Version 4.2.3) is the most common test used to evaluate cook stove performance in the laboratory [18, 20].The objective of this study was to estimate the efficiency of a stove. In literature the most common test used to measure the efficiency is the Water Boiling Test (WBT), for this reason it was adopted this type of procedure in order to have a term of comparison with the results obtained.

The procedures followed were:

- Preparing wood chips of appropriate moisture content and measuring its weight using digital balance
- Recording cross section size of wood fuel and moisture content of wood fuel and woodchip
- Insert the wood chips that measured into pyrolysis chamber of the stove

- Prepare fuel wood of similar(appropriate) size , moisture content and measure its weight
- Packing woodchip into pyrolysis chamber till capacity of cylinder
- Insert the vessel into the stove
- Prepare clean water (make sure that 60 liters of water were added to the vessel)
- Record ambient temperature, environmental humidity and initial water temperature
- Kerosene, for ignition purpose
- Wait for 5 minute after ignition
- At the regular interval of time record the data continuously up to local boiling point of water reached.
- When water is boiled, immediately remove the fuel wood and char, then, cover with pan in order to stop further combustion.
- Measure the wood and char left both chamber(combustion, pyrolysis)

3.6.2. Study Variables

The main parameters under these studies were:

- Temperature
- Moisture content of the firewood
- Fuel consumed (moist)
- Net change in char during the test
- Firepower
- Thermal efficiency
- Specific fuel consumption and
- Burning rate

1. Fuel

The rate of evolution of gases of stove was depends on the temperature gradients within the biomass (fuel) which in itself is a function of the particle size and shape and the rate of heat transfer to the particle surface and from the particle surface into the material.

a) Type of fuel: Juniperus procera (tside)

b) Dimension of fuel: sizes of 1cm *2.5cm with cross-sectional dimensions of solid fuels had been used during WBT.

c)Measuring Moisture content: Biomass fuel and wood chip

3.7. Biomass Fuel and Wood Chip Sample

In a large stack of fuel, there were be variations in the moisture content throughout the stack and take a sample from more than one place to allow for this.

3.7.1. Testing the Samples

- Preheat the oven to the point marked during calibration for an internal temperature of 105°C. The thermometer used during calibration to double check.
- Weigh the samples in the airtight container before opening. This provides an accurate weight of the sample before any material or water was lost from the sample.
- Weigh the container that would be using to heat the biomass fuel and chip.
- Testing more than one sample, label the heatproof containers so that know which results apply to each sample.
- Put all of the samples in the oven at the same time.
- Log each sample weight every two hours
- When the weight of a sample was remains unchanged two consecutive measurements it could consider to be oven dry [36].

Figure 3.12: Balancing biomass fuel and woodchip sample

Figure 3.13:Oven-dry

Table 3.3: Weight of biomass fuel sample

Name of can	Weight of can in gram	Weight of biomass fuel sample with can(gram)	Weight of biomass sample only in gram	biomass fuel sample after staying in oven dry(gram)
B-1	51	84	33	29
B-2	52	89	37	33
B-4	42	65	23	20
B-6	45	79	34	30
Average			31.75	28

- Average mass of biomass (fuel) sample=31.75
- Average mass of biomass (fuel)dried sample =28

MC% = ((Average mass of biomass sample) – (verage mass of biomass dried sample))/(verage mass of biomass sample) *100%

MC% = (31.75 – 28)/(31.75) * 100%

MC% =11.81%

Table 3.4: Weight of wood chips sample

Name of can	Weight of can in gram	Weight with woodchip sample with can(gram)	Weight of woodchip sample in gram	woodchip sample after staying in oven dry(gram)
V	51	58	7	5.76
X	46	53	7	6
B-3	49	55	6	6
B-5	45	52	7	6
Average			6.75	5.84

- Average mass of woodchip sample=6.75g
- Average mass of dried woodchip sample =5.84g

MC% = ((Average mass of woodchip sample) – (verage mass of woodchip dried sample))/(verage mass of woodchip biomass sample) *100%

MC% = (6.75– 5.84)/(6.75) * 100%

MC% =12%

2. Initial Water Temperature: Initial temperature of was taken at initial for the water (to know level of water temperature).

3.8. Water Boiling Test (WBT)

1) The cold-start high-power phase, the tester begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard vessel.

The tester then replaces the boiled water with a fresh vessel of ambient-temperature water to perform the second phase.

2) The hot-start high-power phase was conducted after the first phase while stove was still hot. Again, fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard vessel. The test with a hot stove helps to identify differences in performance between a stove when it was cold and when it was hot.

3) The simmer phase provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world [18].

3.8.1.WBT Phase 1: High Power (Cold Start)

Table 3.5: Meusured parameter of WBT PHASE 1

No	Data, Cold Start High Power section	Units	quantity
1.	Pre-Weight of fuel,	Kg	7
2.	Weight of empty vessel	kg	7
3.	Pre-Weight of chip-wood	Kg	6
4.	Weight of pot with water,start	kg	67
5.	Batch Weight of fuel at once insert tostove	Kg	0.5
6.	Batch Weight of chip-wood insert pyrolysis chamber	Kg	4.5
7.	Water temperature,start	Degree Celsius	21
8.	Time,start	Min	3:40
9.	Time,finish	Min	4:00
10.	Temperature,finish	DegreeCelsius	94
11.	Weight of fuel,finish	Kg	4.5

12.	Weight of biochar + container, finish		1.99
13.	Weight of charcoal + container, finish	Kg	0.7
14.	Weight of pot with water, finish	Kg	66.57

Commonly Used Measures

The measures that most stove use was summarized here.

Stove characteristics: burning rate, firepower, turn-down ratio Efficiency and performance measures: time to boil, specific fuel consumption , thermal efficiency.

Table 3.6:Variables calculated WBT phase 1

`fcm	Fuel consumed, moist
Δcc	Change in char during test
fcd `	Equivalent dry wood consumed
wcv	Water vaporized (grams)
wcr	Effective mass of water boiled (grams)
Δtc	Time to boil (min)
hc	Thermal efficiency (%)
rcb	Burning rate (grams/min)
SCc	Specific fuel consumption
FPc	Firepower (W)

fcm – The fuel consumed (moist) was the mass of wood used to bring the water to a boil, found by taking the difference of the pre-weighed bundle of wood and the wood remaining at the end of the test phase:

$$f_{cm}=(f_{ci}-fcf\ ) + f_{cb}$$

f_{cm} -fuel consumed (moist) cold phase

f_{ci} -pre-weighed bundle of fuel initial at cold phase

fc_f -final weight of fuel at cold phase

f_{ci}=6Kg f_{cf}=2.5Kg

f_{cm}=(6Kg-2.176 Kg) + 2kg =6Kg

ΔC_c-The net change in char during the test was the mass of char created during the test, found by removing the char from the stove at the end of the test phase. Because it was very hot, the char would be placed in an empty pre-weighed container of mass k (to be supplied by testers) and weighing the char with the container, then subtracting the container mass from the total:

ΔC_c=C-K C_c=2.1Kg K =1Kg

ΔC_c=2.1Kg-1Kg = 1.1Kg

wcv – The mass of water vaporized was a measure of the water lost through evaporation during the test. It was calculated by subtracting the initial weight of Vessel(Dist) and water minus final weight of vessel(Dist) and water.

w_{cv}=C_{ci}-C_{cf} , C_{ci} =67, C_{cf} =66.514

C_{ci}-container(vessel) with water initially

C_{cf}-container(vessel) with water finnally

w_{cv} =67- 66.514=0.486kg

wcr – The effective mass of water boiled was the water remaining at end of the test. It was a measured of the amount of water heated to boiling. It was calculated by simple subtraction of final weight of vessel(dist) and water minus the weight of the vessel(dist).

W_{cr}= C_{cf}-c, c=7kg , C_{cf} =66.512, W_{cr}=66.514-7=59.514kg

Δtc - The time to boil water of vessel(dist) was the difference between start and finish times:

$\Delta tc = t_{cf} - t_{ci}$

$\Delta tc = 9{:}20 - 9{:}00 = 20\text{min}$

f_{cd}– The equivalent dry fuel consumed adjusts the amount of dry fuel that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned. The mass of dry fuel consumed was the moist fuel consumed minus the mass of water in the fuel:

Dry fuel= $f_{cm}(1\text{-MC})$

The energy that was needed to remove the moisture in the fuel was the mass of water in the fuel multiplied by the change in specific enthalpy of water.

$\Delta E_{H2O} = m_{H2O}(C_p(T_b - T_{fuel,i}) + \Delta h_{H2O,fg})$

$C_p \approx 4.186[KJ/KgK]$ $\Delta h_{H2O,fg} \approx 2{,}257\ [KJ/Kg]$ $T_{fuel} \approx T_{ambient}$

The mass of water in the fuel is: $m_{H2O} = f_{cm}MC$, MC=11.91%,f_{cm}=6Kg m_{H2O}=0.7587kg

Therefore, $\Delta E_{H2O} = f_{cm}MC(4.186(T_b - T_a) + 2{,}257)$, *Tb* – The local boiling point of water was (94°c)

$T_b = 94^o c = 367k$

$T_a = 27\ ^o c = 300k$

$\Delta E_{H2O} = 0.7587(4.186(367-300) + 2{,}257) = 1{,}925.2KJ$

This quantity of energy was divided by the energy content of the fuel to determine the equivalent mass of fuel required to remove the moisture in the fuel:

Fuel to evap water $= \Delta E_{H2O}/(LHV)$, LHV =17,380 kJ/kg

Fuel to evap water =0.1108Kg

The fuel energy stored in the char remaining ($\Delta E_{char,c}$) was the mass of char multiplied by the energy content of the char:

$\Delta E_{char,c}=\Delta C_c*LHV_{char}$, LHV_{char} ,=29,500kJ/kg ΔC_c=1.1Kg

$\Delta E_{char,c}$=1.1*29,500=32450KJ

This quantity of energy was divided by the energy content of the fuel to determine the equivalent amount of unburned fuel remaining in the form of char:

Fuel in char = $\Delta E_{char,c}$/(LHV)=1.87Kg

Putting it all together we have:

f_{cd}=dry fuel- fuel to evap water- Fuel in char, dry fuel=6Kg , Fuel to evap water =0.1108Kg , Fuel in char=1.87Kg

f_{cd}=6kg-0.1108Kg -1.87Kg = 4.0192 Kg

hc – Thermal efficiency: A ratio of the work done by heating and evaporating water to the energy consumed by burning fuel. It was an estimate of the total energy produced by the fire that was used to heat the water in the vessel. It was calculated in the following way:

$h_c= (\Delta E_{H2O.heat} + \Delta E_{H2O,evap})/E_{released,c}$

The energy to heat the water was the mass of water times specific heat capacity times change in temperature:

$\Delta E_{H2O.heat} = m_{H2O}*Cp*\Delta T$, m_{H2O}=60kg , ΔT = 67k

$\Delta E_{H2O.heat}$=60kg*4.186*67

$\Delta E_{H2O.heat}$= 16,827.72 KJ

The energy to evaporate the water was the mass of water evaporated multiplied by the specific enthalpy of vaporization of water:

$\Delta E_{H2O,evap} = w_{cv}*\Delta h_{H2O,fg}$, w_{cv}=0.486kg , $\Delta h_{H2O,fg}$= 2260kJ/kg

$\Delta E_{H2O,evap}$=0.486kg*2260kJ/kg = 1,098.36 KJ

The energy consumed was the equivalent mass of dry fuel consumed multiplied by the heating value:

$E_{released,c}=f_{cd}*LHV$, f_{cd}= 4.0192 Kg, LHV=17,380 kJ/kg [41].

$E_{released,c}$=4.0192 *17380 = 69,853.696 kJ

h_c=(16,827.72 KJ + 1,098.36 KJ)/ (69,853.696 kJ)=47.87%

r_{cb} – Burning rate: The measure of the rate of fuel consumption while bringing water to a boil. It was calculated by dividing the equivalent dry fuel consumed by the time of the test.

$r_{cb}= (f_{cd})/ \Delta t_c$, f_{cd} =4.0192 Kg, Δt_c=20min

r_{cb}=4.0192 Kg /20min= 0.20096 kg/min =200.96g/min

SC_{cold}-Specific fuel consumption: it was a measure of the amount of wood required to produce one liter of boiling water starting with cold stove. It was calculated as:

$SC_{cold}=(f_{cd})/w_{cc}$, f_{cd}=4.0192 Kg, w_{cc}=59.514liters

SC_{cold}=4.0192 Kg /*59.514lit* = 0.0.0675kg/lit =67.5g/lit

FPc – Fire power:This was 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:

$FPc= (f_{cd}*LHV)/(60\Delta t_c)$

FPc=(4.0192 Kg *17,380 kJ/kg)/(60*30)

FPc = 38.807KJ/s =38,807.6W

Fgure 3.14: WBT of Institutional Bio-char Rocket Stove

3.8.2. Variables For High Power Phase (Hot Start)

In this test, measurements and calculation was identical to the cold start test except that the char remaining was not extracted and weighed. Simply substitute the subscript ‘h’ for the subscript ‘c’ in each variable as in the table below. Char remaining was assumed to be the same as the char remaining from the “cold start” phase.

Table 3.7:Variables meusured WBT phase 2

N0	Data, hot Start High Power section	Units	quantity
1.	Pre-Weight of fuel,	Kg	5
2.	Weight of pot with water,start	kg	67
3.	Batch Weight of fuel at once insert tostove	Kg	0.5
4.	Water temperature,start	Degree Celsius	22
5.	Time, start	Min	4:10
6.	Time, finish	Min	4:27

7.	Temperature,finish	DegreeCelsius	93
8.	Weight of fuel,finish	Kg	3
9.	Weight of charcoal + container, finish	Kg	2.05
10.	Weight of pot with water, finish	Kg	66.25

Table 3.8:Variables calculated WBT phase 2

f_{hm}	Fuel consumed, moist (grams)
`$\Delta c_h = \Delta c_c$	Change in char during test
f_{hd}	Equivalent dry wood consumed
w_{hv}	Water vaporized
w_{hr}	Effective mass of water boiled
Δt_h	Time to boil (min)
h_h	Thermal efficiency (%)
r_{hb}	Burning rate (grams/min)
SC_h	Specific fuel consumption
fP_h	Firepower (W)

$F_{hm}=(f_{hi}-f_{hf}) + f_{hb}$, $f_{ci}=5Kg$ $f_{cf}=2.5Kg$

$f_{cm}=(5Kg-2.5\ Kg) + 2.5kg = 5Kg$

f_{hm} -fuel consumed (moist) hot phase

f_{hi} -pre-weighed bundle of fuel initial at hot phase

f_{hf} -final weight of fuel at hot phase

$\Delta c_h = \Delta c_c$ ΔC_h-The net change in char hot phase

ΔC_c-The net change in char cold phase

f_{hd} =Dry fuel= $f_{hm}(1-MC)$

$\Delta E_{H2O}=m_{H2O}(C_p(T_b-T_{fuel,i})+\Delta h_{H2O,fg})$

$C_p \approx 4.186$[KJ/KgK] $\Delta h_{H2O,fg} \approx 2{,}257$ [KJ/Kg] $T_{fuel} \approx T_{ambient}$

The mass of water in the fuel is: $m_{H2O}= f_{hm}MC$, MC=12.645%,f_{hm}=5Kg m_{H2O}= 0.63kg

Therefore, $\Delta E_{H2O}= f_{hm}MC(4.186(T_b-T_a) +2{,}257)$, *Tb* – This is the local boiling point of water (94°c) $\Delta E_{H2O}=0.63(4.186(94-27) +2{,}257)=1{,}598.6$kg

This quantity of energy was divided by the energy content of the fuel to determine the equivalent mass of fuel required to remove the moisture in the fuel:

Fuel to evap water =ΔE_{H2O}/(LHV), LHV =17,380 kJ/kg

Fuel to evap water =0.092kg

The fuel energy stored in the char remaining ($\Delta E_{char,c}$) is the mass of char multiplied by the energy content of the char:

$\Delta E_{char,h}=\Delta C_h*LHV_{char}$, LHV_{char} ,= 29,500kJ/kg ΔC_c=1.1Kg

$\Delta E_{char,h}$=1.1Kg *29,500=32,450KJ

This quantity of energy was divided by the energy content of the fuel to determine the equivalent amount of unburned fuel remaining in the form of char:

Fuel in char = $\Delta E_{char,h}$/(LHV)

Fuel in char =(32,450KJ)/(17380) =1.867kg

Putting it all together we have:

F_{hd}=dry fuel- fuel to evap water- Fuel in char, dry fuel=5Kg , Fuel to evap water =0.092kg Fuel in char=1.867kg

f_{hd}=5kg-0.092kg -1.867kg =3.041kg

wcv – The mass of water vaporized was a measure of the water lost through evaporation during the test. It was calculated by subtracting the initial weight of Vessel(Dist) and water minus final weight of vessel(Dist) and water.

$W_{hv}=C_{hi}-C_{hf}$, C_{hi} =67, C_{hf} =66.25

W_{hv} =67-66.25=0.75kg

wcr – The effective mass of water boiled was the water remaining at end of the test. It was a measured of the amount of water heated to boiling. It ws calculated by simple subtraction of final weight of vessel(dist) and water minus the weight of the vessel(dist).

$W_{hr}= C_{hf}$-c, c=7kg , C_{hf} =66.25, W_{cr}=66.25-7=59.25kg

Δtc - The time to boil water of vessel(dist) was the difference between start and finish times:

$\Delta t_h = t_{hf}-t_{hi}$

Δt_h =9:57-9:40=17min

h_h – Thermal efficiency:

$h_h= (\Delta E_{H2O.heat} + \Delta E_{H2O,evap})/E_{released,h}$

The energy to heat the water was the mass of water times specific heat capacity times change in temperature:

$\Delta E_{H2O.heat} = m_{H2O}*Cp*\Delta T$, m_{H2O}=60kg , $\Delta T = 94^{o}c - 27^{o}c = 67^{o}c$

$\Delta E_{H2O.heat}$=60kg*4.186*67k

$\Delta E_{H2O.heat}$=16,827.72kJ

The energy to evaporate the water was the mass of water evaporated multiplied by the specific enthalpy of vaporization of water:

$\Delta E_{H2O,evap}$ = w_{hv}* $\Delta h_{H2O,fg}$, w_{hv}=0.75kg, $\Delta h_{H2O,fg}$= 2260kJ/kg

$\Delta E_{H2O,evap}$=0.75kg *2260kJ/kg =1,695KJ

The energy consumed was the equivalent mass of dry fuel consumed multiplied by the heating value: $E_{released,h}$= f_{hd}*LHV , f_{hd}= 3.041kg, LHV=17,380 kJ/kg

$E_{released,h}$=3.041kg*17380=52,852.58KJ

h_h=(16,827.72kJ +1,695KJ)/ 52,852.58KJ =43.46%

r_{cb} – Burning rate:r_{hb}= (f_{hd})/ Δt_c , f_{hd} =3.041kg, Δt_h=17min

r_{cb}=3.041kg /17min=0.179kg/min

SC_{hot}-Specific fuel consumption:

SC_{hot}=(f_{hd})/w_{hc} , f_{hd}=3.041kg, w_{hc}=59.25liters

SC_{hot}=3.041kg /59.25liters = 0.051kg/lit =51g/lit

FP_h–Firepower: This was the fuel energy consumed to boil the water divided by the time to boil. It was the average power output of the stove (in Watts) during the high-power test:

FP_h= (f_{hd}*LHV)/(60Δt_h)

FP_h=(3.041kg *17,380 kJ/kg)/(60*25)

FP_h =51.816KJ/s =51816 W

3.8.3. WBT Phase 3: Low Power (Simmering)

This portion of the test was designed to test the ability of the stove to shift into a low power phase following a high-power phase in order to simmer water for 45 minutes using a minimal amount of fuel.

Table 3.9:Variables that meusured

No	Data, simmer test section	Units	Quantity
1.	Pre-Weight of fuel,	Kg	4
2.	Weight of vessel (dist) with water ,start	Kg	66.25
3.	Batch Weight of fuel at once insert to stove	Kg	0.23
4.	Time, start	Min	10:00
5.	Time, finish	Min	10:45
6.	Temperature,finish	DegreeCelsius	91
7.	Weight of fuel,finish	Kg	2.98
8.	Weight of charcoal + container, finish	Kg	1.2
9.	Weight of pot with water, finish	Kg	65.79

- f_{sm}Fuel consumed, moist (grams) $f_{sm}=f_{si}-f_{sf}$, f_{si} =4kg , f_{sf}=1.02
- f_{sm} = 4kg - 1.02kg =2.98kg
- Δcs - Change in char during test (grams) $\Delta C_s=C_s-K$, ΔC_s =
- f sd -Equivalent dry fuel consumed (grams) Dry fuel= $f_{sm}(1-MC)$
- wsv -Water vaporized (grams) $w_{sv}=C_{si}-C_{sf}$
- wsr - Effective mass of water simmered (grams) $W_{sr}= C_{sf}-c$
- ts -Time to boil (min)
- Δts = ts,f – ts,i
- Hs -Thermal efficiency (%)$h_s= (\Delta E_{H2O.heat} + \Delta E_{H2O,evap})/E_{released,c}$

- r_{sb}-Burning rate(grams/min $r_{sb}= (f_{sd})/ \Delta t_c$
- $FP_s= (f_{sd}*LHV)/(60\Delta t_s)$

3.8.4. Fuel Consumption

Fuel consumption was calculated from the following equation:

$(Fuel_{CS}+ Fuel_{hS})/2+Fuel_{Simmer}=$ Fuel consumption [20]

- $Fuel_{CS}=6kg$
- $Fuel_{hS}=5kg$
- $Fuel_{Simmer}=3.25kg$

Fuel consumption = (6kg + 5kg)/2+3.25=8.75kg

3.8.5. Overall Thermal Efficiency

The overall thermal efficiency of a biomass cook stove indicates how well that stove can transfer the energy contained in the fuel to the cooking vessel [44].

It was found by:

Overall Thermal efficiency = (Thermal efficiency$_{CS}$+ Thermal efficiency$_{hS}$)/2

- Thermal efficiency$_{CS}$=47.87%
- Thermal efficiency$_{hS}$=43.46%

Overall Thermal efficiency = (47.87+ 43.46)/2=45.67%

3.9. Bio Char Production

Air dried wood chip was taken from Jimma Agricultural Engineering Research Center (JAERC), Oromia Agricultural Research Institute (OARI). The dried wood chip then pyrolyzed for 60minute during preformnce evaluation institutional bio-char rocket stove using WBT.

Figure 3.15: a) Wood chip produce Machine b) Wood chip for stove

Figure 3.16: bio-char product of stove

Table 3.10: Biochar yield with charring time (starting from boiling water)

Charing time(strating from boiling water) minute	Weight of biochar yield(kg)	biochar yield %
20	1.99	44.44
25	1.86	41.58
30	1.66	37.19
35	1.59	35.64
40	1.52	34.08
45	1.44	32.25
50	1.42	31.74
55	1.39	31.03
60	1.35	30.17

3.10. Biochar pH Testing

The biochar samples test [37] were taken following the procedure described here

- Sampling consist the amount of the same day of production
- Before sampling, the whole lot had thoroughly mixed
- subsamples was united and milled or crushed the particle size
- using a ratio of 1.0 g of biochar in 20 ml deionized water
- sub-subsamples was united and well mixed deionized water
- Calibration of pH measuring instrument
- The sub-sample was measured using digital meter of pH biochar

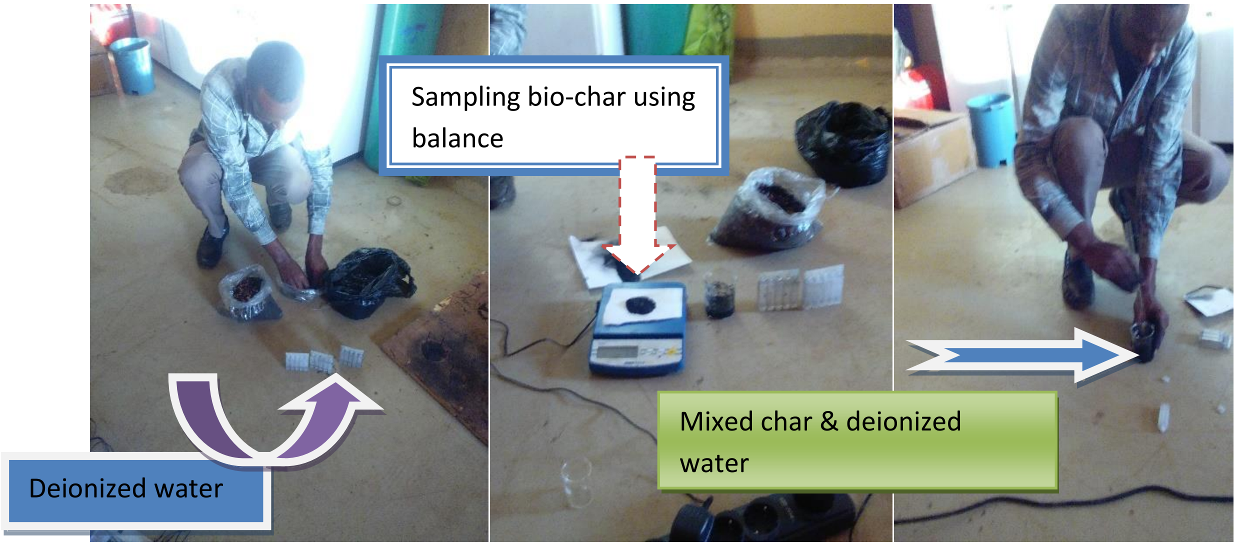


Figure 3.17: Bio-char sample and mixed deionized water

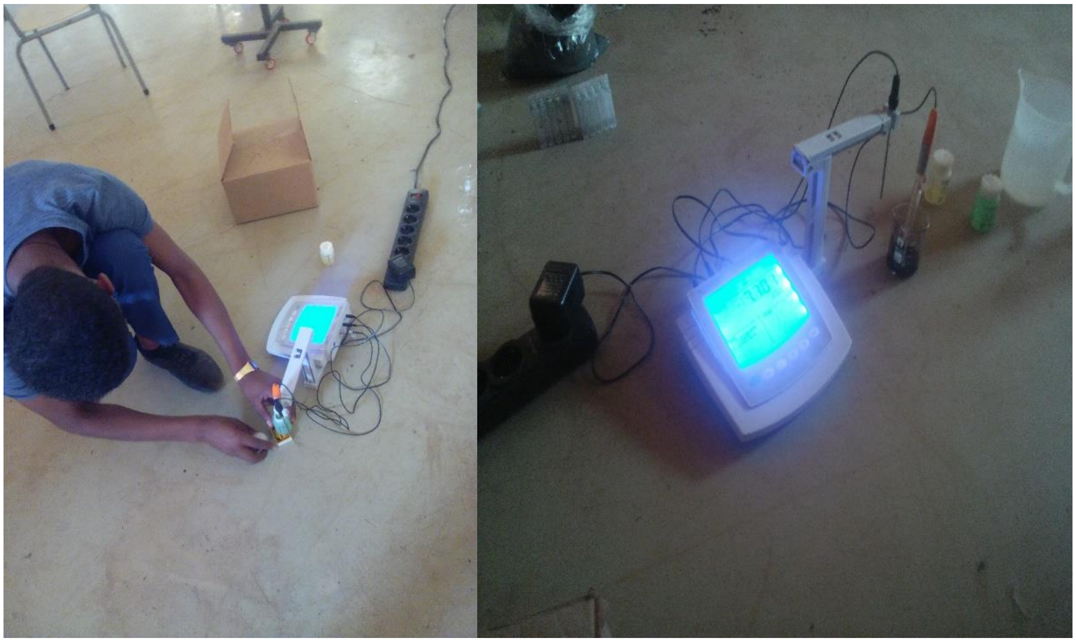


Figure 3.10: Calibration of instrument and measuring biochar sample pH

Table 3.11: pH with charring time (after boiling of water)

PH with Charringtime in minute(starting from boiling water)	pH
20	4.63
25	4.85
30	5.25
35	5.54
40	6.12
45	6.45
50	6.51
55	6.94
60	7.24

Table 3.12: pH of bio-char sample of stove at boiling water

Name of can	Weight of bio-char in gram	Volume of deionezed of water(ml)	pH value
1	1	20	4.80
2	1	20	4.23
3	1	20	4.57
4	1	20	4.93
5	1	20	4.64
Average			4.634

Table 3.13: pH of bio-char sample for 60 minute

No.	Weight of bio-char in gram	Volume of deionezed of water(ml)	pH value
1	1	20	7.091
2	1	20	7.154
3	1	20	7.058
4	1	20	7.327
5	1	20	7.543
Average			7.235

Chapter 4

4. Results and Discussion

4.1. Comparison of Experimental and Simulation Result

CFD-model has been taken from process simulation results that balanced the data gained from the condition of experiments. The convective part was solved together with the solution of the flow field. The diffusive mass transfer contains laminar diffusion (using Diffusion coefficients and Fick´s laws) and turbulent diffusion that was calculated using turbulence parameters generated by turbulence modeling.

The design of the biochar rocket stove with the cooking vessel considering of the vessel gap for the simulation was cut into half (half section) to reduce the time of convergence for the selected mesh size and to observe the temperature increase due to heat transfer within the woodchip packed bed and to the cooking vessel. Figure below shows the temperature gradient in the woodchip packed bed of the symmetrical view. The heat transferred from the inner surface which was around the maximum 600^{o}c to the outer surface which was around the minimum 30^{o}c.

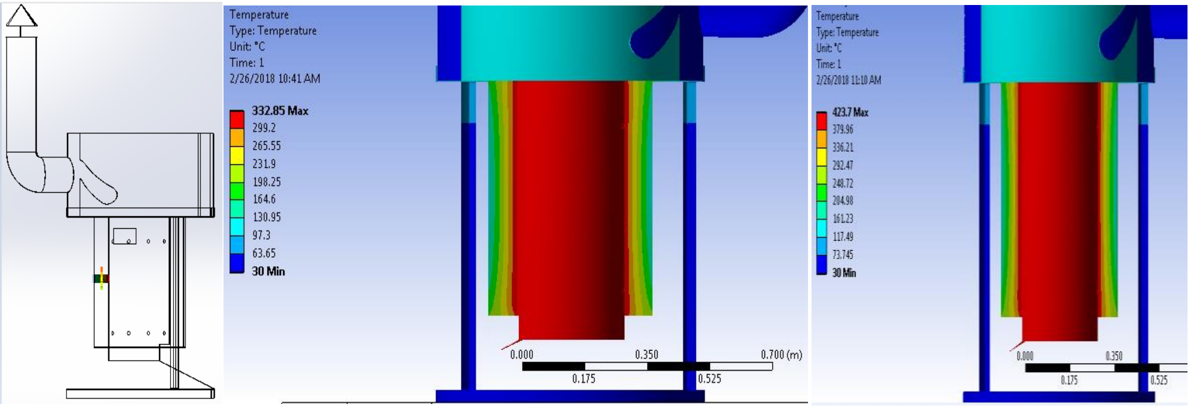


Figure 4.1: Temperature distribution within biomass bed at 15 minute and 30 minute

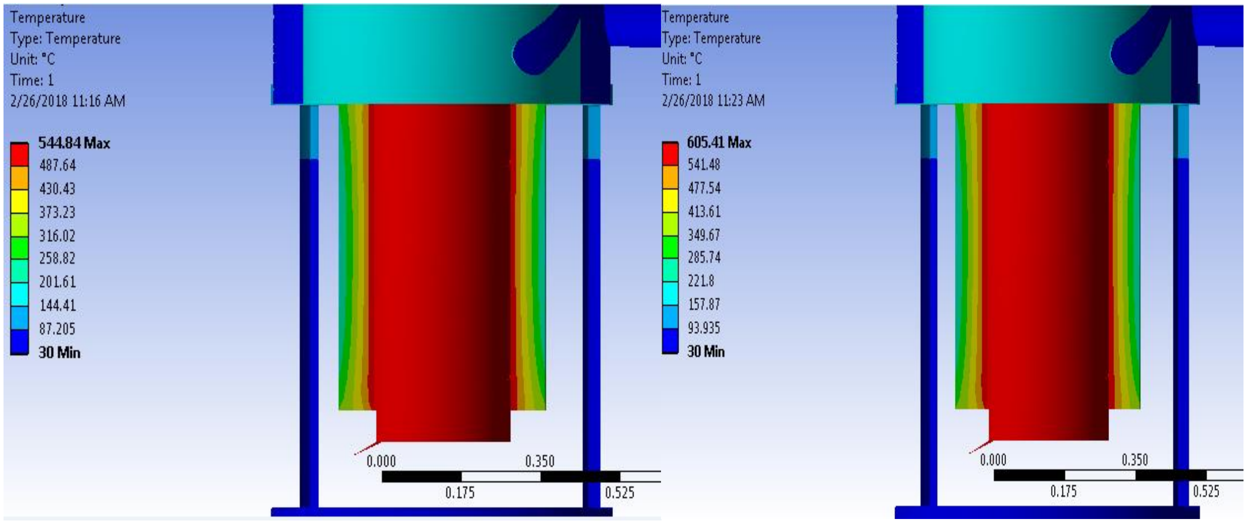


Figure 4.2: Temperature distribution within biomass bed at 45minute and 60 minute

Syngas was started to come out from the pyrolysis chamber through the exhaust outlet start at 8 minutes of pyrolysis. Pressurized gasses come out at this time; it was started burn in combustion chamber. It was because, the wood-chip was not completely dried and the gases have water vapor condense in pyrolysis chamber. After 60 minutes the pressurized combustible gasses (Syngas) was started to stop and gives low combustion.

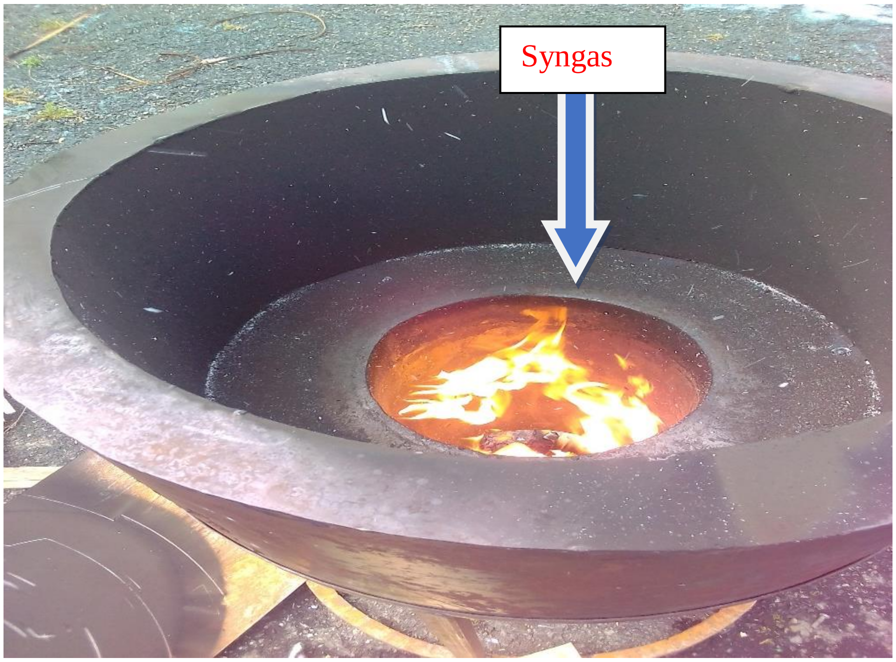


Figure 4.3: Syngas flow from Pyrolysis chamber

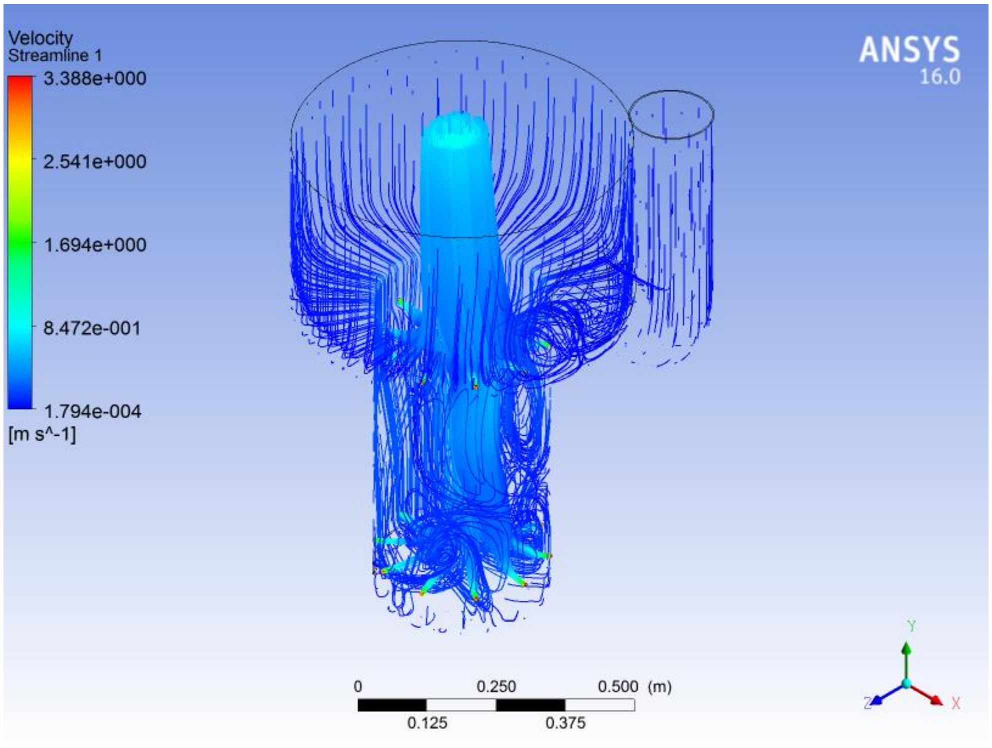


Figure 4.4: Velocity streamline

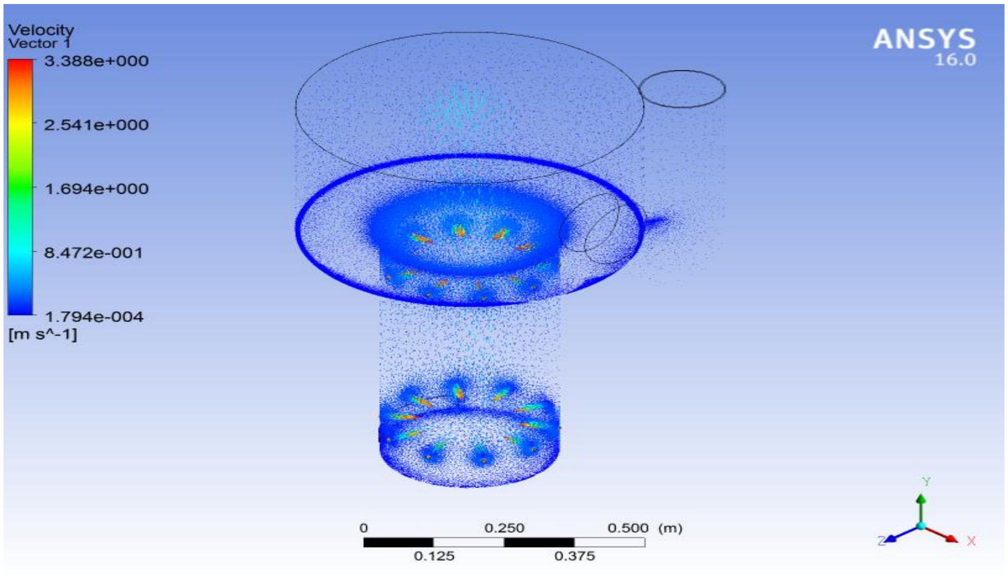


Figure 4.5: Velocity vector

Table 4.1: Comparison of simulated temperature result (K) Vs Experiment

Location	Simulation	Experiment
Vessel bottom	873	851
Chimney exit	458	436

Maximum temperature reached when fuel was burning at a steady rate and there were also heat losses difference to the surrounding when using woodchip and without woodchip in pyrolysis chamber of the stove as shown figure4.8 and 4.9. Usually adiabatic temperatures are not obtained in practice due to heat losses (heat lost in flue gases, heat lost in evaporation of moisture, radiation losses from the surface of combustor, heat lost in excessive air) or due to incomplete combustion resulting from inadequate air supply[45].

Figure below shows temperature distribution with range of time main part of stovefrom appendix table A.5.

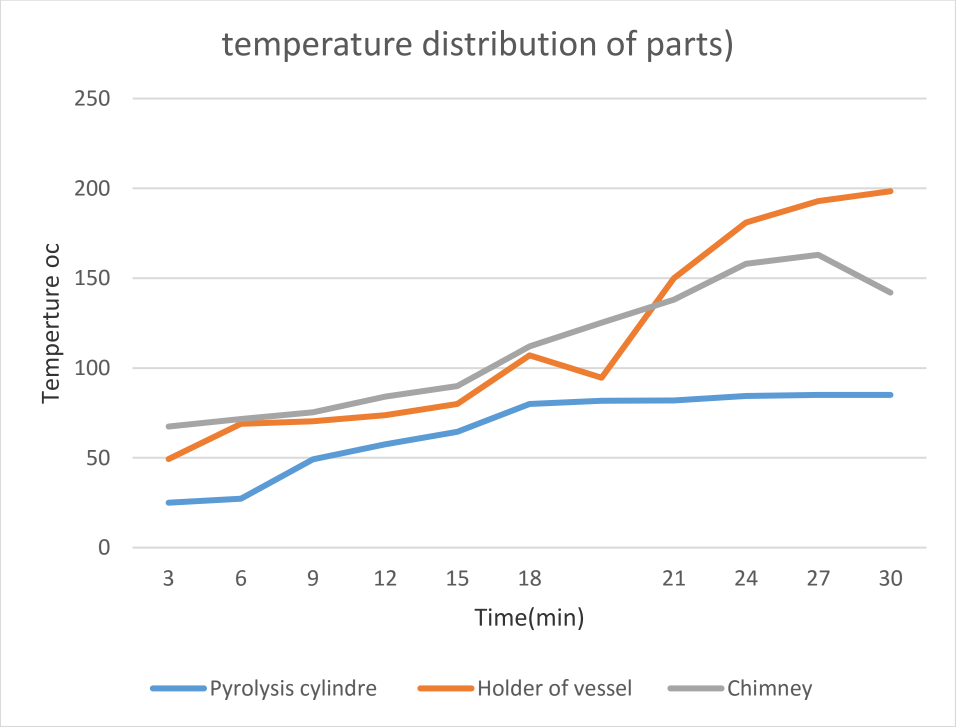


Figure 4.6: Temperature distribution on surface of main parts with woodchip

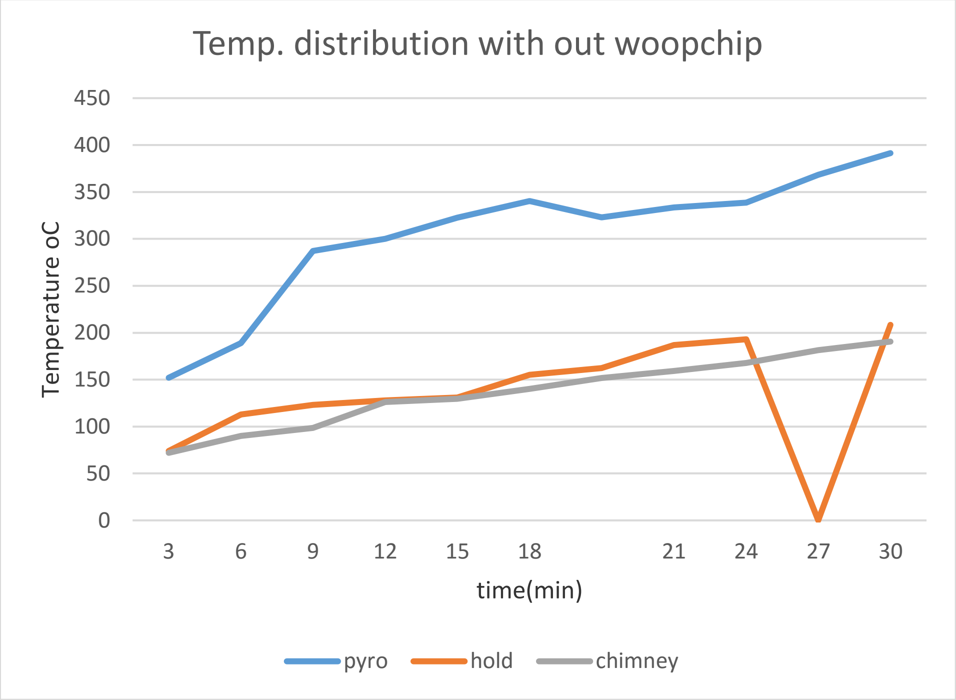


Figure 4.7: Temperature distribution on surface of main parts without woodchip

4.2. WBT Perform

In this section would be explained how the WBT procedure was applied to a real field experiments. And this experiment was done in outdoors. In order to simulate with more accuracy the field conditions, where was supposed to be used. This means that all the boundary condition were uncontrolled. The thermal efficiencies and measured during the experiments, as well as the results of the energy balance calculations, are presented below table. The test result shows the Fuel consumption8.75kg, and water boiling tests were done.

Table 4.2: Summary test of stove Using WBT

Parameters test	Unit	High Power Test (Cold Start)	High Power Test (Hot Start)	low power (simmering)
		Average	Average	Average
Time to boil	Min	20	17	45
Fuel consumed (moist)	Kg	6	5	3.25
Mass of water vaporized	kg	0.486	0.75	1
Effective mass of water boiled	kg	59.514	59.25	59
Equivalent dry fuel consumed	Kg	4.0192	3.041	2.98
Burning rate	g/min	200.96	179	166.22
Thermal efficiency	%	47.87	43.46	32.27
Specific fuel consumption	g/lit	67.5	51	49.67
Firepower	Watts	38,807.6	*51,816*	19,182.37
Turn-down ratio	-	-	-	1.71

4.3. Bio-Char Yield

Previous studies have shown that the temperature of pyrolysis plays an important role on the yields of the char products. Char is created mostly from the thermal decomposition of lignin and some extractive part of biomass, while the volatile matter is transformed into the gas phase and minerals in the biomass are left as ashes. Hence, at the same heating rate and the residence time, the pyrolysis temperature is the most influential factor for the product distribution [24]. It is reported [27] that biochar yield produced from biomass decreased with increase in pyrolysis temperature and the minimum yield was observed at 445°C syngas flow stop.

The decrease in the solid yield with the increasing temperature, and charring time (Figure 4:25)could be due to greater primary decomposition of the sample at higher temperature [26].The bio char 1.35kg (30.12%) produced from stove was found to be suitable as soil amendment. There is a possibility that an intermediate reaction occurred during the pyrolysis process, which converted biomass into large amount of others product (liquid and gases) rather than totally transformed into solid (char) product. Yields of liquid products are maximized in conditions of low temperature, high heating rate and a short gas residence time, whereas a high temperature, low heating rate and long gas residence time would maximize yields of fuel gas [25].

A biochar containing more ash is generally less energy-efficient. There is kinetic reaction occurred during the pyrolysis process which converted the raw woodchip into large amount of others product (particularly combustible gases) rather than totally transformed into solid char [39].

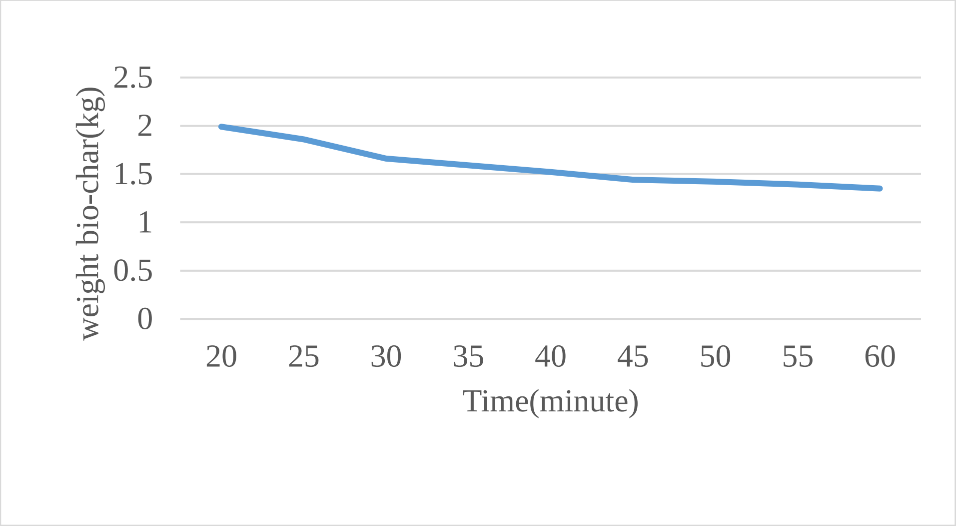


Figure 4.8: Bio-char yield of stove

4.3. Biochar pH

Biochar pH is an indication of the extent, to which the biochar will alter the soil pH, depending on the quantities added. If the pH of the biochar is lower than that of the soil, it will be most likely lower the soil pH, in relation to the quantities applied [31]. In Figure 4.11, it was observed that the pH of the biochar increases with charring time [29]. Heating with high temperature gave pH more alkaline than that of the low temperature heating case [32]. The relative increase of ash content in the biochar at more pyrolysis conditions (higher heating temperature and time) was another contributing factor to the rise in pH [28].The bio-char should be prepared based on the requirement of the pH of the bio- char. pH bio-char has been the effects increasing or lowering the soil pH. As the calibration of pH of the bio char shows in figure below, the pH increases with increasing pyrolysis temperature and time. Hence it is important to apply bio-char in to the soil considering it's' pH [38]. However the char found from the process is not produced in a controlled temperature condition and it is difficult to maintain the required pH of the biochar, [19]. As shown in figure below result tests were done on the stove to assess the char pH with increasing time. After the water boiling test was completed,the biocharhad 4.634 pH value.

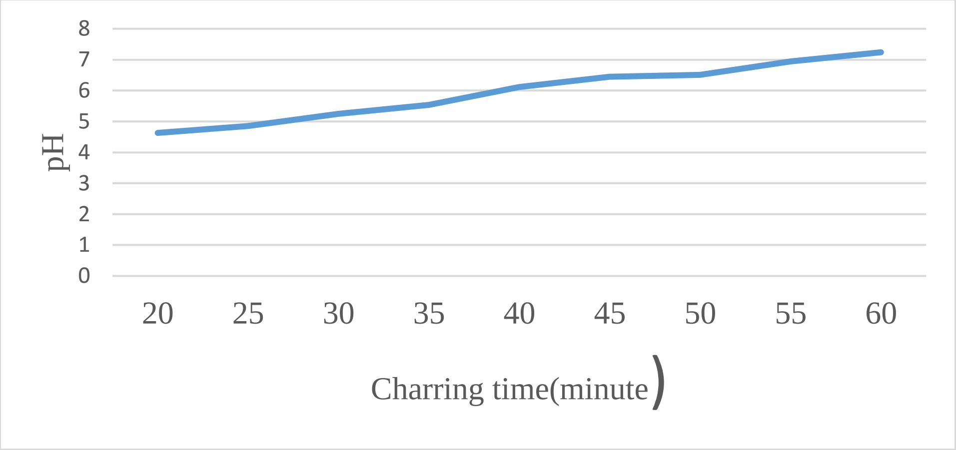


Figure 4.9: Bio-char PH with extending charring time

The char was tested and found to be rich in carbon with a pH of 7.235 when syngas burn upto 60minutes. The results conclude that the biochar produced was good quality used for an acidity soil when used all syngas**.**

Chapter 5

5. Conclusion and Recommendation

5.1. Conclusion

Basic principles in the design of bio char rocket stove of both direct combustion type and indirect type have been identified and a design methodology has been developed from the hybrid principles. The stove designed as per these procedures are found to work well. Several considerations have been taken from the more detailed study of the technology used for biomass burning, and characteristics of cooking stove.

The bio-char rocket stove has gas exhausting hole which takes the combustible gasses (produced during the pyrolysis reaction of the woodchips) directly to the combustion chamber. Taking these combustible syngas to the combustion chamber increases the rate of pyrolysis of wood chips by additional energy. It was seen as the installation of a chimney is of main importance. First to bring outdoor the combustion smoke and soot and as second aspect ensure a better draw.

The test goal was able to know increased overall thermal efficiency, time to boiling and cooking, co- product as well as biomass fuel was used by stove. The test most commonly used, was the Water Boiling Test. Syngas was started to come out from the pyrolysis chamber through the exhaust outlet after 8 minutes of pyrolysis wood chip. Pressurized the gasses come out at this time, it start burn in combustion chamber. After 60 minutes the pressurized combustible gasses starts to stop Syngas and gives low combustion.

The bio char produced 1.35kg (30.12%) from stove was found to be suitable as soil amendment. The bio char rocket stove was found to char the biomass at a higher temperature and the biochar produced has a higher pH, making it more suitable for acidity soils. The stove boiled 60 litres of water in 20 minutes . The char was tested and found to be rich in carbon with a pH of 7.235 when syngas burn upto 60minutes.The results of experiment show that was increased thermal efficiency of stove and the biochar produced was good quality for an acidity soil when used all syngas follow out during processes.

5.2. Recommendation

The methods that easily to control syngas of Pyrolysis chamber with material that available locally and easily manageable to society. Inner insulation of vessel holder chamber can be made by casting from locally available materials clay or ceramic in order to insure less weight and retention of heat during simmering. Energy efficiency validation and comparative evaluation of bio-char yield of the stove using different biomass pyrolysizing. Stove testing for understanding, comparing, and improving design through measures of thermal performance characteristics in terms of stove design characteristics with others institutional stove. Additional research is needed to include issues of Stove protocol testing cooking control test and kitchen performance test of the stove. The influence of particulate matter (PM) on the air quality, ecosystems, human health, and climate changes, it is necessary to be aware of its chemical composition and size distribution of the stove. The final prototype institutional bio-char rocket stove is ready for adaptation.

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Appendix

A.1. Data Collection Form

Thesis Research:- Product development using CFD Simulation and performance evaluation of energy efficient Institutional bio-char rocket stove

1. Researcher name:- Getachew Hailu
2. Advisor:- A.Venkata Ramayya (Prof)
3. Co-advisor:- Debela Genet
4. Name of Stove:- Institutional bio-char rocket stove
5. Site: Jima Town

Measured Parameters

6. Size of
   a. stove:--
   b. vessel (Dist)--
   c. Combustion chamber:--------------------------
   d. Pyrolysis chamber-------------------------
   e. Cylinder that support vessel (Dist)--------------------
   f. Cylinder that support vessel outer-------------------

7. Weight of Stove: ----------------------------

8. Weight vessel (Dist) --------------------------------

9. Way of feeding:

A -------------------------------

B-----------------------------

Calculate Parameters

10. Fuel weight uses (consumption)

A. For combustion: -------------------------

B. For bio-char: ---------------------

11. Moisture Content

A. Wood----------------------------

B. Wood Chips---------------------------

12. Burning rate ---
13. Ambient Temperature (environment) -------------------------

14. Fuel consumed, moist : ------------------------

15.Change in char during test :---------------------

16.Equivalent dry fuel consumed

17.Water vaporized :----------------

18.Effective mass of water:-----------------

19.Time to boil (min) :----------------------

20.Thermal efficiency (%):--------------------

21.Burning rate:------------------------

22. Specific fuel consumption: ------------------

23. Turn down ratio: --------------------------

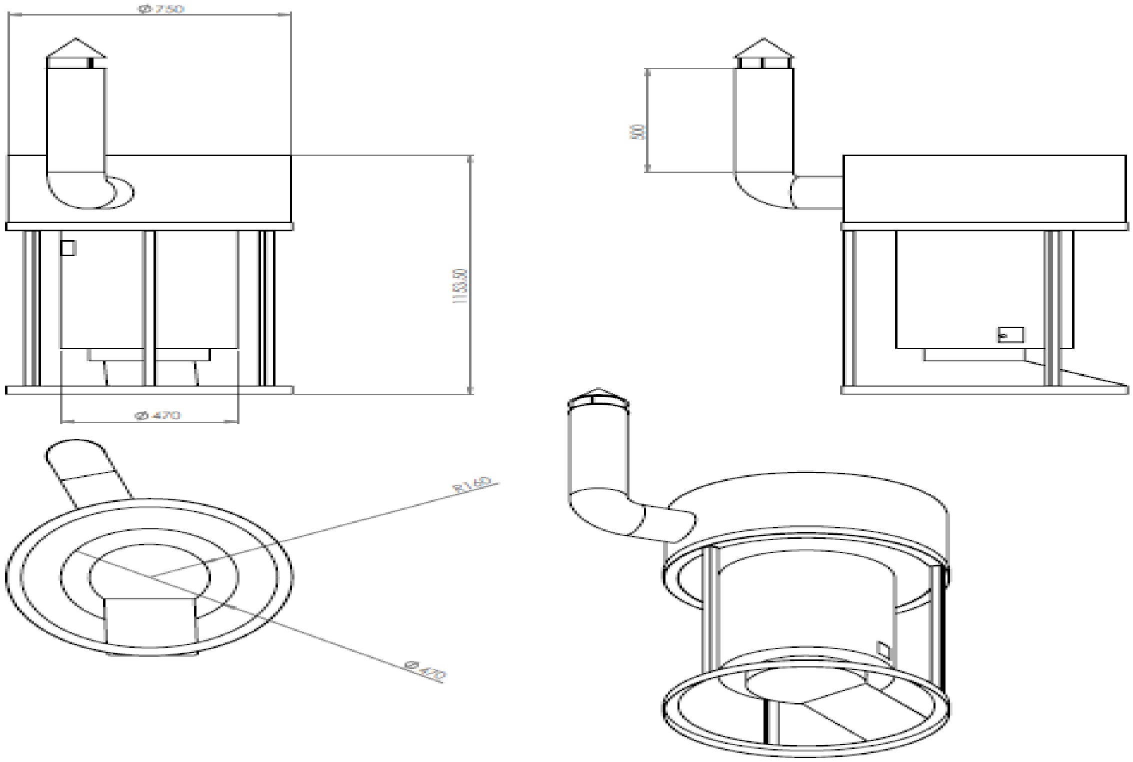

Figure A.1: Stove of 60liter vessel (dimension in mm)

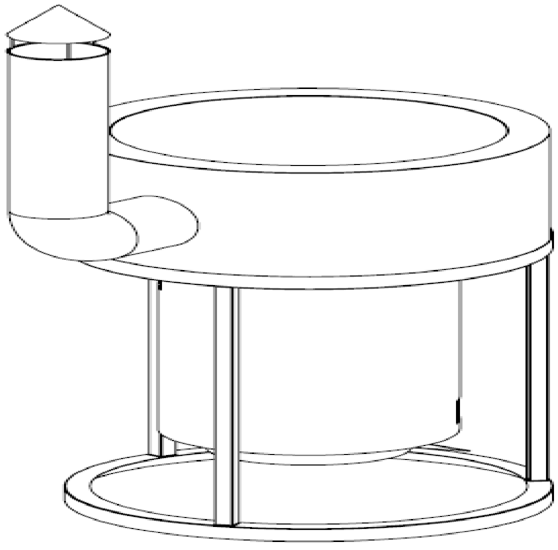

Figure A.2: 3D of stove

A.2. Tables Of Data Collected and Cost of stove

Table A.1:Temperature Variation with interval of time WBT phase one

No.	Time (minute)	Temperature (^oC)
1.	00	22
2.	3	28
3.	6	40
4.	9	52
5.	12	73
6.	15	85
7.	21	94

Table A.2:Temperature Variation with interval of time WBT phase two

No	Time (minute)	Temperature(^oC)
1.	00	27
2.	3	40
3.	6	56
4.	9	66
5.	12	79
6.	15	88
7.	18	94
8.	21	94
9.	24	94

Table A.3:Temperature Variation pyrolysis (ambient Temperature T=27^{o}C)

Time(minute)	Mv	Temperature(^{o}C)	Temperature+ ambient Temperature
05	18.2410	264.41	291.411
10	20.1642	278.493	305.493
15	20.420	293.264	320.264
20	21.275	302.165	329.165
25	22.495	318.632	345.632
30	22.563	320.837	347.837
35	24.016	338.016	365.016
40	27.919	390.919	417.919
45	29.128	403.537	430.537
50	29.795	411.323	438.323
55	30.515	418.347	445.347
60	30.002	413.461	440.461
65	29.362	406.427	433.427

Table A.4: Temperature distribution with range of time on main part of stove

No	Time (minute)	Temperature of stove with woodchips			Temperature with-out woodchips in pyrolysis chamber		
		Pyrolysis surface	Holder of vessel surface	Chimney surface	Pyrolysis surface	Holder of vessel surface	Chimney surface
1.	3	25	49.3	67.4	152	74	72
2.	6	27.2	69	71.5	189	113	89.9
3.	9	49.2	70.4	75.3	287	123	98.7
4.	12	57.5	73.8	84	300.2	128	126.3
5.	15	64.5	80	90	322.7	130.8	129.6
6.	18	80	107	112	340.3	155.2	140
7.		81.7	94.6	125.2	322.8	162.3	151.7
8.	21	82	150	138	333.7	186.9	159.4
9.	24	84.4	181	158	338.5	193	167.7
10.	27	85	193	163	368.46	198,8	181.3
11.	30	85	198.4	142	391.4	208.4	190.54

Table A.5: Raw Materials Cost

No	Items description	Unit	Quantity	Unit Price	Total price
1	Sheet metal 1.5*1000*2000mm	Meter	3	897.49	2,692.47
2	Round bar Ø10mm	Meter	1	127.39	127.39
3	Angle iron 4 *40*6000mm	Meter	1	427.31	427.31
4	Electrode Ø2.5*300mm	pck	1	175.00	175.00
5	Antirust	No	1	252.00	252.00
Sub total					2,776.68

Table A.6: Prototype Production Cost

No.	Type of machine	Machine cost/ hr	Working hour	Cost (ETB)	Labor cost/hr	Working hour	Cost (ETB)
1	Universal metal cutting	10.00	3	30	22.1	3	66.1
2	Welding machine	5.10	24	122.4	22.1	24	530.4
4	Power hack saw	3.67	1	3.67	22.1	1	22.1
5	Rolling machine manual	2.87	4	11.48	22.1	4	88.4
6	Radial drill machine	2.57	1	2.57	22.1	1	22.1
7	Grinding machine	0.74	6	4.44	22,1	6	132.6
8	Bending machine	2.87	3	8.61	22.1	3	66.3
Sub total				183.17			928

N.B. The labor cost is depends on the salary per month of the machinist

Table A.7: Cost Summary of stove

No.	Variable	Cost (ETB)
1	Raw material	2,776.68
2	Materials Wastage = 2.5% of 1	121.64
3	Production (machine + labor)	1,111.17
4	Overhead = 5% of 3	44.72
5	Profit = 10 % of (1+2+3+4)	592.63
6	Sell tax =15% of (1+2+3+4+5)	977.84
7	Selling price = (1+2+3+4+5+6)	6,818.485