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JIMMA INSTITUTE OF TECHNOLOGY

SCHOOL OF MECHANICAL ENGINEERING

POST GRADUATE PROGRAM IN SUSTAINABLE ENERGY ENGINEERING

CFD Simulation Analysis, Scale up and Field Testing of 200 Liters Biomass Fired Institutional Cook Stove.

A Thesis Submitted to the School of Graduate Studies of Jimma University In Partial Fulfillment for Award of Degree of Masters of Science In Sustainable Energy Engineering.

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ABSTRACT

In this work, complete analysis of 200 liter institutional cook stove, design, simulation and field test was carried out. In developing country including Ethiopia biomass is the major energy source especially, for cooking and heating purpose from single family to institutional level. The students' cafeteria kitchen of Jimma University, Ethiopia are using biomass fired traditional three stone and enclosed chimney stoves. To solve the smoky operation problem Jimma University carried out a pilot study with InStove make institutional stove (four with 100 liter size and two 60 liter size). To implement more of these stoves what problem is that students' cafeteria kitchen are using 200 liter size for cooking and boiling tea since large number of students are getting serviced. In this back drop, this project will focus on 200 liter size of institutional cook stove that incorporates secondary air for complete combustion and ease ash removal. Materials were selected for each component of the stove according to their temperature resistance required. Dimensions were derived for each of the components by equating the ratio of volume increment from existing 60 liter to 100 liter, and from 100 liter to 200 liter through scale up. The stove performance test was done using water boiling test protocol for the new stove and parametric calculations were done using WBT (Water Boiling Test) version 4.2.2. Comparative assessment of the result obtained for the stove with and without inner refractory insulation has been done. The inner combustion chamber insulation used was construction sand that is not the right material for insulation purpose. From the result, the one without inner insulation were selected since it recorded a high thermal efficiency of 53.4%.

Validation of CFD (Computational fluid dynamics) simulation was done by comparing with experiment results. Different cases were investigated for different percent of primary and secondary air combination for specific air fuel ratio. The simulation was based on wood-volatile-air as the fuel. Based on simulation result 60:40 primary vs secondary air supply was found to be best option compared to 75 : 25 and 50 : 50. The stove require a SFC of 41.25 gram per liter and average cooking time of 129.5 minute for 200 liters.

Further work is recommended, which explore the possibility of making cast for inner chamber as well as preparing the InStove for other function, like, i.e. cake and enjera baking and working on optimization of the same model.

Key words: primary air, secondary air, CFD simulation, validation, 200 liter institutional cook stove

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LIST OF ACRONOMY

IEA –International Energy Agency

FAO— Food and Agriculture Organization

BEST – Biomass Energy Services and Technology

InStove—Institutional Stove

FGD—Focal Group Discussion

CFD—Computational Fluid Dynamics

WBT--- Water Boiling Test

ISO -- International Organization for Standardization

VITA--- Volunteers In Technical Assistance

EnDev--- Energizing Development

GIZ--- Deutsche Gesellschaft für Technische Zusammenarbeit

ECO--- Energy Coordination Office

ICS--- Improved Cook Stove

IRS--- Institutional Rocket Stove

VF--- View Factors

RDF--- Refuse Derived Fuel

HV--- Heating Value

LHV---Low Heating Value

GHV--- Gross Heating Value

RH---Relative Humidity

3D--- 3 Dimensions

LIST OF FIGURE

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CHAPTER ONE

INTRODUCTION

1.1 Biomass Energy

Globally, biomass accounts for ten percent of energy production, two-thirds of which is used for cooking and heating purposes in developing countries (IEA 2013). Despite increasing access to electricity and modern fuels, consumption of solid biomass fuels continues to increase (FAO 2013). While the combustion of these fuels is generally viewed as a renewable, carbon-neutral energy source, such fuels are generally not harvested or used in a sustainable way. Unsustainable, and often illegal, harvesting of forest resources has resulted in widespread environmental degradation, decreasing fuel availability, and increasing wood fuel costs.

Approximately half of the energy content in the original wood feedstock is lost during traditional charcoal production due to low conversion efficiency and loss of energy in volatile and gaseous emissions. Therefore, the impact of charcoal production on deforestation and environmental degradation is greater than that from wood fuel harvesting.

1.2 The Motivation behind This Work

So many researcher or stove designers were highly working on improvement of biomass cooking stove in recent decades. But, the majority of improved cooking stoves, that built today, are for domestic cooking, often used by single families or households. However, there are also schools, colleges, hospitals, prisons, factories and, perhaps, large temporary settlements such as refugee camps or sites of religious festivals where a large number of people may need feeding at any one time. In a sense, stoves that serve large group of people are known as institutional stoves. It is distinguished from domestic stove mainly by its larger size and more sturdy construction.

Wood is the most commonly used fuel in a number of stoves; 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. So using wood as fuel is not only alternative of energy source but also the obligation of kitchen staff, especially in low and middle income countries.

In addition to deforestation and erosion is a major environmental problem in a country, wood fuel supplies became relatively more distant from the markets, prices increased, and some stove makers began more intensive efforts to improve their models and make them more efficient.

With regard to the stoves themselves, Biomass Energy Services and Technology (BEST), considered the following criteria to be important:

- the kitchen should be free from smoke
- the pot, even with a capacity of 200 liter, should be easy to stir and remove
- the cost of the stove and its installation should be affordable

Improving stoves is an effective way of improving the environment and serving communities. The idea of this project was drawn from visit of the students’ cafeteria kitchen at Jimma University (Kito Furdisa Campus), Ethiopia. During these observations, i came up with following research questions.

Q1. What is the consequence of using traditional open fire three stone cook stove?

Q2. Does the smoke in the kitchen harmful, drudgery and cause death to women and children?

Q3. How can I introduce InStove to Jimma University students’ cafeteria kitchen with modification, low cost, and more efficient, from local market available materials?

Market assessment was done by different staffs in and around Jimma (Wollega, Ilu Aba Bore, Assosa, and Ambo University). More than 85% have willingness to switch their power to this institutional stove as concluded from the questioner they fill, if there is availability of the stove locally (Refer table 1.1).

There was also focal discussion group, FGD with the actual users in Kito Furdisa Campus students cafeteria kitchen, Jimma University on the institutional stove brought from America in 2014 with the capacity of 60 and 100 liter, whereas the majority of higher institutions are using the vessel size of 200 liters capacity. Even if the stove is among the best designed stove(“greenhouse friendly”), some drawback was observed during FGD, like the difficulty of ash removing technique, fire regulation during simmering (fire off mechanism).

Since the university feeds large number of students, more than 10,000 a number of cook stove are required for one meal. Due to these fact, design, analyzing, and constructing the stove was feasible.

Table1.1 Market Assessment for Institutional Stoves in and around Jimma

Name of the Institution	Contact Number In Ethiopia	No. of peope Served per day	vessel size used at present (liter)	Firewood consumption at present m^3/month (wood log)	Other energy sources being used at present	Willingness to switch over to more efficient stoves	Capacity of stove needed (liter)
Jimma University, Jimma -Kito Furdisa *Campus*		8500	200	200 Each m^3 costs 160 Birr	-	yes	200
Main Campus- *Zegeye Cafe*		4000	200	140 Each m^3 costs 160 Birr	50% electric power	No	200
Main Campus- *Obama Cafe*		3200	100 & 200	110 Each m^3 costs 160 Birr	50% electric power	No	200
Main campus Sheraton Cafe		2300	100 & 200	100 Each m^3 costs 160 Birr	50% electric power	yes	200
Agriculture Campus		-	-	-	-	-	-
Wollega University, Nekempte		10,000	100 & 200	$24m^3$ / day	Electric & cylinder gas	Yes	250- 300
Mettu University,		4,080	60	84	-	yes	60/100

Mettu				Each m3 costs 380 Birr			
Mizan Thepi University Mizan Thepi.		2,613	200	10 tracks/month	-	yes	200
Mizan college of agriculture. Mizan		1100	150	60-80 m^3 per month	-	yes	150
Wolkite Un iversity, Wolkite		7500	150 & 200	250 Each m3 costs 160 Birr	-	Yes	200
New generation university college Nekemte		120	60	Charcoal	Electric power	no	60
Jimma Prisoner camp		1900	200	200m^3 per month	-	no	200
Nekemte Prisoner camp		1850	100	38 tracks (45600 Birr)	-	yes	100
Missionaries of charity		500	90	16.67 m^3	-	yes	150
Jimma University Specialized Hospital		600- 700	100	-	Cylinder gas (267,600 to 401,400) birr	no	100
Central Hotel		300-500	100	50m^3 and above		yes	150-200
Mars Food Factory			8000 enjera	90 m^3	-	yes	200

Note: among the interviewed institutions

1.2.1 User Needs and Perceptions

Two important social factors regarding the institutional cook stove design are the user's needs and the local resources. A stove designer must take into consideration various needs of the target group, such as: cooking tasks, cooking utensils, size of cooking operation, and some specific operational parameters.

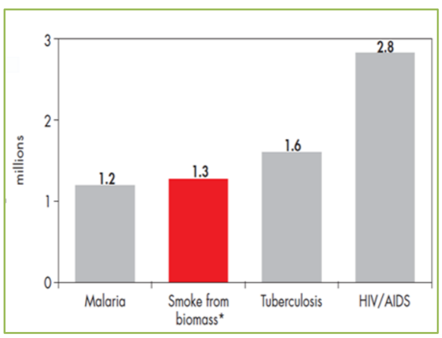
Another important consideration in the design of InStove is the appraisal of locally available resources, especially types of fuel available, construction material, infrastructure and skills for the InStove production and distribution system.

1.3 Problem Statement

As stated under the introduction part (section 1) unsustainable way of using fuel wood has an impact on economy, social, environmental and health of women and children. The traditional cook stove is "survival of the fittest" which is not sustainable for the future generation. It is noted by different researchers that open fire three stone cooking was lasted for 100,000 years ago; still in most countries, biomass is the main source of fuel for many people. No matter it can be, but what i insight, energy is a source always under concern, as scarce, diminishing, costly, time-consuming, uncertain in supply and often inaccessible.

In today's world, in which climate change is drastic using one of clean cooking practice is obligatory. 1) by the use of an electric cook stove, 2) by the use of a cook stove based on clean fuels (biogas, methane, ethanol, solar), and 3) by the use of a cook stove designed to burn biomass inputs (wood, charcoal, other biomass) more efficiently through cleaner combustion, that was under study in this project.

The indoor air pollution associated with biomass use is directly responsible for more deaths than *malaria*, almost as many as *tuberculosis* and almost *half as many as HIV/AIDS*



Source: *WHO Statistical information system (www.who.int/whosis)*

Figure 1.1 comparing indoor air pollution with other disease

1.4 Objective of the Project

The objective of this project can be categorized as main and specific as usual. The main objective indicates the overall aim of the project while the specific objective deals with the action taken over the implementation and analysis of the project.

1.4.1 Main Objective:

The main objective of this project is to design, CFD simulation analysis, scaling up to 200 liters and field testing of biomass fired institutional cook stove.

1.4.2 Specific Objective:

- To scale up the existing size to 200liter
- To work on modification to increase thermal and fuel consumption efficiency
- To perform experiment of WBT with new stove
- To compare the experimental result of new design with CFD simulation result for further modification.

1.5 Scope of the Present Work

In this thesis the design optimization, modification and testing of institutional cook stove was done. The study would try to throw some insights into the existing kitchen working environment and the new cook stoves. The actual performance of scaled up cook stove, efficiency and fuel saving capacity was analyzed and tested. The effect and configuration parameters of cook stove was simulated and optimized. The sequence of this work is described as follows:

Activity one: The dimensions of all components of existing institutional cook stoves (100 liters and 60 liters) were measured. The relationship between each component was determined.

***Activity two*:** Based on the components relationship obtained in activity one, the necessary dimensions were calculated for 200 liters stove.

Activity three: CFD simulation analysis was carried out with 200 liters stove.

***Activity four*:** Fabrication and testing of 200 liters institutional cook stove was conducted.

1.6 Methodology

In order to simplify the overall progress of the project starting from proposal writing to completion of the thesis, some methodology was proposed and implemented.

1.6.1 Study Area

Jimma University is one of the higher institutions in Ethiopia which give services more than 20,000 students. Before this research project started on the title "*CFD Simulation Analysis, Scale up and Field Testing of 200 Liters Biomass Fired Institutional Cook Stove*." another research project was done on the same area by different researchers, interviews were conducted with kitchen worker who has long experience in cooking on traditional cook stove and a few months on the institutional cook stove at Jimma University, Technology Institute.

1.6.2 Study Period

This project was conducted for a last eleven months, from May, 2015 to March, 2016.

1.6.3 Method of Fabrication

- Material was selected for each component of the stove according to their temperature resistance required.
- Dimensions was specified for all components
- Parts/components were fabricated separately
- Assembling
- Painting or other esthetic was completed.

1.6.4 Study Variable and Data Collection Methods

The main variables under these studies were:

- Temperature
- Pressure.
- Moisture content of the firewood
- Boiling point of water
- Thermal efficiency, specific fuel consumption and burning rate

1.6.5 Data Processing and Analysis

- Fuel woods were split, dried and its weight was measured before firing.
- Using different temperature measuring device (thermometer, digital thermometer) boiling of water was measured.
- Recording the starting time and the stopping time of cooking per pot, efficiency was calculated including the fuel used.

- Sample fuel wood were measured (say 1kg) and put in furnace for three hour at a fixed temperature,100℃ then measure again, the difference of that was the moisture content of the fuel wood.
- Mathematical and numerical modeling was carried out.

1.6.6 Instrument Used

During experiment testing of WBT a number of instruments were used.

- ✓ 200 Liter vessel
- ✓ Thermocouple,
- ✓ thermometer,
- ✓ Multimeter,
- ✓ digital thermo and hygrometer,
- ✓ digital weight measuring device and stop watch
- ✓ drying Furnas

1.7 Uses of Institutional Stove

Institutional stoves may be used for one or more of the following purposes, and should be designed accordingly:

- cooking or boiling
- heating water for tea, washing
- as an oven for roasting or for baking bread or cakes

An average institutional stove would supply food and hot water to up to 300 people daily, which might require 50 to 200 m^3 of wood per month, and this might represent about 15% of the total budget of running the institution. It should also be noted that much of the wood used to fire often comes from trees which is far apart from the institution. Due to these reason, efficient use of stoves should be studied carefully. In practical terms stove efficiency can be improved by:

- proper insulation
- careful design and Preparing smoke free kitchen
- Use of pre-dried wood, suitable size and feed rate of fuel (fuel pieces which are too large being particularly inefficient because they burn unevenly and may jam the door open).

CHAPTER TWO

LITRATURE REVIEW

2.1 Back Ground of Biomass Energy

Millions of families around the world use biomass cook stoves. Widespread use, combined with increasing populations, has created growing health and environmental concerns in many nations (Douglas F. 1994). In developing countries, especially in rural areas, 2.5 billion people rely on biomass, such as fuel wood, charcoal, agricultural waste and animal dung, to meet their energy needs for cooking. In many countries, these resources account for over 90% of household energy consumption.

In the absence of new policies, the number of people relying on biomass will increase to over 2.6 billion by 2015 and to 2.7 billion by 2030 because of population growth. That is, one-third of the world's population will still be relying on these fuels. There is evidence that, in areas where local prices have adjusted to recent high international energy prices, the shift to cleaner, more efficient use of energy for cooking has actually slowed and even reversed.

Bio-energy still occupies a place of choice in the energy consumption chain of developing countries. Consequently the demand for wood-based energy is very high in such countries for activities like heating and cooking (Oakham, n.d.).

2.2 Benefit of Biomass Energy

Biomass resource play major role in the overall energy sector of Ethiopia and will continue to be the main source of energy for most of the rural areas at least for some future decades.

Biomass is a renewable energy source because the growth of new plants and trees replenishes the supply. If the amount of new biomass growth balances the biomass used for energy, bioenergy is carbon dioxide "neutral".

Globally, biomass meets about 14 percent of the world's energy needs (Amrose, 2008), by the fact that biomass energy can converted into power, heat, and fuels for potential use in all parts of the country.

2.3 Back Ground of Institutional Cook Stove

There are fewer types of institutional stove on the market than domestic stove because the market for institutional stoves is smaller and, the development of a working stove design is often a very lengthy and needs detailed process. A few numbers of institutional stoves were done by different stove designers (Usinger, 1999).

2.3.1 Surharti Institutional Stove

The Surharti institutional stove is a composite stove made of cast iron and brick and is capable of using several biomass fuels. It can accommodate pots of up to 70 cm diameter and is ideal for restaurants and small hotels.

The stove has a thermal efficiency of 28 % and a high power output. Temperatures of up to 600°C can be attained in the combustion chamber and 300 ℃ in the chimney.

2.3.2 Cuban Institutional Bagasse Stove

The Cuban Institutional Bagasse Stove is designed for the use of sugar bagasse, but can also alternatively be used for other waste fuels such as: sawdust, coffee husks, rice husks etc. The stove has a chimney and can be built in various sizes.

Laboratory tests showed an efficiency of 25 %. This is low for wood stoves, but quite high for bagasse pellets. The stove is generally used for 150 liter pot.

2.3.3 Ghanaian Street Vendor Stove

The Ghanaian street vendor stove was developed for street food sellers, who are found all over Ghana. Street food sellers have very little scope for major investment and can only afford investment which amortize in a few weeks.

Laboratory tests showed an efficiency of 35 %. In field tests fuel savings of 50 % were realized. The stove is generally used for 50 to 100 liter pots.

2.3.4 Gugu Mobile Stove

The gugu mobile is a stove which was specifically designed for use in collective refugee kitchens. It is characterized by a highly ventilated combustion chamber, which allows it also to burn slightly fresh wood. It is mobile so it can be moved to new camp sites. It is made from an oil drum, which is generally available in refugee situations.

Laboratory tests showed an efficiency of 32 %. In field tests fuel savings of 70 % were realized. The stove is generally used for 100 to 150 liter pot.

2.3.5 Argentinean Institutional Stove

The Argentinean Institutional Stove is a sunk-pot design, made from sheet metal and is capable of accommodating pots of 44 cm diameter. It mainly comprises of the external and internal cylinders. Air enters through air-holes at the base of the stove to maintain a high temperature fire. Firewood consumption is reduced by 50 % to 70 % and cooking time by 50% in comparison to an open fire. The technical efficiency is claimed to be 42 %.

2.3.6 Bellerive Institutional Stove

The Bellerive Institutional Stove (SMP 200) is a wood burning stove. It is 87 cm diameter by 76 cm high, made of a mild steel frame, and has a stainless steel pot with a capacity of 200 liter. It is ideal for use in large institutions and is suitable for the preparation of a wide variety of meals. The stove can be used for long cooking tasks due to its high thermal mass.

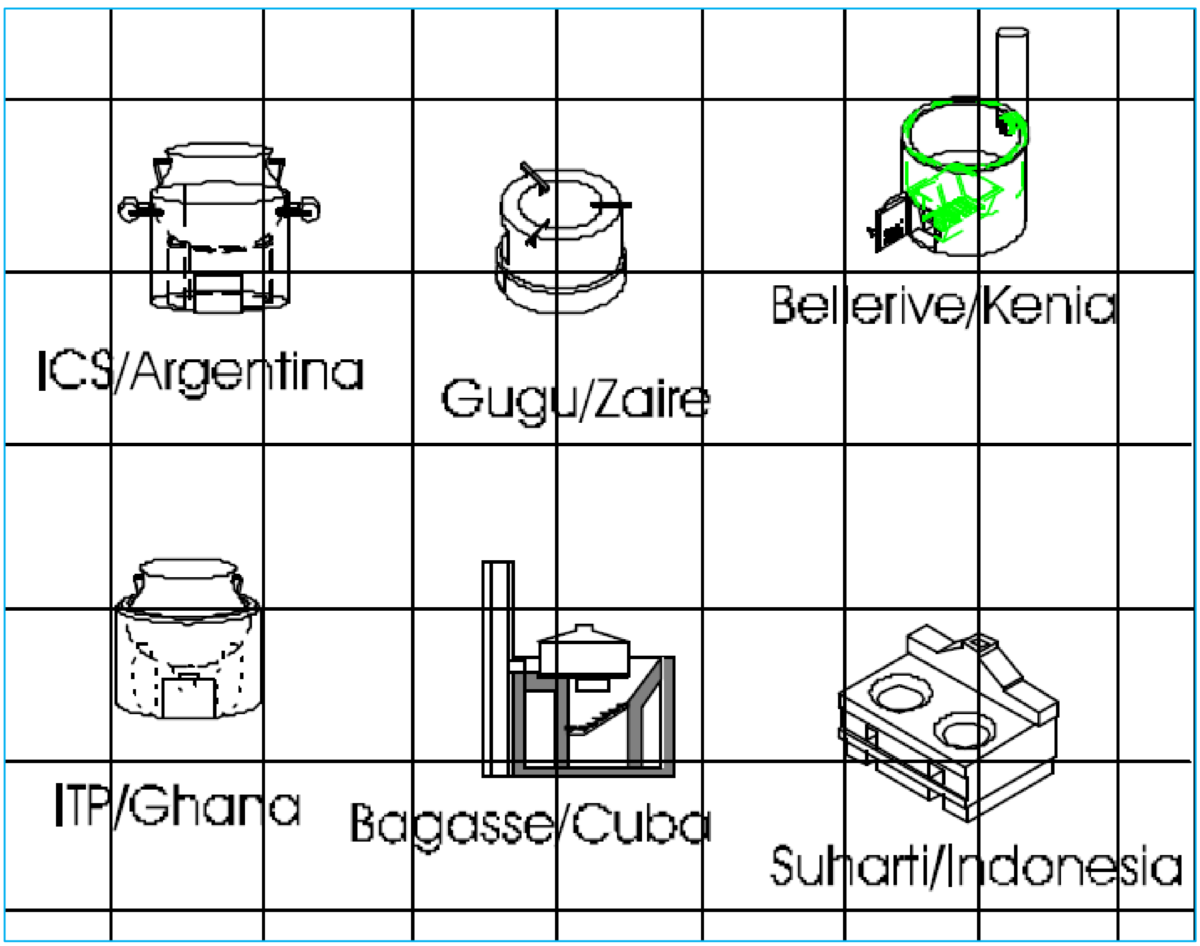


Figure 2.1 Improved Large Scale Cook stoves (Usinger,1999)

2.4 Wood Powered Cook Stove In Ethiopia at Institutional Level

A majority of the institutions in Ethiopia uses baseline stove and enclosed chimney stove for cooking and heating purposes, particularly in higher institution (University), colleges, and prisons. An open fire (3-stone fire) is often 90% efficient at the work of turning wood into heat. But only a small proportion, 10% to 15%, of the released energy makes it into the pot (Jurgen , 1999).

Both types of stoves are inefficient and not recommended for now days, in which climatic change is drastic. Firewood was not cut into pieces that fit into the stove fire chamber Instead; logs are used meaning that fire doors are left open during operation.

Figure 2.2 Enclosed chimney and Baseline stove

2.4.1 Improved Cook Stoves (ICS)

Energizing Development (EnDev) Ethiopia, operating under the name GIZ Energy Coordination Office (GIZ ECO), focuses on construction and advertisement of using ICS instead of the traditional three-stone open fire that reduces the firewood consumption. By facilitating efficient combustion, harmful emissions, like carbon monoxide and particular matter are reduced.

Figure 2.3 Institutional Rocket Stove (IRS) and Tikikil Stove

According to this report (EnDev) Ethiopia, the stoves are used to burn mostly woody biomass and have a minimum fuel-saving potential of 40% compared to the three-stone open fire, as well as a thermal efficiency of at least 20%. They develop three different stoves: Mirt, Tikikil and Institutional rocket stove (IRS).

The Mirt Stove: is used for both baking injera (Ethiopian traditional bread) and for cooking at the same time. It is made of a sand-cement mixture and can save up to 50% fuel compared to the three-stone open fire with a thermal efficiency of around 22%.

The Tikikil Stove: is a portable household cook stove made of galvanized sheet metal with a ceramic liner. Its saves up to 50% of fuel compared to the three-stone open fire; its thermal efficiency is around 28%.

The Institutional Rocket Stove (IRS): is a port-able stove used for larger-scale cooking in institutions. The stove can potentially save up to 70% of fuel compared to the three-stone open fire with a thermal efficiency of 40-50% (Energizing Development (EnDev), 2014).

2.4.2 Institutional Rocket Stove

60 Liter and 100 Liter Biomass Cook stoves use advanced “rocket stove” design principles to maximize fire power and fuel efficiency while minimizing harmful emissions of carbon monoxide and particulate matter by 90%. Field tested under demanding conditions in Africa, Haiti, and the Pacific Islands, the stoves consistently outperform other institutional stoves, and are both safe and popular with cooks. The research project was done with title “Institutional Cook Stoves in a University Setting Jimma University, Ethiopia” in Jimma University, Ethiopia. The research has the objective of “To identify the strength and weaknesses of the existing out-grower scheme arrangements, draw a lesson, and write a brief policy recommendation for policy makers.

2.5 Institutional Cook Stove Design Perspective

As it is the case in any design of cook stove, the thermal performance of an InStove depends upon the efficiency of the heat conversion system, i.e. conversion of chemical energy of fuels into thermal energy. It also depends upon the efficiency with which the thermal energy produced is transferred to the delivery systems, especially the cooking vessel and its eventual transfer to the food being cooked. Thus, an InStove designer should have a complete understanding of the complex interaction between the different processes that take place in a cook stove, e.g. combustion, heat transfer and fluid flow (Regional Wood Energy Development program, 1993).

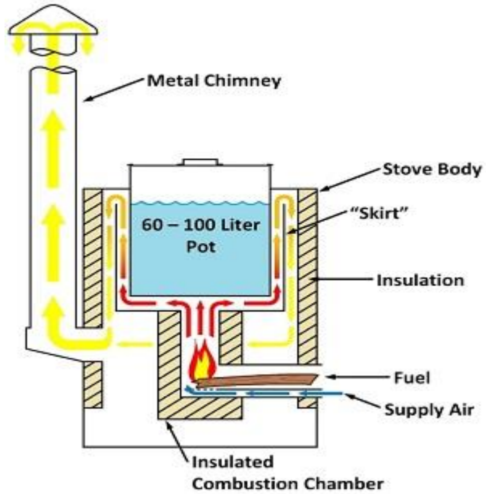


Figure 2.4 Institutional stove configuration

As it can be observed from figure 2.4 above, kitchen workers' environment cleaning method is applied by introducing chimney for smoke removing in addition to efficient combustion that takes place in the combustion chamber.

It is usually difficult to effectively control the amount of air supplied in the char combustion phase. Especially, since natural draught is applied, the excess air ratio will be quite high. This, much lowers fuel consumption rate, may decrease the temperature in the combustion chamber below the level needed for complete combustion

Table 2.1 processes in stove design (Regional Wood Energy Development program, 1993)

Process Consideration	Heat Transfer	✓ Convection	➢ Natural
			➢ Forced
		✓ Conduction	
		✓ Radiation	
	Fluid Flow	✓ Laminar	
		✓ Turbulent	
	Combustion	✓ Mass Transfer	
		✓ Heat Transfer	
		✓ Thermodynamics	
		✓ Kinetics	
	Material Science	✓ Thermal Properties	
		✓ Chemical Properties	

Fuel size is an important variable in large-scale biomass combustion applications, smaller fuel particles will need a shorter residence time in the combustion chamber. The homogeneity of the fuel is also of importance: increasing homogeneity, which improves with decreasing fuel size, enables better process control and active surface area of the fuel also influences the reactivity of the fuel.

CHAPTER THREE
WOOD COMBUSTION

3.1 Introduction

Solid fuel burns by a series of steps: (1) initial particle heat up and drying (most solid fuels have some degree of moisture); (2) evolution of volatile matter from the solid particle; (3) combustion of volatile gases, and (4) residual carbon or char oxidation. The design of a suitable firing system for a given solid fuel must take into account the relative importance of each of these steps, which will in turn depend on fuel characteristics and particle size.

For gaseous fuels, only step 3 is required and thus firing system design is focused on appropriate fuel–air mixing to achieve desired heat release and emissions levels. For liquid fuels, steps 1 to 3 are required and thus firing systems must allow for droplet heat up and evaporation in addition to suitable fuel–air mixing.

Firing systems for solid fuels (i.e. wood, coal) must provide for these steps as well as ensuring adequate burnout of the residual carbon material (which can be as high as 95% of the fuel in some cases). The time scales for these processes can vary greatly for solid fuels.

3.2 Biomass Composition

The biomass has three constituent compounds, namely: Cellulose $(C_6H_{10}O_5)$ x, Hemicellulose $(C_5H_8O_4)$ y and Lignin $(C_9H_{10}O_3(CH_3O)_{0.9\text{-}1.7})$z. The composition of these constituents varies with the plant species. In the case of wood, for example, *hardwoods* generally contain about 43% cellulose, 35% hemicellulose and 22% lignin, while *softwoods* contain nearly 43% cellulose, 28% hemicellulose and 29% lignin (Shafizadeh and De Groot 1976). Biomass consists of three major elements: carbon, oxygen and hydrogen with the approximate proportion of about 50% C, 6% H and 44% O on a moisture and ash free basis. In general it can be represented by the empirical formula of $CH_{1.44}\,O_{0.66}$. Ash, with a few exceptions, is normally considered as a minor component in biomass.

Biomass contains a number of inorganic compounds which do not burn, but are left as ash after combustion. Depending on the type of biomass, the ash content varies from less than 1% for wood to as high as 20-25% for rice husk. Ash comprises CaO, K2O, Na2O, MgO, SiO, Fe2O3, P2O5, and Al2O3. CaO and K2O constitute nearly 50% and 20% of the ash, respectively.

The heat of combustion of biomass based fuels is dependent on the percentage of the three main constituents. Lignin has the highest (26.63 MJ/kg), while holocellulose (cellulose and hemicellulose) has a value of 17.46 MJ/kg. Therefore, wood with a greater percentage of lignin has higher heat of combustion.

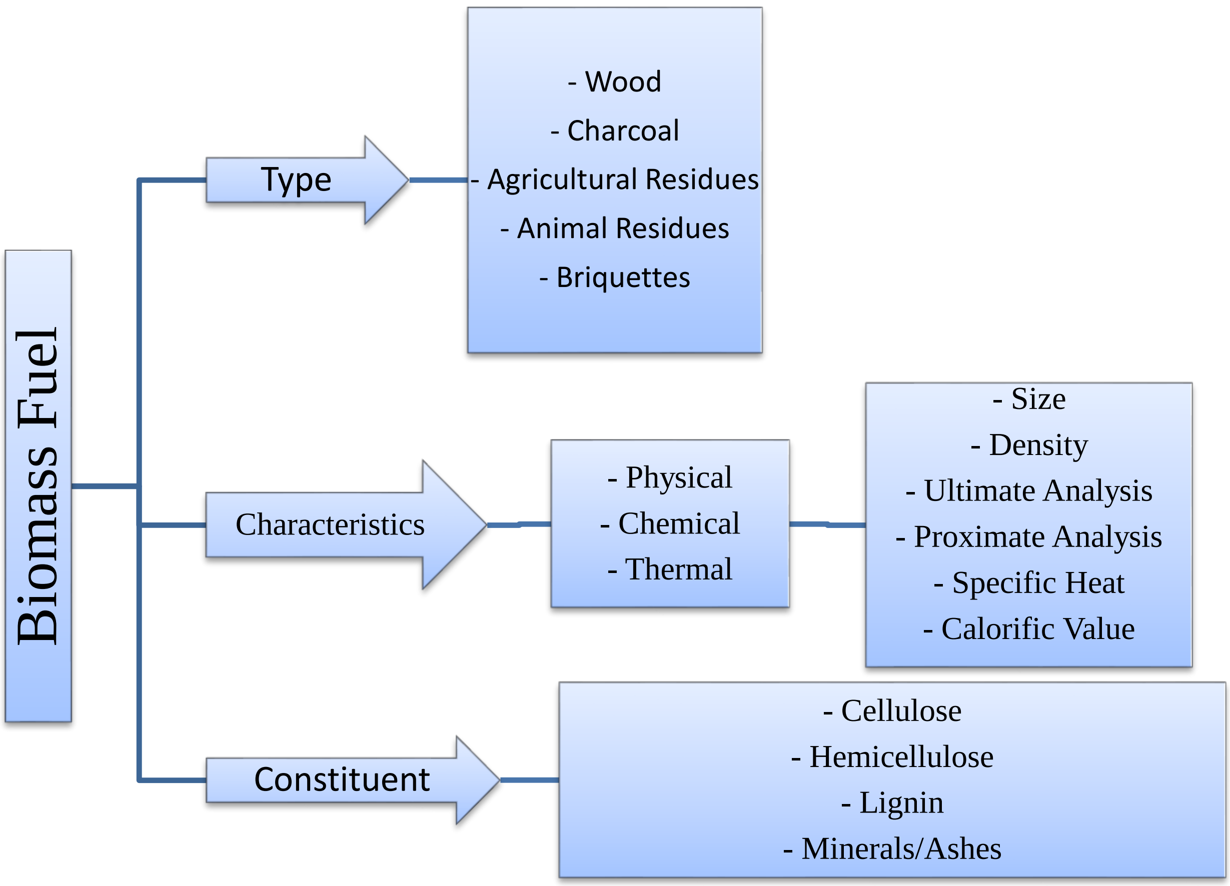


Figure 3.1 Biomass property

3.3 Stages of Wood Combustion

Fuel is normally burned on a grate at the bottom of the stove with voids in the grate to promote air flow through the stove and to facilitate cleaning out the ash. In an efficient stove the majority of air will flow through the grate rather than through the fuel inlet door.

In the case of InStove, the stove itself is well insulated to reduce heat wastage, prevent the kitchen getting uncomfortably warm to work in and to prevent burns when touching the stove.

To make practical, primary and secondary air openings, chimney with proper dimension is required. Even when this is done, testing and modification are usually necessary to get efficient and convenient operation and good fuel economy.

One of the factors affecting the efficiency of a stove is proper mixing of flow rate of fuel with air in natural convection. In order to attain complete combustion and good efficient stove secondary air is required in addition to primary air. Both deficiency and excess reduces the performance of the stove; so careful design is required.

3.3.1 Primary Combustion

Primary combustion is the initial burning of the wood at relatively low temperatures. During primary burn, water is evaporated and large amounts of creosote gas are produced. This creosote holds 60% of the potential energy of the wood, but it is deposited inside of the stove and the lining of the chimney.

3.3.2 Secondary Combustion

However, the combustion chamber is insulated sufficiently to raise the core temperature and exactly the correct amount of oxygen is introduced, at 600ºC the creosote spontaneously combusts. This creates a chain reaction which increases the temperature inside the stove from 600ºC to 900ºC with no extra use of fuel. This is the secondary burn (Morgan De Foort, n.d.).

3.5 Wood combustion process

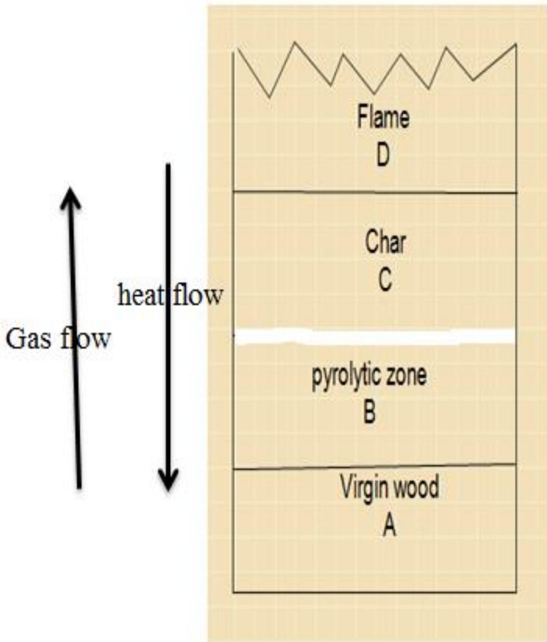
Biomass fuel is the stored solar energy in the form of chemical energy of its constituents, as a result of photosynthetic reaction. This energy is released during combustion reaction, in which oxygen reacts with the chemical constituents of wood to produce carbon dioxide and water, with the release of heat. Combustion of wood can be divided into four phases:

1) **Drying:** water inside the wood boils off.

2) **Pyrolysis (Degasification):** gas content is released from the wood

3) **Gasification:** the gases emitted mix with atmospheric air and burn at a high temperature

4) **Combustion:** the rest of the wood (mostly carbon) burns.



Gaseous phase combustion, diffusion flame, mostly turbulent - a 'free' fire.

T≥ 1000℃ (probably≤ 1200℃)

- Simultaneous heat & mass transfer with chemical reaction; surface combustion- a slow process. $500℃ \leq T \leq 800℃$
- Problem same as in zone "B" but with source/sink due to pyrolytic reactions. $200℃ \leq T \leq 500℃$
- Heat conduction in a medium with moving boundary. Migration of moisture and gases, uncertain properties. $T \leq 200℃$

Figure 3.2 Processes and temperatures in a burning Piece of wood (Hasan Khan and Verhaart, 1997)

The process of release of thermal energy from fuel is known as combustion, we can define, and Combustion is the process through which the fuel and air chemically interact at sustainable elevated temperatures.

Any combustion process can be depicted by the fire triangle shown in figure 3.3. The figure shows that for self-sustained combustion, three components are essential, namely: fuel, air and heat. The amount of energy released during combustion reaction depends on the temperature, pressure, the products of reaction and the state of water produced.

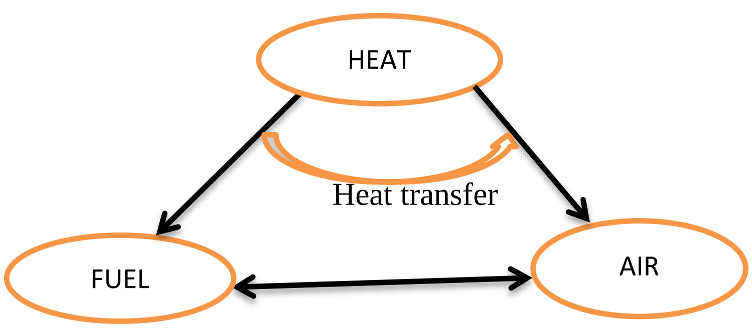


Figure 3.3 Fire Triangles

But, the way these three parameters are combined is which must be taken into consideration as well, so as to maximize efficiency and minimize emissions. There are a number of factor that govern the process: design, fuel and operational factors:

Fuel factors: Physical and chemical properties of fuel such as volatile matter, moisture, ash, etc.

Operational factors: Burn rate/size of the fuel ratio, volume to surface ratio, mode of fuel supply, cooking time, etc.

Stove factors: Fuel/air ratio, temperature of flame and/or envelope, mode of fuel supply, primary and secondary air, mass of the stove, etc.

It is difficult to predict the quantitatively effect of the variables on the overall efficiency. Qualitative effects of some of these factors on combustion and thermal efficiency are given in *table 3.1*. A critical examination of the factors given in this table shows that the fuel parameters are uncontrollable as they depend on the type of fuel. On the other hand, operational parameters such as fuel size and fuel feeding are user specific, while the stove parameters are design specific.

Table 3.1 Qualitative effects of different factors on thermal and combustion efficiency

Factors	Action taken to	
	Minimize emissions	Maximize efficiency
Fuel factors		
- Ash content	Minimize	Minimize
- Volatile contents	Minimize	Minimize
- Moisture contents	Optimize @ 25%	Optimize @ 10%
Operational factors		
- Burn rate	Maximize	Minimize
- Size of fuel charge	Minimize	Minimize
- Ratio of charge size to burn rate	Minimize	Minimize
- Volume to surface ratio	Maximize	Maximize
Stove factors		
- Combustion confinement	Minimize	Maximize
- Temperature	Maximize	Minimize
- Excess air	Optimize	Optimize
- Preheated primary air (down draft stove)	Maximize	Maximize
- Mass, short cooking time	Minimize	Minimize
- Mass, long cooking time	Maximize	Maximize
- Time during burn	High early	Low early
- Altitude	-	-

Source: smith, 1987

The materials used to construct a stove, have also a distinct bearing on the durability, cost, heat losses, safety, the skills required to make a stove and the scale of production envisaged, etc.

3.6 Important Variables in Biomass Combustion

Biomass combustion is a complex process, involving many variables that directly or indirectly influence emission levels and energy efficiency. Variables that are of importance (mainly in large-scale biomass combustion applications) are briefly described below.

Heat transfer mechanisms: Heat can be transferred by conduction, convection of radiation. To achieve low emission levels of emissions from incomplete combustion, it is necessary to minimize heat losses from the combustion chamber, which is done by optimizing those variables that directly affect the heat transfer mechanisms. However, to achieve a high thermal efficiency, efficient heat exchange is necessary between the combustion chamber and the chimney inlet.

Heat storage: A significant amount of heat will accumulate in the walls of the combustion chamber, stealing heat from the combustion chamber in the start-up phase. This is of special importance in small-scale biomass combustion applications.

Insulation: Heat is transferred by conduction through the walls of the combustion chamber. Consequently, by improving the insulation of the combustion chamber, a higher combustion chamber temperature can be achieved. The insulation can be improved by either increasing the thickness of the insulation or using a material that insulates better. However, insulation occupies space and is an additional expense, and should be utilized with care.

Air pre-heating: The combustion chamber temperature can be significantly increased by air pre-heating. The inlet air may be pre-heated through heat exchange with the flue gas, after the flue gas has left the combustion chamber. Stealing heat directly from the combustion chamber for air pre-heating will have no effect, unless the goal is to reduce the temperature in one part of the combustion chamber, by moving heat to another part. One example is pre-heating of secondary air at the expense of the fuel bed temperature.

Excess air ratio: A given fuel requires a given amount of air (oxygen) in order to be converted stoichiometrically, i.e. the amount of excess air λ (lambda) should be equal to 1. The fuel is converted stoichiometrically when the exact amount of oxygen that is required for the conversion of all of the fuel under ideal conditions is present. In biomass combustion applications, it is necessary to have an excess air ratio well above 1, to ensure a sufficient mixing of inlet air and fuel gas. In small-scale applications the excess air ratio usually has to be above 1.5. This means that there will be an overall excess of oxygen.

Fuel type: The fuel type influences the combustion process through various characteristics of different fuel types, mainly with respect to fuel composition, volatile/char content, thermal behavior, density, porosity, size and active surface area. The fuel composition is important with respect to GCV and emissions, though mainly emissions from complete combustion and ash-related problems. In batch combustion applications, the fuel composition will vary continuously as a function of degree of burnout. Biomass generally contains a high volatile content and low char content compared to coal, which makes biomass a highly reactive fuel. However, the volatile content varies for different biomass fuels, and influences the thermal behavior of the fuel. The thermal behavior of a fuel is also influenced by the different chemical structures and bonds present in different biomass fuels. This results in significantly different devolatilization behavior as a function of temperature

Moisture content: The moisture will be released in the devolatilization phase, and the moisture content decreases as a function of burnout. Hence, the moisture content and its negative effects on the combustion process may be substantial in the early stages of the devolatilization phase, resulting in high emission levels of emissions from incomplete combustion.

Combustion temperature: in batch combustion applications**,** the moisture content and fuel composition will vary continuously as a function of burnout. This will influence the adiabatic combustion temperature. The adiabatic combustion temperature will increase as a function of degree of burnout at a constant excess air ratio. However, as char is much less reactive than the volatile fraction of biomass fuels, the fuel consumption rate and the oxygen need will be much lower.

3.7 Requirements for Complete Combustion

The combustion process is dependent on the physico-chemical properties of the fuel (size, shape, density, moisture content, fixed carbon content, volatile matter, etc.), quantity and mode of air supply (primary and secondary air) and the conditions of the surroundings (temperature, wind, humidity, etc.).

When wood is heated, water begins evaporating from the surface of the wood. Hence two things occur: Gasification occurs at the wood surface – pyrolysis (the heating of a fuel without the introduction of gasification medium, i.e. oxygen and water, is termed pyrolysis) – and the temperature deeper inside the wood will increase resulting in evaporation of moisture from the interior of the wood.

The most important parameters for complete combustion conditions are (1) a high combustion temperature, (2) a sufficient amount of combustion air supply, and (3) adequate mixing of combustion air and fuel gas.

3.8 Biomass Fuel Characteristic Analysis

As described in figure 3.1 above the characteristics of the biomass depends on the physical, chemical and thermal property of the wood. The volume to surface ratio of the wood has great influence on the combustion property. This ratio has an important bearing on the combustion characteristics of the wood and other woody biomass. Fire penetration rate, which is the rate at which the char boundary advances into the virgin wood, is a function of volume to surface ratio (v/a), as is given by following equation:

$$\text{Peneration rate} = \frac{\text{power output} * \text{volume/surface ratio}}{\text{volatile fraction} * \text{total fuel used} * \text{net cal.value}} \quad \text{-------------------------3.1}$$

Where: power output in kW, volume/surface ratio in mm, total fuel used in kg, net calorific value in kJ/kg. Power output of a fire is given by equation:

$$\text{power output} = \frac{\text{sum of individual changes} * \text{net calorific value}}{\text{total duration of expriment}} \quad \text{--------------------------------3.2}$$

3.8.1 Ultimate Analysis

The ultimate analysis involves the estimation of the important elements of biomass such as: C, H, O, N, and S, another impurities like phosphorous and chlorine are almost absent in the case of biomass, although these are very important in the case of coal. An ultimate analysis coupled with gas analysis data is required to make the overall material and energy balance calculations for a combustion process.

3.8.2 Proximate Analysis

The proximate analysis involves, simple test methods, estimating the main constituents of biomass which have a direct influence on the combustion characteristics, e.g. the moisture content of a biomass sample, the amount of volatiles, fixed carbon (char) and the amount of ash. All these components of the proximate analysis are related in some way to the combustion characteristics of the biomass.

A proximate analysis starts with the determination of the moisture content. This is necessary as the moisture has a direct influence on the determination of the other constituents, in particular the amount of volatile matter.

The moisture content of biomass can be estimated by taking a small pre-weighed sample. The sample with an initial mass of M_i is placed in a drying oven in which a temperature of 100℃ is maintained. Every 6 hours the change in mass is noted and the process is continued till the mass becomes constant (Me). The moisture content $[m]$ in percent of the biomass on dry basis is then calculated as:

$[m] = \frac{M_i - M_e}{M_e} * 100\%$ (Mass of moisture in the fuel wood) --------------------------------------3.3

The second step in a proximate analysis is the determination of the amount of volatile matter. The volatile matter of biomass is that component of the carbon present in the biomass, which, when heated, converts to vapor. In almost all types of biomass the amount of volatile matter, which is a function of the carbon to hydrogen ratio is high and will be about 70%-80% of the weight of the dry biomass.

The amount of volatile matter is determined by heating a dried ground sample of biomass with an initial mass of M_i in a closed crucible in an oven with a temperature of 600°C for six minutes followed by heating the sample in an oven with a temperature of 900°C for another six minutes. The amount of volatile matter [v] in percent, in the biomass is equal to the loss in the weight and is calculated as:

$[v] = \frac{M_i - M_e}{M_e} * 100\%$ ---3.4

After the volatile matter, the amount of ash is determined. The higher the amount of ash in a fuel, the lower is the calorific value of the fuel. The amount of ash is determined by heating a dry sample of biomass in a crucible in a furnace which is kept at 900°C. The amount of residues left is weighed and the amount of ash $[a]$ in percent is calculated as:

$[a] = \frac{M_i - M_e}{M_i} * 100\%$ ---3.5

The final step in the proximate analysis is the determination of the amount of fixed carbon $[c]$ by using mass balance calculations. The fixed carbon is the difference between 100 and the sum of the moisture content $[m]$, the amount of ash $[a]$ and the amount of volatiles [v] in a sample of biomass calculated as:

$[c] = 100\% - ([m]\% + [a]\% + [v]\%)$ --3.6

3.8.3 Specific Heat

Specific heat capacity of a material is the amount of heat required to raise the temperature of one kilogram of a material by one degree Celsius. The principal heat capacities of a material are those at constant volume and constant pressure.

3.8.4 Calorific Value

The calorific value of a fuel is defined as the amount of heat evolved when a unit weight of fuel is completely burned and the combustion products such as CO_2 and H_2O are cooled to a standard temperature of 298K. It is usually expressed in kilo joules (kJ). The calorific value of any given species of biomass is dependent on the moisture content and its density as stated in the previous section.

The calorific value is termed as *gross calorific value* when the sensible and latent heat of the condensation of water, produced during combustion, is included in the value. However, in actual practice such as in a stove, any moisture in the fuel as well as that formed by the combustion of hydrogen is carried away through the stack as water vapor. For that reason, the heat of condensation of water is not available as useful heat and has to be subtracted from the gross calorific or higher heating value resulting in the net heating or lower heating value.

3.9 Mode of Heat Transfer

It is clear that a large part of the heat is lost to the surroundings through three distinct heat transfer mechanisms: conduction, convection, and radiation (see fig. 3.4). In order to minimize the losses to the surroundings and maximize the transfer of heat to the food in the pot a thorough knowledge of heat transfer mechanisms and their underlying principles is required to determine the reasons for the losses, how these losses can be reduced through modifications of the design of the cook stove, etc.

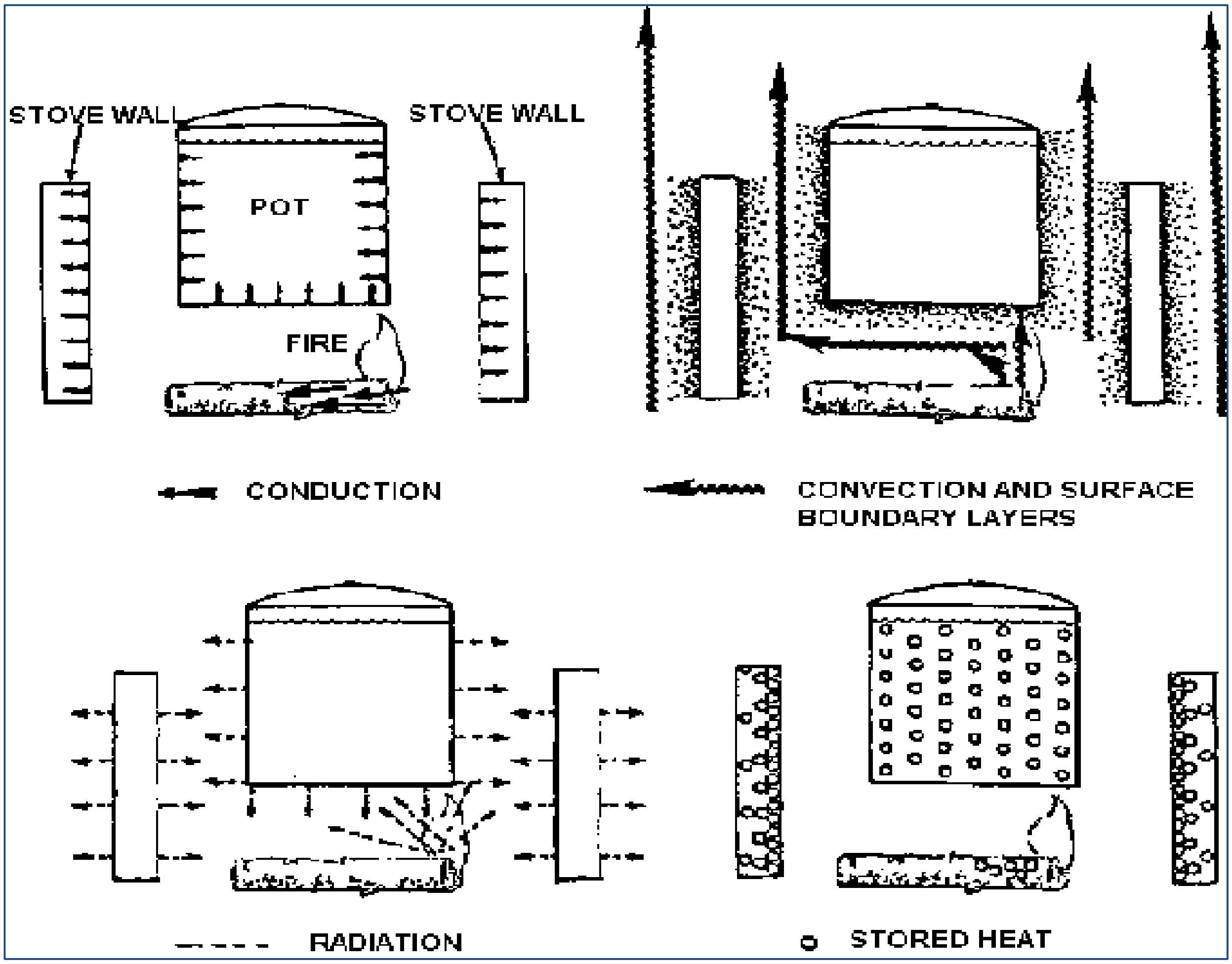


Figure 3.4 Conduction, convection, radiation and store heat. (Baldwin 1986)

3.9.1 Conduction Heat Transfer

This mechanism of heat transfer through conduction is happened by movement of high velocity free electrons from high temperature regions to low temperature regions, where they collide with and excite atoms. In general, heat conduction by free electrons is more significant than adjacent atoms exciting each other. The transfer of heat through conduction can be calculated using the following equation (Fourier conduction law):

$$q = -\frac{k*A*(\Delta T)}{\Delta X} \quad \text{------------------------------------}3.7$$

Where, q is the rate of heat transfer, k the thermal conductivity, A the area, X the thickness of the surface through which the heat is conducted and ΔT being the difference in the temperatures of the hot and cold sides. X/kA is called the thermal resistance.

The change in the total amount of heat stored) Q, when the temperature of the stove with mass m is changed by) T, is given by the equation

$Q = m * C_p * \Delta T$ --3.8

Where, C_p is the specific heat of the material of a stove.

During conduction, the following regions are interest from the viewpoint of conduction:

- Transfer of heat from the pots to the contents of the pot;
- Loss of heat through the stove walls;
- Transfer of heat from the flame to the interior of the wood;
- Storage of heat in wood, pot and its contents and the body of the stove.

3.9.2 Convective Heat Transfer

Convective heat transfer involves the transfer of heat by the movement of fluid (liquid or gas), followed by conductive heat transfer between newly arrived hot fluid and the matter.

Convective heat transfer is the predominant mode of heat transfer in cook stoves. In convective heat transfer, fluid flow and heat transfer take place simultaneously. The theoretical analysis requires the solution of continuity, momentum and energy conservation equations simultaneously that make the solution complex but it can be simplified by introducing the concept of boundary layer resistance.

In natural convection the hot gas temperature decides the flow as well as the heat transfer rates, which in turn decides its temperature. In an empirical approach, the convective heat transfer is estimated using a general equation:

$q = h * A * \Delta T$ --3.9

In the case of heat transfer by natural convection, generally encountered in naturally vented Cook stoves, the Nusselt number can be evaluated from the relation:

$N_u = C * (G_r * P_r)^n$ --3.10

Where G_r and P_r are the Grashoff and Prandtl numbers respectively which are defined as:

$G_r = \frac{g * \beta * T * l^3}{v^2}$ ---3.11

$P_r = \mu * \frac{C_p}{k}$ ---3.12

Where, g is the acceleration due to gravity, B the volumetric expansion coefficient (approx.= 1/T), T is the temperature difference between the surface and the ambient, µ the viscosity of the fluid, k the thermal conductivity and v the kinematic viscosity. For flow over vertical cylindrical surfaces, the characteristic length is equal to the height. In cookstoves the values of C and n are taken as 0.53 and 0.25 respectively (Peter, 2002/03).

3.9.3 Radiation

Energy in the form of heat radiation is emitted by all bodies above the absolute temperature due to molecular and atomic motion as a result of the internal energy of the material. The internal energy is proportional to the temperature of the body in the equilibrium state. The ability of an object to emit and absorb radiation is given by its emissivity and absorptivity, which are usually functions of the wavelength of the radiation. The emissivity and absorptivity of a black material are equal. Heat radiation is absorbed, reflected, and transmitted when these come in contact with any solid body.

In a cookstove, the radition region of interest from the radiation point of view are:

- Radiation emitted by the flame;
- Radiation exchange between the inner walls, pot and the wood;
- Radiation loss to the atmosphere from the wall, pot, chimney, and the opening of the fire box.

It can be concluded that radiation emitted by the burning flame is in the range of the visible spectrum while that emitted by the stove surfaces at lower temperature is in the range of infrared radiation.

$q = \sigma * A * T^4$ ---3.13

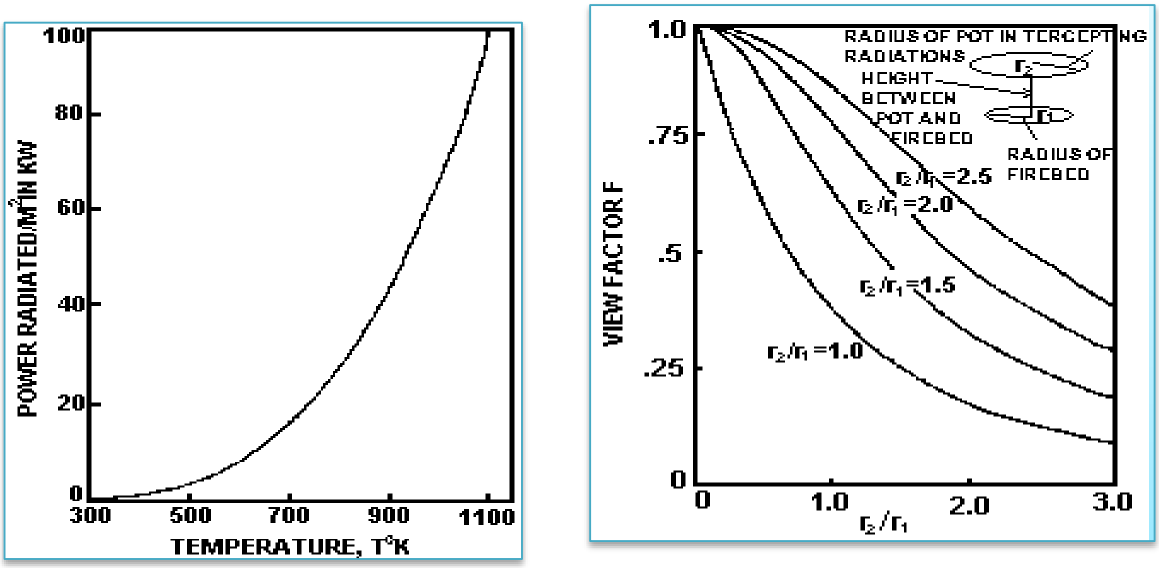
Where σ is the Stefan-Boltzman constant, which is equal to 5.6697 * 10-8 W/m^2 K^4, A is the emitting area of the object in square meters, and T is its temperature in K.

Black bodies have absorptivity equal to 1, regardless of wavelength. Such bodies are impossible to find in actual practice. In actual practice, bodies behave as grey bodies, which absorb only a fraction of radiation impinging on it. For these bodies, the Stefan-Boltzmann law is modified as:

$q = E_m * \sigma * A * T^4$ ---3.14

Where, E_m is the emissivity of a material.

The important parameter in radiation heat transfer are temperature and View Factor (VF) (between the emitting and the absorbing) surface. The View Factor is the fraction of energy emitted by one surface that is intercepted by the second surface. It is determined by the relative geometry of the two surfaces.



(a) (b)

Figure 3.5 (a) Total power radiated by a black body as a function of the temperature. (b) View Factor versus the height to the pot. (Baldwin 1986)

The energy intercepted by the cooking pot from the fire bed can be calculated from the following equation if the View Factor is known.

Energy intercepted by the pot = Power emitted by the fire bed × A × VF -----------------------3.15

View Factor = h/r_2

Radiate heat transfer from the fire bed in a cook stove can be increased, either by increasing the fire bed temperature (by controlling the air supply to the fire bed) or by increasing the View Factor. The latter can be increased by either decreasing the distance between the pot and the fire bed or by increasing the diameter of the pot. However, too small a distance between the pot and the fire bed will result in quenching of the fire resulting in incomplete combustion and increased emission of CO and hydrocarbons. This distance should be more than the combined height of the fuel bed and the flame length. Flame length is dependent on the type of fuel.

3.10 Mixing of Combustion Air and Fuel Gas

During mixing of the fuel and air, it is important to achieve good contact between the oxidizer and the combustible constituents of the wood. The better the contact is the faster and more complete is the combustion. Complete combustion requires good mixing of air and combustion gases, and a satisfactory residence time for the flue gases for oxidation.

Good mixing reduces the amount of air needed, providing a local and overall excess air ratio and higher combustion temperature. Inadequate mixing in the combustion chamber leads to local fuel rich combustion zones and increases emissions.

The larger the fuel particle is, the longer is the combustion process. There is no good contact between fuel and air; it will take a long time before it is burnt out. The size of the fuel, therefore, has great importance to the speed of combustion.

3.10.1 Stoichiometry and Air Fuel Ratio

The fuel wood being used in most institution in Ethiopia, including Jimma University students' cafeteria are eucalyptus tree. The property of the Eucalyptus tree, based on dry bases were in the following table.

Table 3.2 elementary analysis of eucalyptus tree (Luger, n.d.)

Gross calorific value = 19611 KJ/kg	
Ash content = 1.76 Wt.%,dm	
Elementary analysis	Wt.%, dm
Carbon	50.43
Hydrogen	6.01
Nitrogen	0.17
Sulfur	0.08
Chlorine	0.02
Oxygen: by difference	43.29

3. 10.1.1 Stoichiometry

The fuel is converted stoichiometry when the exact amount of oxygen that is required for the conversion of all of the fuel under ideal conditions is present. If more oxygen is introduced than an amount required, oxygen will be present in the flue gas. If insufficient oxygen is present in the combustion chamber more carbon monoxide is present in the flue gas. Both deficiency and more than the required amount influence on the combustion efficiency. Complete combustion produces carbon dioxide (CO_2) and water (H_2O). Disproportion mixture of fuel and air, type of heating system, and introduction of air may result in an unsatisfactory result.

In this document, I assume 20% of excess air during combustion, due to the entrance of air through the wood inlet in addition to air entrance opening (fuel entry and air entry are not totally controlled).

Fuel (wood) + air (oxidizer) $\longrightarrow$ product of combustion + Energy

$C_xH_yO_z + a_{th}(O_2 + 3.76N_2) \longrightarrow xCO_2 + yH2O + zN_2$

3.10.1.2 Air Fuel Ratio

Proper air to fuel ratio is essential for efficient combustion of fuel. Both rich (deficient in air) and lean (deficient in fuel) will result in incomplete combustion. Wood contains nearly 43-44% oxygen and hence a major part of the oxygen required for combustion is supplied by the wood fuel itself while the rest is to be provided from the air.

In actual practice, even when the theoretical minimum amount of air, or a little more, is supplied for combustion, the carbon may not get fully oxidized to carbon dioxide. In such situations, the fraction of carbon converted to carbon dioxide as well as carbon monoxide is estimated and used for calculating the amount of air required for combustion from ultimate analysis of the wood. This can be calculated by the following correlation.

$$n_{a.st} = \frac{1}{0.21}\left[\left(1 - \frac{1}{2} * f\right) * \frac{[C]}{12} - \frac{Y}{32}\right] \text{[Mol]} \quad \text{------3.16}$$

Where, $n_{a.st}$ is the stoichiometric amount of air required for combustion, [c] is the % of carbon in the wood, *f* is the fraction of wood that is converted into CO; *Y* is the percentage of oxygen minus eight times the percentage of hydrogen and the detailed calculations are present in the appendix A of this document.

Assuming the amount of air required for burning 1 kg of fuel; the air fuel ratio will be:

$$A/F = m_{air}/m_{fuel} = \frac{n_{air}M_{w,air}}{n_{fuel}M_{w,fuel}} \quad \text{------3.17}$$

The value of, A/F = 7.2:1. (The detailed calculation of air fuel ratio were done in appendix A of this document)

The mechanism of combustion of fuel with less than the stoichiometric air results the following events:

(1) the available oxygen firstly burns all the hydrogen in the fuel to water vapor.

(2) All the carbon in the fuel is then burnt to carbon monoxide.

(3) The remaining oxygen is consumed by burning carbon monoxide to carbon dioxide

It can be seen that as the air supply falls below the stoichiometric requirement the percentage of carbon monoxide in the flue gas increases very quickly.

3.11 Combustion Controlling Factors

Important factors which influence combustion are:

- Physical and chemical properties of the fuel;
- Air/fuel ratio;
- Temperature of the flame/envelope;
- Mode of fuel supply;
- Primary and secondary air supplies.

3.11 Model Performance Analysis

The physics of the stove have been simplified to two basic and fundamental driving processes: heat addition from combustion (at point 2), and kinetic energy addition/conversion (between points 1 and 2) due to the chimney effect. The two processes are interconnected and together govern the simplified overall stove operation.

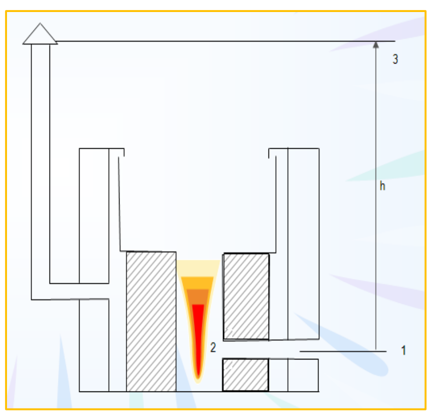


Figure 3.6 Situation of model

1. V= 0	2. Heat addition; T_H , ρ_H	3. V = 0
ρ_{amb}	$P_2 < P_1$	ρ_{amb}
T_{amb}	V > 0	T_{amb}

3.11.1 Heat Addition

The ignited fire releases a heat into the passing stove flow, increasing its temperature and decreasing its density. Heat addition is assumed to be perfectly efficient and is greatly simplified as taking place entirely, instantaneously, and uniformly at point 2. Using the first law of thermodynamics for a control volume, the flow temperature can be calculated from a given mass flow rate, $\dot{m}_A$, and heat release rate(essentially the stove firepower), $\dot{Q_{in}}$.

For an isobaric system with no mechanical work, assuming ideal gas behavior, and constant potential and kinetic energy, the temperature increase can be calculated using the constant pressure specific heat of air (C_P). The heat addition from combustion translates into an enthalpy (h) increase and distributed over the mass flow rate ($\dot{m}_A$).

$$\dot{Q_{cv}} = \dot{m}_A (h_{amb} - h_H)$$

$$= \dot{m}_A \int_{T_{amb}}^{T_H} C_p(T)dT$$

$$= \dot{m}_A C_{p,avg}(T_H - T_{amb}) \text{ ---3.18}$$

Where T is the bulk flow temperature and the subscripts H and amb denote hot and ambient (cold) respectively.

3.11.2 Chimney Effect

The Air flow through the stove is dependent on the chimney effect resulting from the buoyant force of the decreased density of air after combustion takes place. The decreased density of air in the chimney between points (2) and (3) creates a lowered pressure at point (2) compared to ambient air pressure at point (3).

$$\Delta P = g \int \rho(h)dh \text{ ---3.19}$$

Where g is gravity, and the density, ρ is a function of chimney height (h).

$$\Delta P_{1-2} = (P_3 + g \int_3^1 \rho_{amb} dh) - (P_3 + g \int_3^2 \rho(h)dh) = g\rho_{amb}h - g \int_3^2 \rho(h)dh \text{ ---3.20}$$

Assuming the chimney walls to be adiabatic, than the temperature and density of the gas in the chimney (T_H and ρ_H) will remain constant, and Eq. (3.19) simplified to:

$$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) \text{ ---3.21}$$

As stated by different researchers, approximately one third of the energy may be lost to the chimney walls. In this case the integral from point (2) to (3) could be performed if the temperature/density profiles were known.

From Bernoulli's equation for compressible flow, pressure difference can be equated to gain kinetic energy of the chimney flow at point (2) and the stagnation ambient air at point (1) using the following equation.

$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H v_2^2$ --3.22

Where, the hot gas density and velocity (v) at point (2) are used for calculating the stove flow kinetic energy. Utilizing the relations of volume and mass flow rate:

$gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H (\frac{\dot{V}}{A})^2$

$\dot{V} = CA\sqrt{2gh(\frac{\rho_{amb} - \rho_H}{\rho_H}}$ --3.23

The detailed steps for converting the density ratio to a corresponding temperature will be in Appendix C of this document.

$\dot{V} = CA\sqrt{2gh(\frac{T_H}{T_{amb}} - 1)}$ ---3.24

Multiplying by the density and substituting with the ideal gas law, the mass flow rate will be determined as follows;

$\dot{m}_A$ = CA $(\frac{P}{R_s})(\frac{1}{T_H})\sqrt{2gh(\frac{T_H}{T_{amb}} - 1)}$ --3.25

Where, C is loss coefficient introduced to account for uncertainties and inefficiencies in the chimney effect, i.e. viscous losses, chimney wall heat transfer, and the unrealistic ideal point heat addition at point two. $(0 \le C \le 1)$

The air fuel ratio and excess air ratio can be calculated using the chimney effect driven mass flow rate and the fuel mass burn rate. The mass flow rate of fuel ($\dot{m}_F$) is calculated from the fire power ($\dot{Q}_{in}$ and the heating value (HV) of the fuel.

$\dot{m}_F = \frac{\dot{Q}_{in}}{HV}$ ---3.26

Air Fuel Ratio (AFR) = $\frac{\dot{m}_A}{\dot{m}_F}$ --3.27

$\varphi = \frac{AFR_{Stoich}}{AFR}$ ---3.28

% of excess air ratio = $\frac{(1-\varphi)*100\%}{\varphi}$ ---3.29

The lower or the gross heating value (LHV or GHV) can be used (where the LHV is essentially the heat of combustion).

3.11.3 Loss Coefficient Analysis

In this case loss coefficient is calculated to account two main inefficiency; 1) viscous losses due to stove wall friction and, 2) geometric flow disturbance.

3.11.3.1 Viscous Losses

Viscous losses including wall friction and geometric flow disturbances induce mixing and flow separation resulting in irrecoverable viscous dissipation of energy. Flow disturbances due to geometry are often termed "minor losses" as they are often small relative to frictional losses in common industrial application, but, in the case of cook stove, frictional losses will be relatively insignificant and the "minor loss" is replaced by "geometric loss" will be used instead.

Both frictional and geometric losses are commonly included in Bernoulli's equation as a sum of the lost pressure head ($\sum h_L$).

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + Z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + Z_2 + \sum h_L \quad \text{------3.30}$$

Multiply all the terms by a factor of ρg inorderto work with energy terms as opposed to the pressure head terms of equation above and rearranging:

$$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H v_H^2 + g\sum \rho_i\, h_{L,i} \quad \text{------3.31}$$

The head loss term is commonly calculated using a "resistance coefficient,"(k_L), and it is proportion of the flow kinetic energy that will be lost in overcoming viscous losses.

$$h_{L,i} = k_{L,i}\frac{v_i^2}{2g} \quad \text{------3.32}$$

A resistance coefficient, $k_{L,i}$ is included for each i viscous loss. v_i is the characteristic velocity at loss i.

Substituting this value into equation (34)

$$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H v_H^2 + \frac{1}{2}\sum \rho_i\, k_{L,i} v_i^2 \quad \text{------3.33}$$

From this equation, it is observed that losses will depend on each $k_{L,i}$ and the kinetic energy at i given by $\rho_i v_i^2$. The kinetic at i will vary depending on the stove.by conservation of mass the product of velocity, cross-sectional area and density will remain constant and equal to mass flow rate.

$$\rho_i v_i A = constant = \dot{m}_A \quad \text{------3.34}$$

Density (and with the ideal gas law, temperature), varies in a complex manner with both position and time. In order to reach a practical solution, it will be assumed that each i viscous loss takes place either in the hot or cold flow region of the stove.

With this assumption, the summation will be;

$$gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H v_H^2 + \frac{1}{2}\rho_H v_H^2 \sum k_{L,H} + \frac{1}{2}\rho_c v_c^2 \sum k_{L,C} \quad \text{-----3.35}$$

Using the concept of conservation of mass, and including the mass flow rate from equation (3.38) cold and hot flow velocities can be related as:

$$v_c = \frac{\rho_H}{\rho_C} V_H \quad \text{-----3.36}$$

$$gh(\rho_{amb} - \rho_H) = \frac{\rho_H (\frac{\dot{m}_A}{\rho_{H\,A}})_H^2}{2}\left(1 + \sum k_{L,H} + (\frac{\rho_H}{\rho_C})\sum k_{L,C}\right)$$

$$\dot{m}_A = \frac{A}{\sqrt{1 + \sum k_{L,H} + \left(\frac{\rho_H}{\rho_C}\right)\sum k_{L,C}}}\left(\frac{P}{R_s T_H}\right)\sqrt{2gh(\frac{T_H}{T_{amb}} - 1)} \quad \text{-----3.37}$$

Where, $C_{viscous\ losses} = \frac{1}{\sqrt{1 + \sum k_{L,H} + \left(\frac{\rho_H}{\rho_C}\right)\sum k_{L,C}}}$

If all restrictions are assumed to take place in the hot flow condition, C remains constant for stove operation. With the $\frac{\rho_c}{\rho_H}$ scaling, a fitting will contribute significantly high losses in the hot flow, especially at higher fire powers and C can be assumed 0.5.

Stove flow Reynolds number will vary with mass flow rate, as well as the temperature dependency of viscosity. (Assuming 0.5 loss coefficient)

$$R_e = \frac{\rho V D}{\mu} = \frac{\dot{m}_A}{\rho_A}\rho\frac{\sqrt{A/\pi}}{\mu(T)} = \frac{\dot{m}_A}{\mu(T)\sqrt{A\pi}} \quad \text{-----3.38}$$

3.11.3.2 Wall Friction Losses

Wall friction viscous losses are well understood for both turbulent and laminar internal flows.

$h_L = f\frac{L}{D}\frac{v^2}{2g}$ Where $f = \frac{64}{R_e}$ - Darcy friction factors and $k_L = f\,\frac{L}{D}$

Stove flow is observed to be in the laminar to transitional region.

The geometric losses of InStove without a cooking vessel in place will be calculated as a 90° bend an inlet (infinite sudden contraction) and an exit (infinite sudden expansion). For the case of a stove with the cooking vessel in place flow restriction would not be easily determined, and is not considered here

CHAPTER FOUR

EXPERIMENTAL SETUP AND METHODS

4.1 Introductions

Cook stove design is a complicated task, since it is highly considered as a consumer-specific device. In designing an appropriate cook stove both engineering and non-engineering parameters need to be taken into consideration that makes the exercise much more complex when compared with the design of other types of engineering equipment. These design considerations can be classified into three major criteria, namely: social, engineering, and developmental & ecological.
Social: cooking task (boiling, frying, baking, grilling, steaming etc.), utensils used, size of cooking operation, affordability, culinary practices.

Engineering: power output, pot and pan sizes and shape, materials available, knowhow and skills needed for manufacturing

Developmental & ecological: fuel access, smoke problems (indoor/outdoor cooking), potential for job creation, etc.

Kitchen workers (mainly women) are familiar with open fire traditional cook stoves since it has some advantages for the them, i.e. easy to make their own specification, It is free, easy to adapt to various cooking pots and sizes, Cooks food fast. Even if the adaptation of institutional cook stove with community is another task, the three criteria mentioned above should be unforgettable design factors.

In another case, the stove technology assessment, i.e. construction material, function (mono function or multifunction), portability (fixed or portable, double or single pot holes) and size also greater influence in stove design. Large pots have greater surface area compared to smaller pots. Using larger pot means that both less wood and fewer harmful emissions are made when cooking.

4.2 Fabrication Methods

Fabrication of the cook stove considers many factors, i.e. the availability of construction materials, economic factors, thermal efficiency, durability, etc. The institutional cook stove is differing from other stove types by shape that the cooking pot sits snugly within the body of the stove rather than on top. The side of the stove is thick to add strength and insulation.

The thermal performance of an InStove depends upon the efficiency of the heat conversion system, i.e. conversion of chemical energy of fuels into thermal energy.
A designer therefore should have a complete understanding of the complex interaction between the different processes such as: combustion, heat transfer, fluid flow taking place in a cook stove and how the material used for InStove construction.

4.2.1 Material Selection

The institutional stove was constructed from different materials in which number of criteria was considered for the selection of construction material. The thermal property of materials (i.e. material's melting point, thermal conductivity etc.) could have compared with flame temperature whether it is melted, softened, lost strength, etc.

The combustion chamber, including the grate made from stainless steel due to the presence of high temperature above the grate. The other parts of the stove were made up of mild steel of different thickness (1mm - 2mm). The mild steel is highly corroded metal, but anti-rust was painted on the outer part of the stove.

Table 4.1 bill of material to construct Institutional stove

Parts/components	Materials	Property of materials
Inner combustion chamber	stainless steel	Resist high temperature
outer combustion chamber	Mild steel	cheap and available
Pot holder	Mild steel	“
Insulation material holder	Mild steel	“
Stove’s outside body	Mild steel	“
Combustion chamber insulator	Construction sand	Resist high temperature
Body insulator	Glass wool	light weight & low thermal conductivity
Chimney	Galvanized (28 gage)	
Bottom and top plate	Mild steel	
paint	Anti-rust	
	Stucco	

4.2.1.1 Insulation Material

One of the methods to reduce the thermal energy (heat) loss from thermal heat storage system to the surrounding environment is using insulation. The energy lost for an insulating material depends on the thermal properties and thicknesses of the insulation. The heat loss depends on a number of factors, such as the heating system or heat source temperature, selection and thickness of insulation used, and exposure of insulated surfaces to ambient conditions. The stove itself should be well insulated to reduce heat wastage, prevent the kitchen getting uncomfortably warm to work in and to prevent burns when touching the stove.

Thermal insulation is one of the most effective means of protecting workers from second and third degree burns resulting from skin contact for more than 5 seconds with surfaces of hot body and equipment operating at high temperatures. There are different types of insulation material depending on the amount of temperature the material withstand.

Low Temperature Insulators (up to 90ºC): The insulation can be classified into three groups according to the temperature ranges for which they are used. Commonly used materials are wood, mineral fibers, polyurethane and polystyrene.

Medium Temperature Insulators (90 – 325ºC): Insulators in this range are used in low temperature, heating and steam producing equipment, steam lines, flue ducts etc. The types of materials used in this temperatures range include 85% magnesia, asbestos, calcium Silicate and Mineral fibers.

High Temperature Insulators (325ºC and above): These are used in systems like super-heated steam systems, oven dryers and furnaces. The most extensively used materials in this range are asbestos, calcium silicate, mineral fiber, mica and vermiculite based insulation, fireclay or silica based insulation and ceramic fiber.

4.2.1.1.1 Criteria for Selecting Insulation Material

Thermal conductivity (k): thermal conductivity is defined as the quantity of heat transmitted through a unit thickness of a material – in a direction normal to a surface of unit area – due to a unit temperature gradient under steady state conditions. Thermal conductivity units are W/(m K) in the SI system.

High thermal conductivity material has less insuation property. The recommended insulation materials by different researcher were listed in the table 4.2. To use these insulation materials a number of criteria are required, i.e. availability, affordability, the temperature in a combustion chamber, melting point of the material must be account into consideration.

Based on these criteria, the material selected for this stove was construction sand to insulate combustion chamber; since sand is easily available material and has high melting point (1713℃) to withstand the high temperature formed inside of the combustion chamber. The sand retains the heat for a long time, not less than 40 minute that is indirect advantage of using sand as insulation material. While cooking, once wot/food was boiled, it stayed for simmering time usually not less than 45 minute. The kitchen workers know the test of wot/food that was passed through the proper simmering time, it had well test. The thermal conductivity of dry sand ranges (0.15-0.25). The sand has some demerits besides its advantage of using as insulation material that is, it has high weight.

The other insulation material selected for preventing the heat from conducting with outer wall of the stove is glass wool for its property of less weight and low thermal conductivity. The necessity of this insulation includes the safety for kitchen workers.

Table 4.2 Thermal conductivity of selected insulation material

Materials	Thermal conductivity (W/m k)	Condition of Temperature
Calcium silicate	0.0462	At room temperature
Rock wool	0.042	“
Fiber glass	0.05	“
Clay	0.13 – 0.30	“
Ash	0.14	“
Sawdust	0.08	“
sand	0.15 – 0.25	“
Asbestos loosely packed	0.15	“
glass wool insulation	0.04	“

Specific heat capacity: is one of the important parameters for determining the insulation property. Specific heat capacity of a material is the amount of heat required to raise the temperature of one kilogram of a material by one degree Celsius. The principal heat capacities of a material are those at constant volume and constant pressure.

Thermal diffusivity α,: is the parameter which determines the temperature distribution in non-steady state or transient conditions. Thermal diffusivity measures the ability of a material to transmit a thermal disturbance. It indicates how quickly a material's temperature will change.

Like thermal conductivity, specific heat capacity and thermal diffusivity are functions of temperature, porosity, density and particle sizes.

4.3 Design Specification

After the material was selected for each component of the stove according to their temperature resistance required. The next step were specifying dimensions for each components from already existing size stove (60 liter and 100 liter). The method I used were equating the ratio of volume increment from 60 liter to 100 liter, from 100 liter to 200 liter with size increment ratio as well. Multiplying the original size by increment factor (IF) obtained, then add to the original size itself in order to get the new dimension.

$$Volume\ \ incre\left(\frac{60\ L\ to\ 100\ L}{100\ L\ to\ 200L}\right) = Size\ incre\left(\frac{60\ L\ to\ 100\ L}{100\ L\ to\ 200L}\right)$$

100/60 = 1.667 (the volume increment factor is 0.667 or 66.7% for 60 liter to 100 liter size)

200/100 =2 (the volume increment factor is 1 or 100% for 100 liter to 200 liter size)

Similar technique was applied for every size of a components, then equating as follow.

0.667/1 = x/z where: x, z is size increment of 60L to 100L and 100L to 200L respectively.

(Original size * IF) + Original size = new dimension

The main improvements incorporated were scale up to 200 liters, introducing secondary air and ash removing technique. There are two pipes with 50 cm diameter from outside in opposite direction at the neck of combustion chamber and 10 holes with 10cm diameter on the inner most combustion chamber. The air directly entered into the stove using two pipes and circulates on the circumference of the inner most combustion chamber before entering to the flame zone. This has two advantages; first, the entered air will heated before reaching the combustion cylinder. Second, it is distributed on the circumference of combustion cylinder.

200 liter vessel has large diameter that require propagation of flame under the bottom of the vessel, so, introducing secondary air is necessary. Secondary air is not only for producing flame turbulence but also for complete combustion that reduces the formation of carbon monoxide.

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

Figure 4.1. a) Inner combustion chamber, b) combined chamber, c) assembly with insulation holder, d) Assembled body

Table 4.3 components of the stove

S.N	Main components	Dimensions, cm
1	inner chamber diameter	23
2	outer chamber diameter	74
3	chamber height	44
4	inner insulation thickness (between two chamber)	20
5	pot diameter	80
6	pot holder (skirt) diameter	84
7	pot holder height	32
8	outer insulation thickness	5
9	stove height	80
10	chimney height	150
11	chimney diameter	17

4.4 Types of Testing

There are two types of testing that are important when designing and attempting to build a user base stove: *laboratory testing* and *field testing*. Although the majority of this report concerned field testing, it is important to understand the major differences between the two types of testing and the useful contexts of each testing.

4.4.1 Laboratory Testing

Laboratory testing is a tightly controlled process that is intended to provide repeatable, reproducible results (Regional Wood Energy Development Program, 1993). The main characteristics that are tested in the laboratory are safety, durability, and physical performance characteristics such as combustion quality, emissions, heat transfer, power range, and thermal efficiency. In developing country such as Ethiopia laboratory testing is focus on physical performance characteristics in which nearly all tests involve heating water as this process can often be used to simulate an actual cooking task and also provides a convenient means to measure the "useful output" of the stove.

The laboratory testing by itself is unsuitable for verifying real-world performance outcomes. Real users do not use stoves in a tightly-controlled, repeatable, reproducible way, and this influence cannot be ignored when attempting to verify whether a certain stove design has reduced actual fuel use or has led to lower emissions in the home.

4.4.2 Field Testing

Field testing is loosely testing that takes place with actual users, in their environment. It is the Study of actual fuel use, emissions concentrations in users' homes/environment and studies of user attitudes toward a stove. Rather than lab testing, field test is the proper way to verify a performance outcome such as reduced fuel use or emissions, since it is not tightly controlled as lab testing because they rely on monitoring actual use rather than the idealized use required by a strict laboratory procedure.

4.5 Experimental Methods

Experimental testing is a systematic approach to the evaluation of the useful and adverse characteristics of a particular model. It is helpful for comparing different models from the end-use point of view. Testing also helps in gaining in-depth knowledge about the performance of the individual components which is useful for undertaking further design modifications or incorporating other design features.

The experiment was done using water boiling test, to assess stove performance, heat leaked from the circumference of the stove and raise of temperature under bottom of the vessel as well from the grate.

The Water Boiling Test (WBT) is a relatively short, simple simulation of common cooking procedures and it is a useful tool for approximation of the cooking process. The total testing period is divided into two parts, namely, the high power phase (heating or cooking period) and the low power phase (simmering period). In this test only high power phase was done, because during high power phase, the performance of stove is evaluated by estimating the thermal efficiency, the specific standard consumption and the power output of the fire. The low power phase (simmering) is for actual cooking of food that lasts for the next 45 minute after boiling.

4.5.1 Objective of Experiment

- To asses overall performance of the stove
- To compare the efficiency of stoves with (traditional and improved stove)
- To analyze the influence of different parameters of the stove-pot-system on wood consumption
- To measure the stove's quality of heat transfer
- To measure the heat loss through different part of the stove

4.5.2 Experiment Setup

The thermal efficiency of the stove depends on the number of factors:

Environmental conditions - Air temperature, water temperature, wind velocity, atmospheric pressure, relative humidity and the kitchen environment.

Operating Conditions - The feeding and burning rates, the flame temperature, the mass of water load, the accuracy of measuring instruments and the age of the cook stove (as the material may become degraded with use).

In institutional stove, the vessel is inserted in to the stove, it cannot totally affected by environmental conditions like wind velocity. The combustion is occurred inside the stove and the outer part is insulated. As mentioned under objective of this section, this experiment was done to investigate heat leakage through the circumference of the stove, in chimney and how fire propagates under the vessel. The Figure 4.2 shows the configuration of temperature measuring technique using thermocouple in different positions of the stove. Positions 1-4 were from the circumference of the stove, position 5 and position 6 were in chimney (at the bottom and at the outlet), position 7 and position 8 were under the bottom of the vessel and position 9 was from the grate. The rise of temperature of water in the vessel was measured by thermometer parallel with thermocouple.

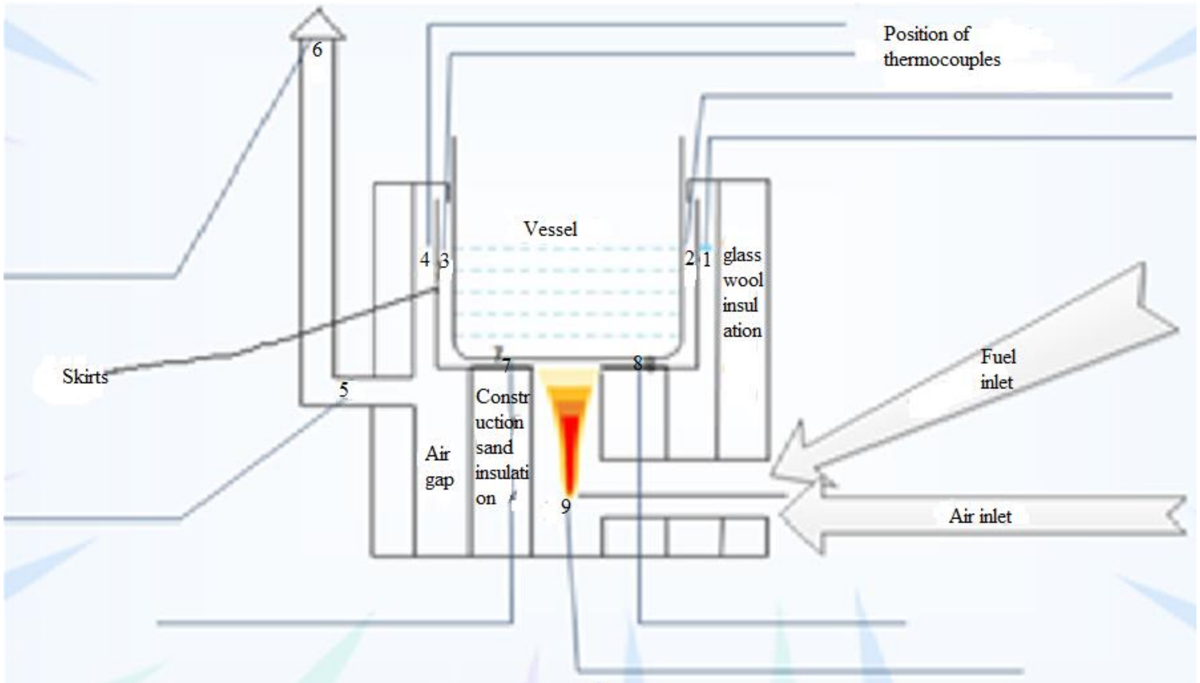


Fig. 4.2 experiment setup

4.5.3 Experiment Procedure

During experiment work, different equipment were used i.e. 200 liter size vessel, thermocouple, thermometer, Multimeter, digital thermo and hygrometer, fuel wood, digital weight measuring device and stop watch.

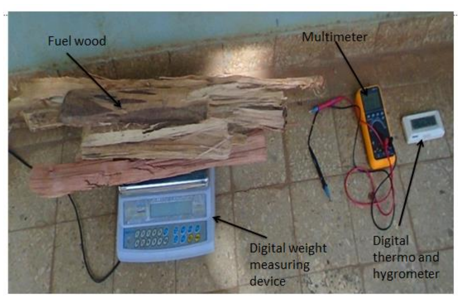


Figure 4.3 measuring devices

The procedures followed were:

- Prepare fuel wood of appropriate size and measure its mass
- Kerosene, not more than 10ml (for ignition purpose)
- Wait for 3-4 minute after ignition
- Insert the vessel into the stove
- Prepare clean water (make sure that 200 liters of water were added to the vessel)

- Record ambient temperature, environmental humidity and initial water temperature
- At the regular interval of time record the data continuously up to local boiling point of water
- When water is boiled, immediately remove the fuel wood and char left, and cover with pan in order to stop further combustion.
- Measure the weight of wood and char left

Stove tests are often conducted with lidded pots to reduce the effect of drafts on evaporation rate from the pot. However, if the testing site is properly protected from drafts (not totally exposed to outside environment), lids can be left off.

With small vessel, often the vessel and its contents can be weighted together, and the weight of the empty stove subtracted later. However, in the case of InStove testing it is difficult to measure the vessel with filled water, so separate measurement is recommended and converts the liter of water to its equivalent mass.

"High power" and "low power" tests may be conducted separately. Low power test can last for next 45 after boiling with 5℃ less than the local boiling point of water, and all measurements are recorded. The weight of the fuel used during the "high power" phase is subtracted from the total amount used in the "low power" phase.

It is important to know how to interpret the results of the WBT, and to remember that a low Specific Fuel Consumption (SFC) indicates a high efficiency. As efficiency declines, SFC rises.

4.5.4 Experiment Result

The water boiling test done intended to measure the thermal efficiency, specific fuel consumption, time-to-boil, fuel consumption, fuel burn rate, and fire power.

During the test two cases were taken; in the first case, the stove has inner insulation on the surface of combustion chamber. The insulation material was construction sand and it has a thickness of 20 cm over the cylinder of combustion chamber.

In the second case, the insulation material was removed from the stove and test was conducted. In this case I am not assuming that the space where the sand removed was vacuum, it may occupy by air and I expected there was an insulation material that was atmospheric air.

There is slight difference between two cases, but both of them have their own merit and demerits. In the first case starting time was slightly longer but retains heat for a long time after boiling that is advantages for simmering of food/wot. In the second case, I observed fast starting time and high thermal efficiency but it require continues feeding up to the time of pot removing.

The local boiling temperature of water depends on atmospheric pressure, which is mainly a function of altitude above sea level. At an altitude (*H*) the normal boiling temperature can be computed from: (H = 1676m, for Jimma)

$Tb = (100 – H / 300)$ [°C] ---4.1

$Tb = (100 - \frac{1676}{300}) = 94.5°C$ (local boiling point)

Figure 4.4 InStove during operation

The inner insulation material used has high thermal conductivity, due to this reason the test shows slight different result with and without inner insulation. The time taken to boil 200 liter of water shown in the figure 4.5 below.

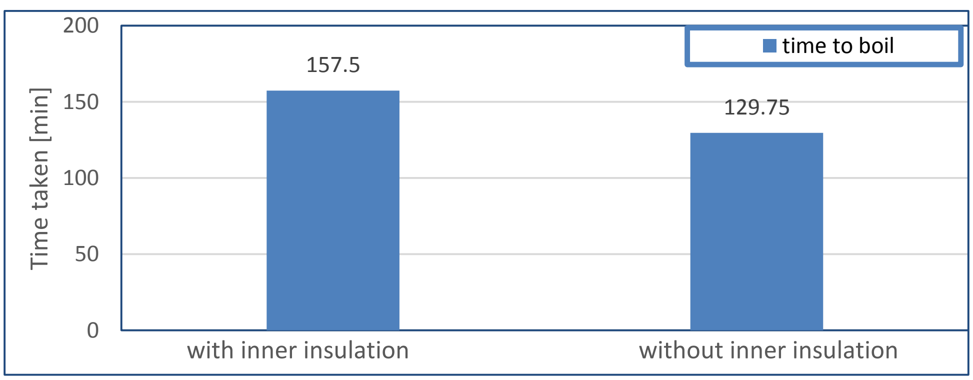


Figure 4.5 Comparison of time to boil with and without inner insulation

fcd –The equivalent dry fuel consumed: It 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.

f_{cd} = dry fuel - fuel to evaporate water minus fuel in char

$f_{cd} = f_{cm}(1 - Mc) - \frac{fcm\ Mc(4.186(Tb-Ta))+2,257}{LHV} - \frac{\Delta Cc\ LHVchar}{LHV}$ --4.2

$f_{cd} = \frac{Fcm\ (LHV(1-Mc)-Mc(4.186(Tb-Ta))+2,257-\Delta ci\ LHVchar}{LHV}$ ---4.3

h_c– Thermal efficiency: is a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot. The remaining energy is lost to the environment.

$h_c = \frac{\Delta E_{H20,heat} + \Delta E_{H20,evap}}{E_{released,c}}$ ---4.4

The energy to heat the water is the mass of water multiplied by specific heat capacity and change in temperature.

$\Delta E_{H20,heat} = m_{H20}\ cp\ .\Delta T$ --4.5

The energy to evaporate the water is the mass of water evaporated multiplied by the specified enthalpy of vaporization of water.($\Delta h_{H_2}O$,f g = 2260 kj/kg)

$\Delta E_{H20,evap} = Wcv.\Delta h_{H20,fg}$ ---4.6

The energy consumed multiplied by the heating value

$E_{released,c} = f_{cd}.LHV$ --4.7

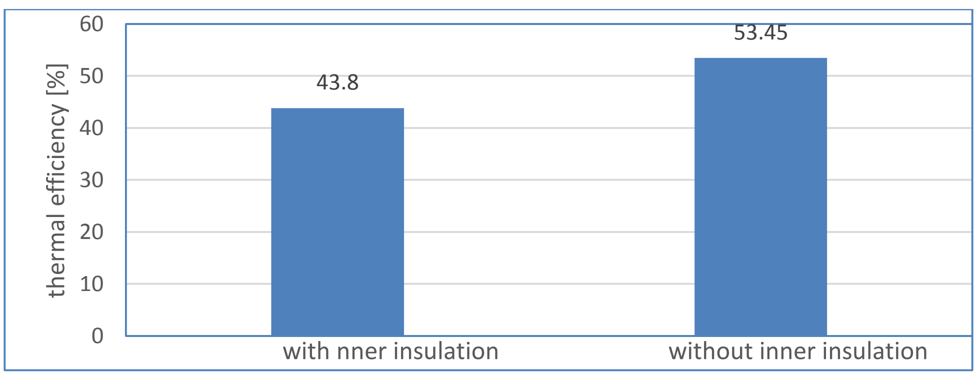


Figure 4.6 comparison of thermal efficiency of InStove with and without inner insulation

r_{cb} – Burning rate; is the measure of rate of fuel consumption while bringing water to a boil

$r_{cb} = \frac{weight\ of\ fuel\ consumed}{time}$ (gm/min) ---4.8

SCcold – specific fuel consumption: The fuel required to product a unit output in the case of cold start high – power WBT, it is a measure of the amount of wood required to produce one liter (or kilo) of boiling water starting with cold stove.

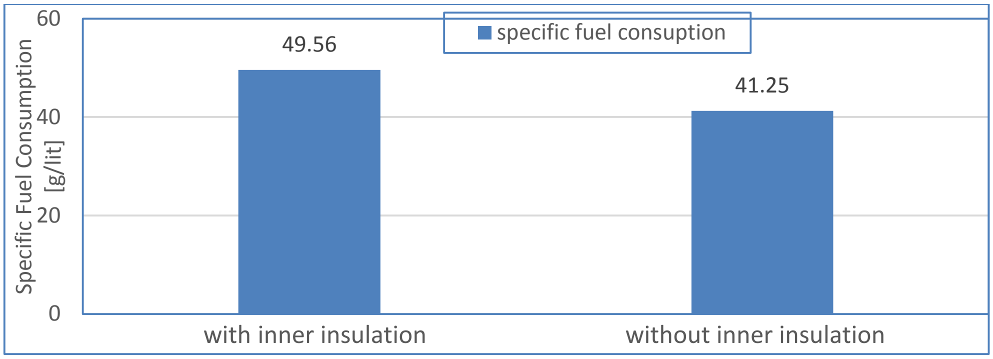


Figure 4.7 comparison of specific fuel consumption with and without insulation

SCc = Temperature corrected specific fuel consumption

$Sc^{T}c = S_{Cc} * \frac{75}{T_{1cf} - T_{1ci}}$ --4.9

$SE^{T}c$ – temperature corrected specific energy consumption: similar to the temperature corrected specific fuel consumption, this metric is a measure of the amount of fuel energy required to produce one liter (kilo) of boiling water starting with cold stove.

$SE^{T}c = Sc^{T}c * \frac{LHV}{1000}$ --4.10

FPc – fire power: 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 watt) during the high power test.

$FPc = \frac{f_{cd} * LHV}{\Delta t_{c} * 60}$ --4.11

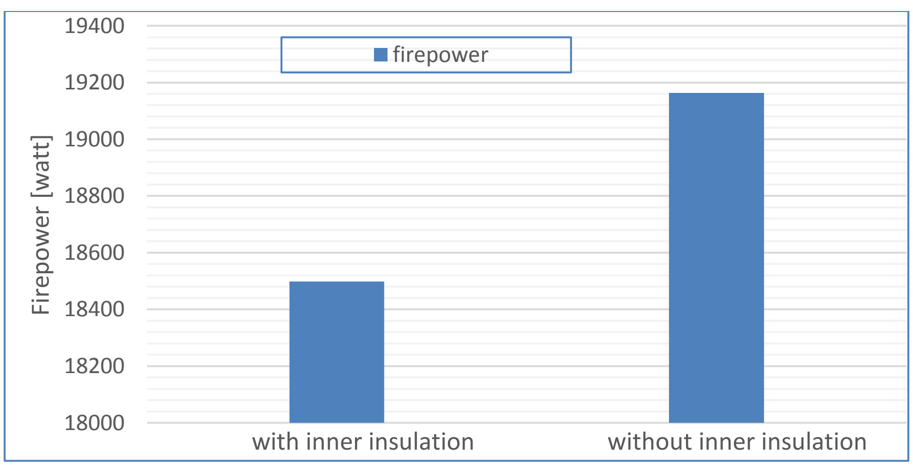


Figure 4.8 comparison of firepower with and without inner insulation

There are a number of ways for looking at stove performance and measuring stove efficiency. A widely used method compares energy that goes into the stove with the energy that comes out, to determine Percentage of Heat Utilized (PHU). A broader concept of efficiency accounts for energy losses in evaporation. Once food reaches the boiling point, the amount of additional heat it absorbs is relatively small.

In WBT the pot requires only enough heat to maintain boiling temperatures all else is excess. This excess heat is used to generate steam, which escapes from the pot without adding anything to the cooked food.

According to (Harker,A.P.,A.Sandels,et al.(1982) and FAO (1993)) the standard heating value tree species were recommended for Eucalyptus Deglupta (Rainbow Gum Tree). During calculation with the standard WBT protocol, I took as initial test condition.

- The standard Water Boiling Test- Version 4.2.2
- Stove type – Institutional stove
- wind condition = Moderate
- Ambient temperature = 25 ℃
- Fuel type: Eucalyptus tree
- Local boiling point of water = 95 ℃
- Gross calorific value (dry fuel) = 18,700 kj/kg (HHV)
- Net calorific value (dry fuel) = 17,380 kj/kg (LHV)
- Effective calorific value (accounting for fuel moisture) = 14,190 EHV
- Char calorific value = 29,500 kj/kg

Table 4.4 Summary of WBT Result

Test phases	unit	With inner insulation	Without inner insulation
1.HIGH POWER TEST (COLD START)	units	Average	Average
Time to boil	min	183	135.5
Temp. corrected time to boil	min	181.3	133.71
Fuel consumed (moist)	kg	12.629	11.20
Equivalent dry fuel consumed	kg	11.00	8.126
Burning rate	g/min	51.92	62.57
Thermal efficiency	%	47	53.6
Specific fuel consumption	g/lit	48.35	41.25
Temp. corrected specific cons.	g/lit	47.9	40.71
Temp. corrected specific energy cons.	Kj/lit	832.5	707.58
Firepower	watts	15040	18416
2.HIGH POWER TEST (HOT START)			
Time to boil	min	132	124
Temp. corrected time to boil	min	130.76	123.40
Fuel consumed (moist)	kg	10.20	11.00
Equivalent dry fuel consumed	kg	8.874	7.963
Burning rate	g/min	75.80	68.74
Thermal efficiency	%	40.6	53.3
Specific fuel consumption	g/lit	50.77	41.25
Temp. corrected specific cons.	g/lit	50.3	40.98
Temp. corrected specific energy cons.	Kj/lit	874	712
Firepower	watts	21956.8	19911

4.5.4.1 Energy Losses

The test was not only investigating WBT, but also includes estimation of heat loss/leak through different part of the stove and in smoke (in chimney) using thermocouple.

In a wood-burning cook stove, useful heat is absorbed in the food, but heat losses are associated with the different mechanisms. The detail heat losses associated with wood burning cook stove were listed in the figure 4.9 below.

1) Evaporation
2) Distance From Fuel to Pot
3) Convective Loss from Wind
4) Unburned Volatile Gases and carbon dioxide
5) Radiation from Pot
6) Poor Seal at Pot/Stove Interface
7) Cool Combustion Air or Fuel
8) Radiation From Stove
9) Conduction Through Stove
10) Wet Wood
11) Radiation from chimney
12) Pot Contents

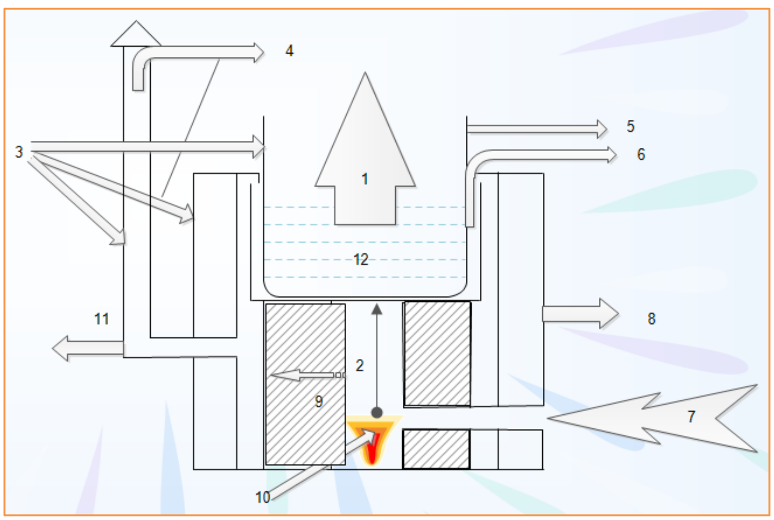


Figure 4.9 heat loss parameters

All the heat loss mechanism listed on the figure 4.9 were not conducted under this work. Referring to the section 4.5.2 (experimental setup) the average heat loss investigated were described in the following table.

Table 4.5 comparison of temperature leakage through the circumference of the stove

	Average Temp.	circumference of the stove				chimney		bottom of the vessel,7
		1	2	3	4	base, 5	surface, 6	
With inner insulation	T_{ave}	84.2	94.6	194	176	160	123.13	611
Without inner insulation	T_{ave}	107	153.25	151.9	169	196.1	117.08	-

Measuring of flame temperatures to a high degree of precision is quite difficult because of two reasons; (1) intrusiveness of instrumentation; and (2) interpretation difficulties due to the time-varying nature of the measurement.

Non-intrusive (e.g., optical laser techniques) methods are available, but these are difficult and expensive to make and are generally not applied to the study of building fires. In most cases, thermocouples are used for temperature measurement. These have a multitude of potential errors, including surface reactions, radiation, stem loss, etc. The temperatures are vastly higher than what any thermocouple inserted into a building fire will register. The temperature recorded from bottom of the vessel was shown in figure 4.10.

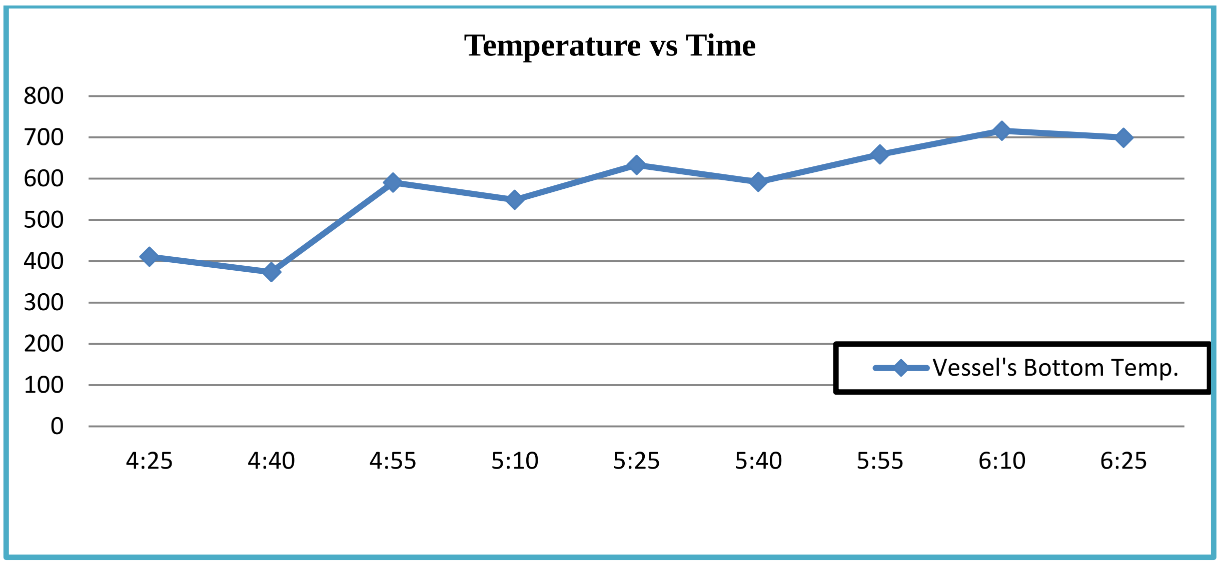


Figure 4.10 steady state temperature at the bottom of the vessel

The surface loss temperature was taken from some positions of the stove, as described in the table 4.6. Little bit high temperature is recorded from the fuel inlet side and on the surface of chimney, but the other surfaces of the stove were almost the same with the ambient temperature.

Table 4.6 average surface temperature

variable	position					RH	$T_{amb.}$	Description
	01	02	03	04	05			
T_{avg}	37	28	51	30	41	43.5	25	with inner insulation
T_{avg}	42	31	57	34	50	47	23	without inner insulation

Key: 01 – *wood inlet side, 02 – opposite of wood inlet side, 03 – opposite of chimney side, 04 – chimney base, 05 – surface of chimney*

4.6 Factors Affecting Stove Performance during Testing

Stove performance can be affected by many factors, among that the climatic condition is the most important factor: air temperature, wind conditions, relative humidity, altitude and moisture content of wood.

- Air temperature affects the rate of heat loss from stove and pot. It also establishes initial water temperature in the Water Boiling Test. Ideally, air temperature measurements should be taken before and after each test so that a mean value can be estimated.
- Wind conditions affect the stove's draft and can have considerable influence on stove performance. Ideally, stove testing should be done only when conditions are calm. Where this is not possible, a windbreak should be erected around the stove to reduce air movement and convective heat losses.
- Relative humidity (RH) provides one indication of the moisture content of air-dried fuel. It is a simple and useful condition to measure during stove testing. Keep digital humidity measuring device 5m away from the stove and record the data with interval of time provided

4.7 Factors Limiting To High Temperature

There are a number of factors that rob the heat from the fire and results lowers combustion temperature, decrease efficiency and increase smoke. These factors are; Cold stove body/cold earth, Cool wood, Cool air/too much air, Cool cooking pot.

The solution implemented for the challenges of limiting factors are:

- Low mass, heat resistant materials in order to keep the fire as hot as possible
- Effective stove insulators pumice, vermiculite and wood ash
- Dense things such as earth, sand, cement, water and cast iron are poor insulators.
- Use small sticks whenever possible
- Maximize the surface area of the wood exposed to coals
- Heat only the fuel that is burning
- Burn the tip of the sticks only as they enter the combustion chamber
- Don’t allow too much or too little air to enter the combustion chamber

4.8 Power and Energy Determination

The equation for overall stove efficiency can be expressed in more detail as:

$\eta_{stove} = \frac{\text{(mass of cooked food)} * C_{pf} * \Delta T}{\text{(mass of consumed dry wood)} * \text{heating value}} = \frac{Q_w}{Q_{wood}}$ --4.12

The heat absorbed in cooked food (in the WBT test the heat absorbed in the water, Q_w) can be calculated with the following equation:

$Q_w = C_w * m_{WB} * (\vartheta_B - \vartheta_S) + m_{evap} * h_{evap}$ --4.13

Where C_w (4.18kj/kg * k) is the specific heat capacity of water, m_{WB} is the amount of water after boiling, ϑ_B is the temperature of the boiling water, ϑ_S is the temperature of the water at the Beginning(starting), m_{evap} is the amount of evaporated water and h_{evap} (2260kj/kg) is the evaporation enthalpy of the water.

The energy potential in the fuel wood can be expressed by the following equation.

$Q_w = m_{drywood} * LHV$ ---4.14

Where $m_{drywood}$ is the mass of consumed dry wood and LHV is heating value of the consumed dry wood(19MJ/Kg GTZ recommendation).

The average power of the stove $\dot{Q}_{\text{stove}}$ as the firepower of the stove can be expressed by:

$\dot{Q}_{\text{stove}} = \frac{Q_{wood}}{\Delta T}$ --4.15

The average cooking power $\dot{Q}_{\text{cook}}$ as the transferred heating power to the water can be expreesed by:

$\dot{Q}_{\text{cook}} = \eta_{cook} * \dot{Q}_{\text{stove}}$ ---4.16

$\dot{Q}_{\text{cook}} = \frac{Q_w}{\Delta T}$ ---4.17

Where ΔT is the time to reach the boiling temperature in the water.

CHAPTER FIVE

SIMULATION RESULT VALIDATION

5.1 Introduction

In today world, CFD models are well established tools that help in design, prototyping, testing and analysis. The motivation for development of modeling methods (not only CFD) is to reduce cost and time of product development, and to improve efficiency and safety of existing products and installations.

It is important to note that analytical methods will continue to be used by many, especially for simple fluid flow problems, and experimental methods will feature significantly for prototype testing as well as for the validation of CFD models. Hence, we still require analytical and experimental methods to complement the CFD analytical tool in some specific investigative studies and analyses. For most flow problems, there are, however, numerous advantages in applying CFD over analytical and experimental methods.

Verification and validation for modeling approaches by comparing computed results with experimental data is necessary.

5.2 Objective of Simulation

- First and foremost, the cost-effectiveness of carrying out multiple parametric studies with greater accuracy allows the construction of new and more improved system designs and concerted optimization carried out on existing equipment with substantial reduction of lead times, which results in enhanced efficiency and lower operating costs.
- Secondly, the primary objective is to gain an increased knowledge of how systems are expected to perform, so evolutionary improvements during the design and optimization process can be made. Based on this second point, CFD therefore continually asks the question “What if . . . ?” in all investigative studies and analyses.

5.3 Model Description

The 3D model shown in Figure 5.1, describes half of the geometry with a symmetry plane to reduce the computational domain and the corresponding boundary conditions. The wood volatile mixed with atmospheric air is considered here.

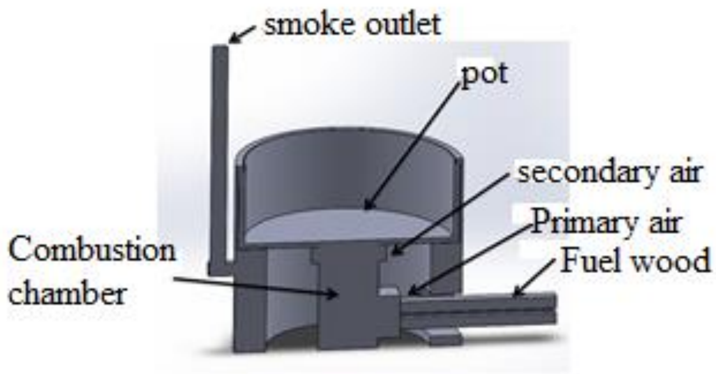


Figure 5.1 model description

A balance between primary and secondary air is needed to control the combustion so that there is sufficient air to produce complete burning of the volatile gases and good mixing between air and the pyrolysis gases. In this work, comparison between simulation results and experimental result obtained shows related value.

This study can reasonably confirm that most features for better wood stove performance under different operating conditions can be identified accurately by this CFD model. Future work will focus on using this model to investigate possible improvements for the design of a better air delivery system to reduce emissions.

Assumptions of the proposed model

- ✓ The viscous dissipation is negligible
- ✓ Pressure - based, double precision and absolute velocity formulation.
- ✓ The flow will be Turbulent and standard K & ε models were used.
- ✓ Eddy dissipation model was selected
- ✓ Process assumed to be Steady state.
- ✓ Cmu =0.09,c1-Epsilon = 1.44, c2-Epsilon = 1.92 and TKE Prandtl number = 1 ,were taken as default model constant.

The air can be assumed to enter into the combustor in radial direction and stagnation pressure were taken equal to the ambient pressure. The temperature at port can be taken as the ambient temperature and air will flow due to free convection.

Governing Equations for Reactions during Combustion

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

5.3.1The Mass Conservation Equation

The equation for conservation of mass, or continuity equation, can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho\vec{v}) = 0 \quad \text{----------} 5.1$$

For an incompressible fluid, this reduces to; $\nabla.\vec{v} = 0$

5.3.2Momentum Equations

Transport of momentum in i th direction in an inertia (non-accelerating) flows.

$$\frac{\partial \rho}{\partial t}(\rho\vec{v}) + \nabla.(\rho\vec{v}\vec{v}) + \Delta p = \Delta.(\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \quad \text{----------} 5.2$$

Where p is the static pressure, $(\bar{\bar{\tau}})$ is the stress tensor and $\rho\vec{g}$ is the gravitational body force, $\vec{F}$ - contains other source terms that may arise from resistance, sources, etc.

The stress tensor $(\bar{\bar{\tau}})$is given by:

$$(\bar{\bar{\tau}}) = -\frac{2}{3}\mu\frac{\partial u_i}{\partial x_i} + \mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}) \quad \text{----------} 5.3$$

$$\sigma_{ij} = \tau_{ij} - p\delta_{ij} \quad \text{----------} 5.4$$

Total stress tensor (1 if i=j; o if i$\neq j$)

5.3.3 Species Transport Equations (y_k)

$$\frac{\partial}{\partial t}(y_k) + \nabla(\rho(u + v_k)y_k) = \dot{\omega}_k \quad \text{----------} 5.5$$

$\dot{\omega}_k$ - Reaction term for k and v_k - diffusion term for k $\sum_{k=1}^{n}\dot{\omega}_k = 0$ and $\sum_{k=1}^{n} v_k y_k = 0$

Sum all species equation:

$$\frac{\partial}{\partial t}(\rho y_k) + \nabla\left(\rho(u\sum_{k=1}^{n} y_k) + \rho(\sum_{k=1}^{n} v_k y_k)\right) = \sum_{k=1}^{n}\dot{\omega}_k$$

$\frac{\partial}{\partial t}\rho + \nabla(\rho\mu) = 0$ ---5.6

To solve conservation equations for species, '*Airpak*' predicts the local mass fraction of each species, *Yi*, through the solution of a convection-diffusion equation for the *i*th species. This conservation equation takes the following general form:

$\frac{\partial}{\partial t}(\rho \mathrm{y_i}) + \nabla.(\rho u \mathrm{y_i}) = -\nabla.J_i + S_i$ ---5.7

Where, *Si* is the rate of creation by adding from user-defined sources. An equation of this form will be solved for *N* −1 species where *N* is the total number of fluid phase species present in the system.

5.3.4 Energy Conservation Equation

The energy equation for a fluid region can be written in terms of sensible enthalpy;

$\mathrm{h}=\int_{T_{ref}}^{T} c_p dT$ ---5.8

(Where T_{ref} is 298.15 k) as

$\frac{\partial}{\partial t}(\rho h) + \nabla.(\rho h v) = \nabla.[(k + k_t)\nabla T] + S_h$ --5.9

5.3.5 General Equation of Combustion

Combining all the governing equation and simplifying the following equation is obtained.

$\rho c_p \frac{DT}{Dt} = \frac{\partial}{\partial x_i}\left(\lambda \frac{\partial T}{\partial x_i}\right) + \frac{DP}{Dt} + \tau_{ij}\frac{\partial u_i}{\partial x_j} - \frac{\partial T}{\partial x_i}\rho \sum_{k=1}^{n} v_k y_k c_p + \dot{w}_T'$ ----------------------------5.10

Heat Diffusion	pressure increase	power of viscous stress	comes from diffusion velocity	heat released

Where: $\dot{w}_T' = -\sum(\Delta H f'_k + h_{jk})\dot{w}_k$

5.4 Boundary Condition for Simulation

The combustion was modeled using a global one step reaction mechanism, assuming complete conversion of the fuel to CO_2 and H_2O. The species in the volatile gases are represented by the time mean mass fractions of CO2, CO, H2O, H2, light hydrocarbons, and heavy hydrocarbons.

Wood-volatiles + air $\longrightarrow$ CO_2 +H_2O

This reaction was defined in terms of stoichiometric coefficients, formation enthalpies, and parameters that control the reaction rate. The reaction rate was determined assuming that turbulent mixing is the rate-limiting process; with the turbulence-chemistry interaction modeled using the eddy-dissipation model.

5.5 Geometry and Grid

The computational domain of the 3D geometry used in this study includes unstructured grid of different mesh size and different cases for the purpose of verifying the necessity of secondary air.

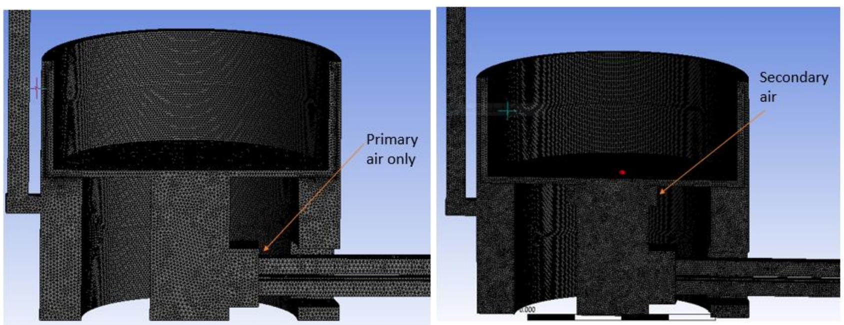


Fig. 5.2 model symmetry

5.7 Mesh Sensitivity of Simulation

Different Mesh sizes were studied in order to insure independency of mesh sensitivity of CFD numerical solution. “Bulk” none mesh element size is varied first and the mesh element count is also included to note increasing computational cost. Different mesh sizes were conducted with the element size of 8, 6, and 4 millimeters.

Table 5.1 model boundary condition

Models	Element size	Boundary Condition	No nodes	No elements
case 1	8	Supply only primary air	160,783	728,162
	6	“	211,594	982,044
	4	“	458,175	2,205,060
case 2	8	75% primary air and 25% secondary air	160,783	728,162
	6	“	211,594	982,044
	4	“	458,175	2,205,060
case 3	8	60% primary air and 40% secondary air	160,783	728,162
	6	“	211,594	982,044
	4	“	458,175	2,205,060
case 4	8	50% primary air and 50% secondary air	160,783	728,162
	6	“	211,594	982,044
	4	“	458,175	2,205,060

5.6 Validation Cases

The validation study was to simulate two operating conditions: in the first case, 200 liter stove was supplied with primary air only through the bottom of the grate. In the Second case, simulating the same size of stove by introducing secondary air around the neck of the combustion chamber in addition to primary air. In both cases thermal load and temperature distribution were compared.

Case one: simulation result for different mesh size.

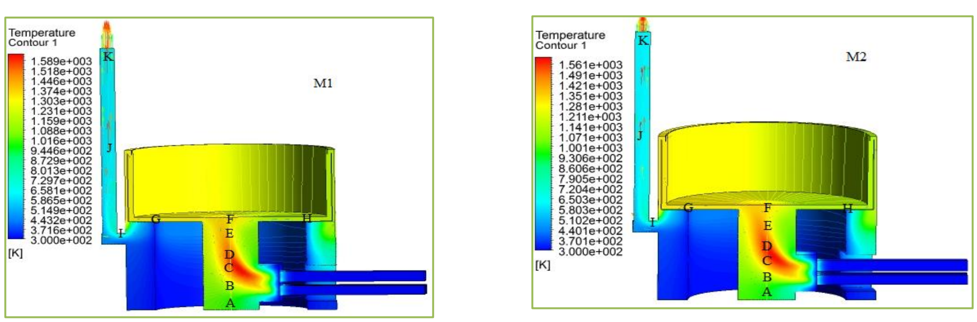


Figure 5.3 simulation result for supplying primary air only

Table 5.2 Temperature of different position inside a combustion chamber for case one

Description		A	B	C	D	E	F	G	H	I	J	K
Tem.(k)	M_1	986	1171	1563	1538	1352	1334	1305	1169	608	610	610
	M_2	951	1141	1555	1544	1328	1322	1301	1148	613	611	612
	T_{ave}	968	1156	1559	1541	1340	1328	1303	1158	610	610	611

Case two: in this case, as a flame diffused in the combustion chamber, additional air supply is required in order to strength and insures turbulence of a flame. Keeping air fuel ratio constant, 75% of air as primary and 25% secondary air is supplied. The simulation results obtained were the following for different mesh size.

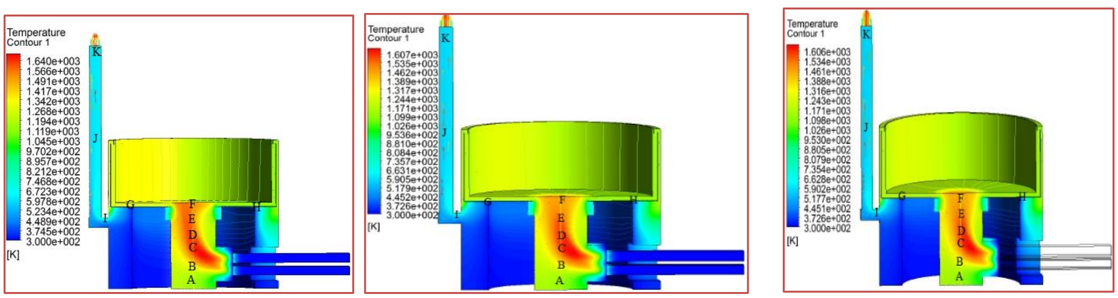


Figure 5.4 simulation result of supplying both primary and secondary air

The following table 5.3 show the value of the temperature at the labeled point by letter and the average value of each points.

Table 5.3 Temperature of different position inside a combustion chamber for case two

Description		A	B	C	D	E	F	G	H	I	J	K
Tem.(k)	M_1	1145	1330	1653	1617	1518	1540	1276	1122	598	601	602
	M_2	1115	1291	1602	1591	1512	1454	1190	1117	645	577	581
	M_3	1115	1288	1584	1587	1491	1438	1186	1125	590	576	579
	T_{ave}	1125	1303	1613	1598	1507	1477	1217	1121	611	584	587

From the CFD post contour result, it may difficult to judge which case is efficient model. But, using probe, it is possible to find the temperature at different points inside the combustion chamber. The following graph shows the comparison of thermal load for both cases.

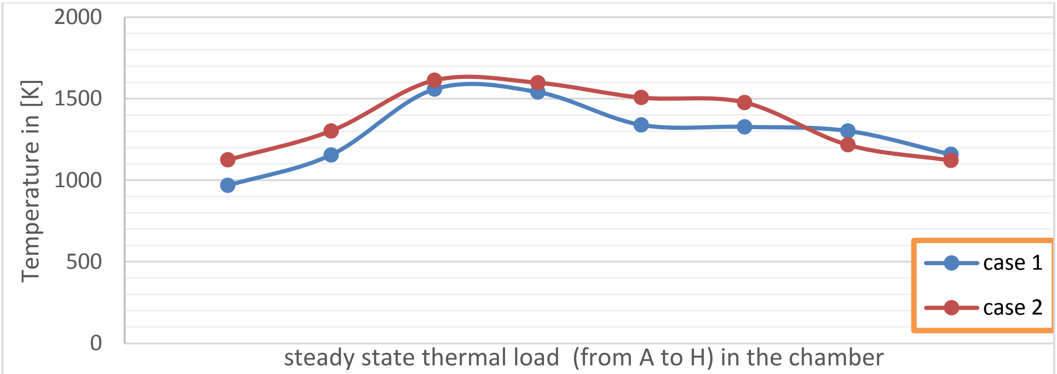


Figure 5.5 comparison of thermal load inside a combustion chamber

It is easily concluded that, case two has greater thermal load comparing to case one. Secondary air has great contribution in increasing flame turbulence in addition to this.

As far as the second case was selected, the other necessary validation goes to answer which ratio is appropriate in order to maximize thermal load among the secondary air.

Case three: allowing 60% through the primary air inlet and 40% through the secondary air hole. The CFD post contour result looks like the following.

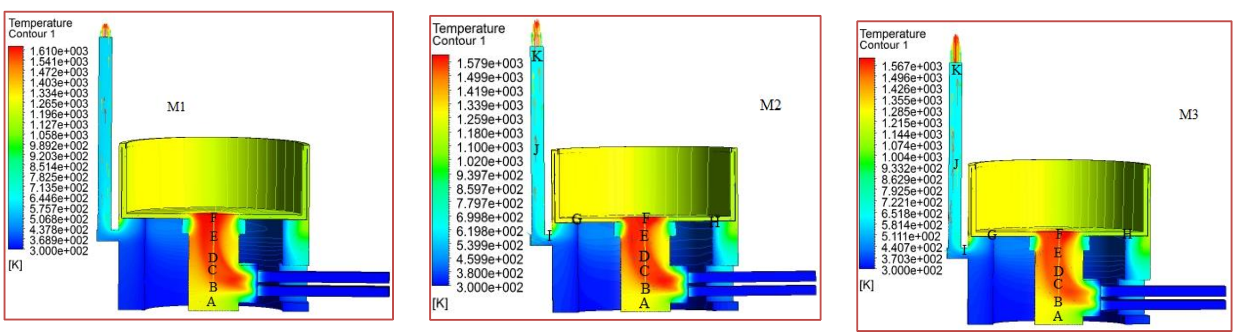


Figure 5.6 simulation results of different mesh size with secondary air (60%-40%)

For the sake of simplification, the following table 5.4 match the labeled position with corresponding probe reading and the average temperature of each point.

Table 5.4 Temperature distribution inside a combustion chamber (60%-40%)

Description		A	B	C	D	E	F	G	H	I	J	K
Tem.(k)	M_1	1251	1406	1543	1562	1600	1630	1237	1133	587	580	584
	M_2	1252	1415	1554	1561	1577	1608	1318	1128	608	610	610
	M_3	1201	1374	1520	1524	1551	1584	1276	1110	615	604	605
	T_{ave}	1234.6	1398	1539	1549	1576	1607	1277	1123.7	603	598	599.7

Case four: The last assumption was allowing equal amount of air in both primary as well as secondary hole. 50% primary air and 50% secondary air.

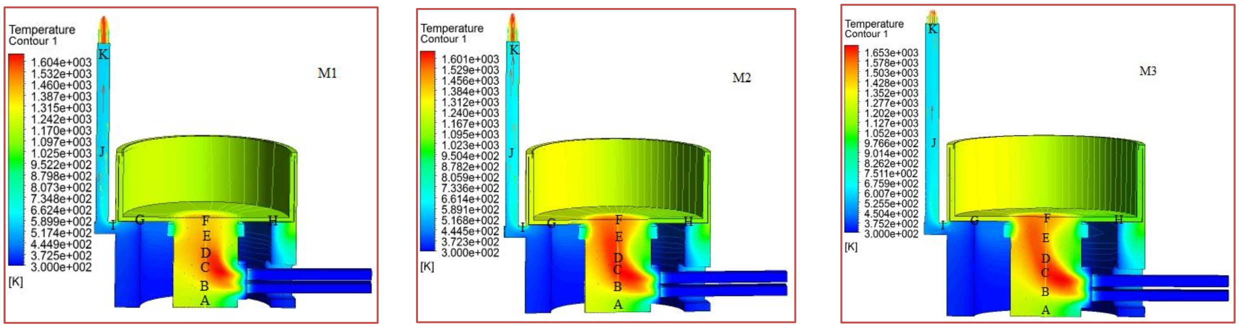


Figure 5.7 simulation results of different mesh size with secondary air (50%-50%)

Sometimes it is not easy to identify which point has highest value from CFD post contour result so, to avoid this confusion using probe the following table filled with the value which corresponding the labeled position. The table show the temperature at each point and the average of all them.

Table 5.5 Temperature distribution inside a combustion chamber (50%-50%)

Description		A	B	C	D	E	F	G	H	I	J	K
Tem.(k)	M_1	1161	1339	1534	1536	1420	1380	1173	1111	682	589	585
	M_2	1134	1395	1632	1588	1555	1514	1245	1076	698	627	617
	M_3	1163	1409	1654	1606	1493	1520	1274	1065	675	627	620
	T_{ave}	1152.7	1381	1606.7	1576	1489	1471	1230	1084	685	614	607

Among the secondary air again not easy to identify which model is efficient from CFD post contour only, but using probe it is visible to judge the case that has highest thermal load. In the next graph, it is clearly seen that the assumption with (60% - 40%) was show interesting feature with greatest thermal load.

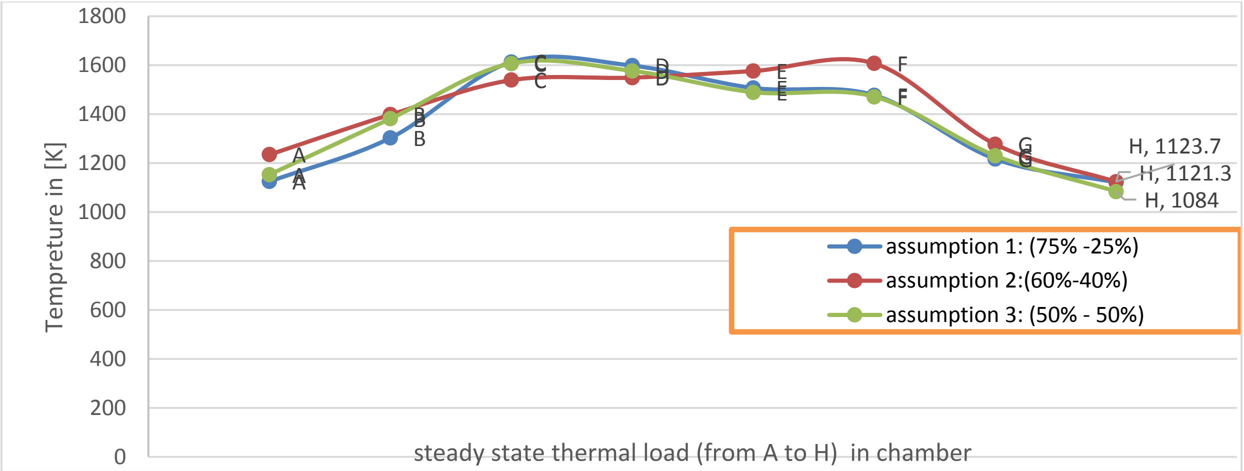


Figure 5.8 comparison of thermal load inside a chamber for secondary air assumption

One of the objective of this project is to create environment, free from extra hot to kitchen worker and reduce difficulty during operation. The following table shows chimney exit temperature for different percent of air supply.

Table 5. 6 comparison of chimney exit Temperature

parameter	Primary to secondary air ratio			
	primary, 100%	75% to 25%	60% to 40%	50% to 50%
Chimney exit Tem. [K]	611	587.3	599.7	607

In all cases wood volatile - air was selected from the ANSYS data base with the ratio of $1.26e^{-5}$ kg/s and $7.679e^{-3}$ m/s respectively.

The model were assumed under natural convection in which density difference is a driving force. The streamline velocity and velocity vector shown here.

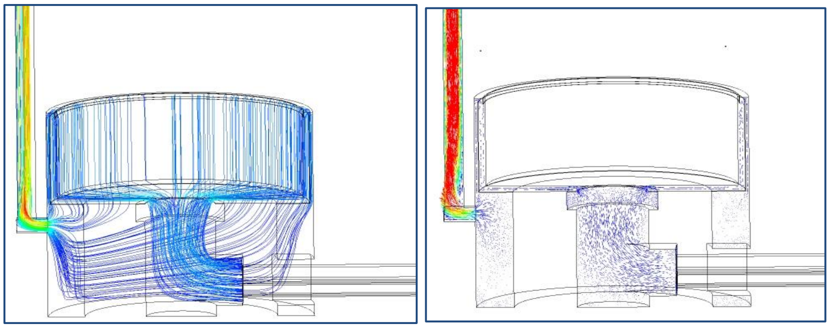


Figure 5.9 a) stream velocity b) velocity vector

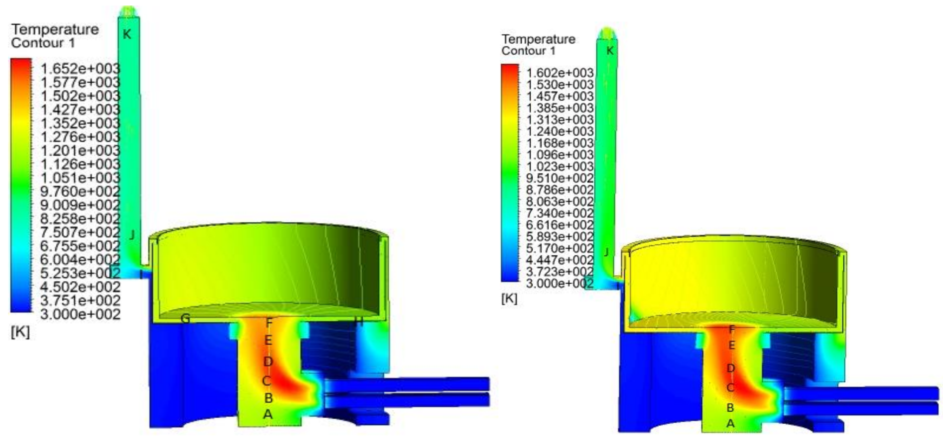


Figure 5.10 simulation results of different mesh size with secondary air and moving the chimney position up.

In this condition, high temperature zone was created from the side of the chimney and low temperature zone was read from opposite side. This condition make the cook stove not uniformly boil the water/food in all circumference at the same time. There were also high temperature recorded at the chimney exit (see column J and k) that leak with flue gas from the stove. This create extra hot to the environment and reduces the thermal efficiency of the stove. The following table shows probe reading for specified points.

Table 5.7 Temperature distribution for chimney position move up

Description		A	B	C	D	E	F	G	H	I	J	K
Temp.[K]	M1	1181	1538	1644	1632	1530	1482	1234	1120	515	920	861
	M2	1125	1516	1632	1599	1509	1561	1318	1156	407	993	915
	Tave	1153	1527	1638	1615	1519	1521	1276	1138	461	956	888

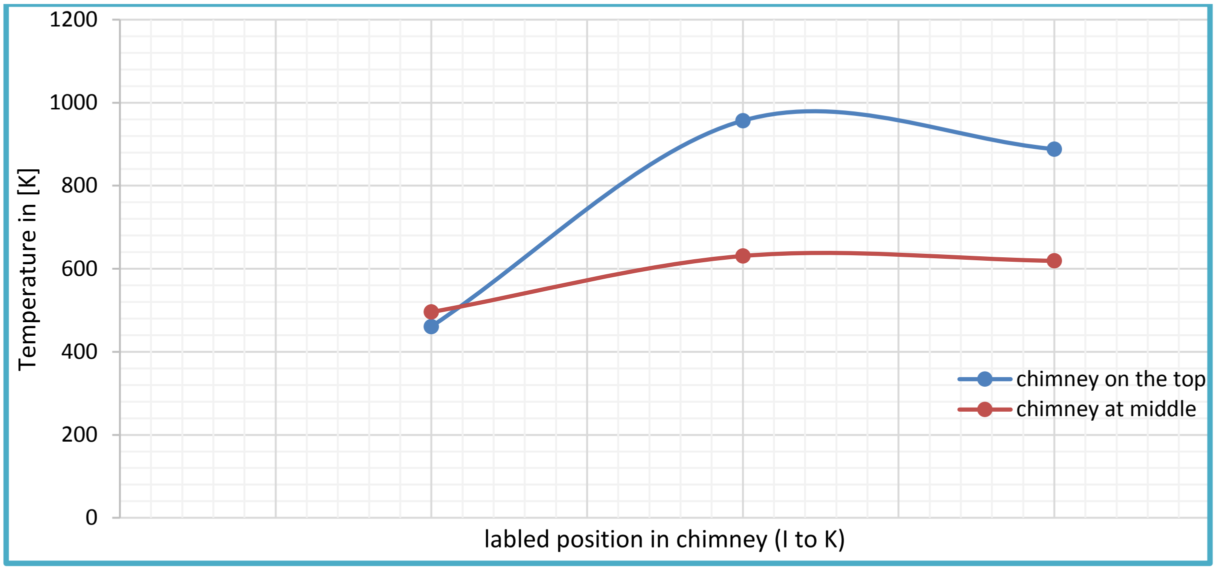


Figure 5.11 comparison of temperature inside a chimney (I to k)

Based on experimental observation and some suggestion from actual users those have long experience in kitchen working, some modification are necessary.to make these suggestion practical, I decide to increase the diameter of inner combustion chamber and move up the position of chimney. The CFD post contour result that ensure the assumption proposed were shown (figure 5.12).

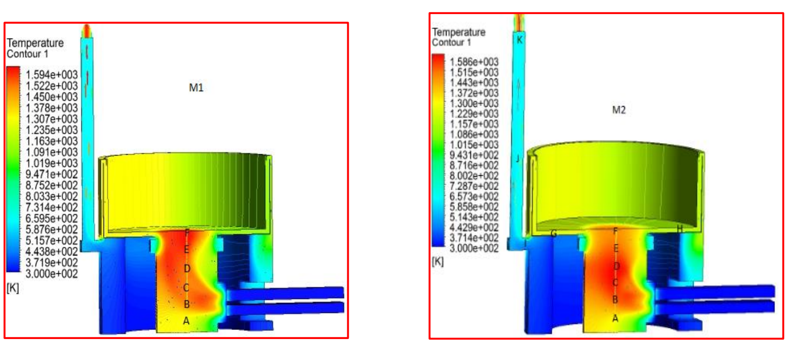


Figure 5.12Institutional stove improved model

From section 5.6 above, I select the model with secondary air that is (60% -40%) due to its high thermal load and attractive propagation of flame. The following table shows the temperature distribution inside a combustion chamber.

Table 5.8 Temperature distribution inside a combustion chamber

Description		A	B	C	D	E	F	G	H	I	J	K
Tem.(k)	M_1	1289	1530	1538	1538	1596.7	1634	1288	1065	508	638	626.5
	M_2	1315	1575	16.4	1630	1532	1488	1216	1138	484	624	612
	T_{ave}	1302	1552	1571	1584	1564.4	1561	1252	1102	496	631	619.25

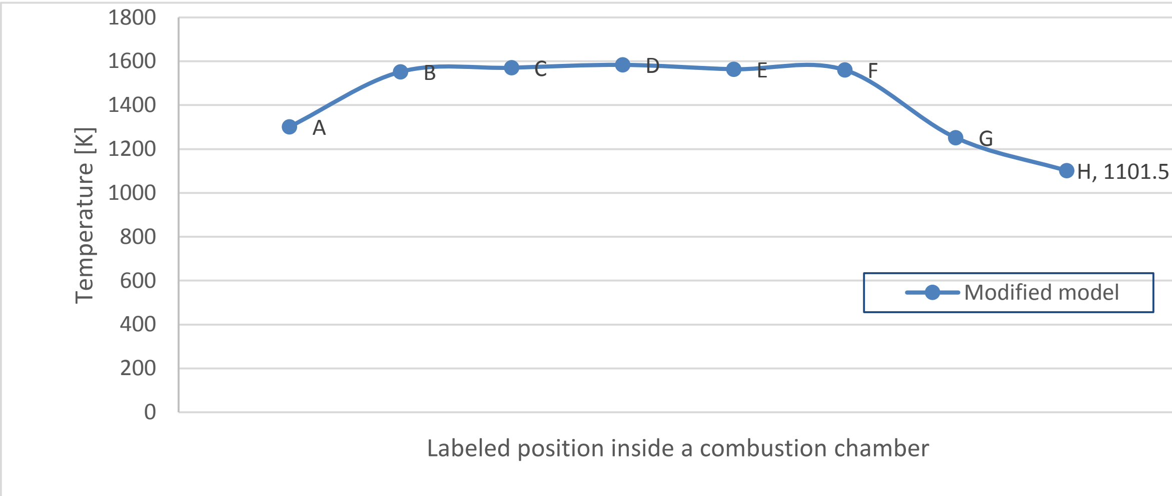


Figure 5.13 Temperature distribution with corresponding point

5.9 Result Comparing Note

The result may not the same in magnitude with the experimental result. This may arise due to two reasons. The first, the accuracy of thermocouple in measuring high temperature is not acceptable; there is always error in read temperature. The second is the limitation of Eddy Dissipation model that radical or intermediate species, such as CO, cannot be calculated with adequate accuracy that may lead to over-prediction of flame temperature, in particular in fuel-rich regions. In other hand the Eddy Dissipation model has an advantages, it tracks each individual chemical species (except for the constraint material) with its own transport equation. This model is flexible in that you can readily add new materials, such as additional fuels, to the simulation without complications.

In actual stove studied under this experiment, the fuel wood inlet and chimney position were not symmetric. They were in 90° position angle, but the point mentioned in table blow were from similar position with my thermocouple reading. Even though controlling the air hundred percent is difficult like in the case of simulation, the temperature read was related. The following table show the comparison of actual temperature with the simulation result at specified point.

Table 5.8 comparison of experiment result with simulation result

Experiment Result, Temperature in [K]					
At a bottom of the vessel			At chimney exit		
Cold start		Hot start	Cold start		Hot start
Day 1	Day 2	Day 2	Day 1	Day 2	Day 2
847	989	1147	418	430	465
Simulation Result, Temperature in [K] at the Same place					
At point "H"			At point "K"		
75% - 25%	60% - 40%	50% - 50%	75% - 25%	60% - 40%	50% - 50%
1121	1123.7	1084	587	599.7	607

5.10 Environmental Implication

According to the market assessment done on different institutions (University, Prison and Hotels) in and around Jimma zone (table 1.1) the wood log consumed per month in cubic meter was surveyed. In Jimma University students' cafeteria (Kito Furdisa campus, Zagaye cafeteria, Obama cafeteria and Sheraton cafeteria) are using inbuilt stove and an average wood log consumed are: 200,140,110,100 cubic meters per month respectively. Totally, 550 cubic meters is consumed per month and 5500 cubic meter of wood log is consumed annually. Each cubic meter of wood log is 160 Birr and the total cost would be 880,000 Birr per year. Almost all of these fuel wood are not harvested from the immediate vicinity of the campus, brought to the campus by vehicle which needs additional cost for vehicle transportation.

The annual fuel wood savings are estimated at the technical potential for Kito-Furdisa campus, Jimma University with the following formula.

Annual Savings = $(\frac{current\ kitchen\ Use}{month})(\frac{10\ months}{year})$(fuelwood savings) ---------------------------5.11

Plugging numbers into the above equation:

Annual Savings = $(\frac{200m^3}{month})(\frac{10\ months}{year})$(0.66) =1,320 cubic meter per year

In turn there will be economic saving of (160*1320) equal to 211,200 Birr per year.

CHAPTER SIX
CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Water boiling test showed thermal efficiency of 53.4 %, specific fuel consumption of 41.25 gram per liter, average time to boil is 129.5 minute for specified vessel capacity (200 liter) and fuel saving of 66% as well. The stove has a burning rate of 65.6 gram/minute. But, always note that, combustion highly affected by moisture content of the fuel, so best practice of use wood for combustion at least wait for three days after splitting of wood/logs. Fuel consumption is found to be one third of open fire three stone stove.

Based on current cost of wood log per cubic meter, the stove saves 211,200 Ethiopian Birr per year considering only Jimma University Technology Institute students cafeteria. The stove makes the kitchen environment free from smoke, in turn avoids diseases and drudgery caused with this problem on kitchen workers. It is easy to operate (cook) on it, remove ash, char left and It has suitable height and ergonomics with comfort for stirring.

The CFD simulation for reacting flows can be sensitive to the boundary conditions, in particular the incoming velocity field and the heat transfer through the walls. As expected, adding secondary air during combustion process resulted in good flame height in order to reach the bottom of the vessel and insure flame turbulence. The total temperature is higher than the one with primary air only. The air supply of 60% primary and 40% secondary was selected among the cases under investigation for optimal benefit with high heat transfer.

There is no extra heat to the environment during operation. The maximum average temperature recorded from outer most surface of the stove was 57℃, which totally eliminate sudden burning of kitchen workers, while the average temperature is 153 ℃ in the inner surface.

As two cases of the stove configuration were compared, the one without inner insulation (refractory) was selected from the perspective thermal efficiency, burning rate and specific fuel consumption. This fact ensures, using heavy material for insulation purpose is undesirable, since heavy material like construction sand, rock, and earth etc. are high thermal conductivity material and they have less insuation property.

6.2 Recommendation for Further Work

The following aspects are recommended for further works

1. Inner insulation can be made by casting from locally available materials (i.e. clay or ceramic) in order to insure less weight and heat retention during simmering.
2. Elaborating the concept of InStove, preparing the stove for different purpose i.e. Cake, enjera, baking.
3. Parallel with combustion, the stove can be made for co-production of char.
4. Changing the diameter of inner most combustion chamber to appropriate size and the position of the chimney, the model can be made for more efficient, and this needs additional investigation.

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Appendix A

Model Performance and Stoichiometric Analysis

A1. Stoichiometric Analysis

The initiating concept upon which all of the following calculations depend is the chemistry of wood combustion and creating stoichiometric conditions for combustion. A balanced equation for the combustion of wood follows:

Fuel (wood) + air (oxidizer) ⟶ product of combustion + Energy

$CxHyOz + a_{th}(O_2 + 3.76N_2) \longrightarrow xCO_2 + yH2O + zN_2$

Table A1 oxygen required for elementary analysis and product produced

	Mass (per kg)	O_2, Required	Products
Carbon	0.5043	0.5043*32/12 =1.3448	0.5043*44/12 = 1.849
Hydrogen	0.0601	0.0601*16/2 = 0.4808	0.0601*18/2= 0.5409
Sulfur	0.0008	0.0008*32/32 = 0.0008	0.0008*64/32 = 0.0016
Oxygen	0.4329	-0.4329	-
Nitrogen	0.0017	-	0.0017
Chlorine	0.0002	-	0.0002

Oxygen required to burn 1kg of eucalyptus wood is obtained from ultimate analysis of oxygen required as stated in the table above under column two. Note that the oxygen already exists in the hydrocarbon of wood must be subtracted from total oxygen required.

1.3448 +0.4808 + 0.0008 – 0.4329 = 1.3935kg.

It is known that the percent of oxygen by mass in air 23.2 and nitrogen is 76.7 in atmosphere. Dividing the oxygen required in the stoichiometry by mass percent of oxygen yields the air required for the combustion.

Air required = 1.3935/0.232 = 6.01kg

Assuming 20% excess air, the actual air supplied = 6.01*1.2= 7.212kg, per kg of wood, of which oxygen is 7.212 * 0.232 = 1.673kg, and nitrogen 7.212 * 0.767 = 5.532kg.

Since there is excess air, the products contain oxygen which is equal to; 1.673 – 1.3935 = 0.2795kg and 5.532 + 0.0017(nitrogen already in the wood) = 5.533kg nitrogen.

Air fuel ratio (AFR_{stoich}) 7.21: 1

To get stoichiometric amount of air required based on the above elementary analysis table C1 and using by the following formula.

$$n_{a,st} = \frac{1}{0.21}\left[(1 - 0.5f) * \frac{[C]}{12} - \frac{Y}{32}\right]$$

Referring the above table C1; f = 1.849, [C] = 0.5043 and Y = % of oxygen – 8 * % hydrogen

Y = 0.4329 – 8 (0.0601) = 0.0479

Substituting the value, $n_{a,st}$ = 0.02224 mol.

A2. Model Performance Analysis

From Bernoulli's equation for compressible flow, pressure difference can be equated to obtain kinetic energy of the chimney flow at point (2) and the stagnation ambient air at point (1) using the following equation.

$$\Delta P_{1-2} = gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H v_2^2$$

Where, the hot gas density and velocity (v) at point (2) are used for calculating the stove flow kinetic energy. Utilizing the relations of volume and mass flow rate:

$$gh(\rho_{amb} - \rho_H) = \frac{1}{2}\rho_H (\frac{\dot{V}}{A})^2$$

$$\dot{V} = CA\sqrt{2gh(\frac{\rho_{amb} - \rho_H}{\rho_H})}$$

Using the ideal gas law, solving for air density and substituting into the above equation:

$$\rho_H = \frac{P}{R_s T_H}$$

$$\dot{V} = CA\sqrt{2gh(\frac{\frac{P}{R_s T_{amb}} - \frac{P}{R_s T_H}}{\frac{P}{R_s T_H}}}$$

The difference inside the parenthesis can be simplified by rearranging to the form:

$$\dot{V} = CA\sqrt{2gh(\frac{PR_s(T_H - T_{amb}}{R_s^2 T_{amb} T_H}) * \frac{R_s T_H}{P}}$$

$$= CA\sqrt{2gh(\frac{T_H - T_{amb}}{T_{amb}})}$$

Multiplying by the density and substituting with the ideal gas law, the mass flow rate will be determined.

$$\dot{m}_A = \text{CA}\,(\frac{P}{R_s})(\frac{1}{T_H})\sqrt{2gh(\frac{T_H}{T_{amb}} - 1)}$$

With the following specification, volume and mass flow rate will be calculated.

(A= $\frac{\pi * D^2}{4}$ = 0.0415m^2; $T_H = 1200°K$; $T_{amb} = 300°K$; h =1.51m and loss coefficient, C = 0.5)

The volume flow rate of air, $\dot{V}$

$$\dot{V} = CA\sqrt{2gh(\frac{T_H}{T_{amb}} - 1)}$$

$$\dot{V} = 0.5 * 0.0415\sqrt{2 * 9.81 * 1.51(\frac{1200}{300} - 1)} \quad = 0.1955\ m^3/s$$

Mass flow rate of air, $\dot{m}_A$

$$\dot{m}_A = CA\ (\frac{P}{R_s})(\frac{1}{T_H})\sqrt{2gh(\frac{T_H}{T_{amb}} - 1)}$$

$$\dot{m}_A = 0.5*0.0415*\ (\frac{0.82*10^5}{287.2})(\frac{1}{1200})\sqrt{2 * 9.81 * 1.51(\frac{1200}{300} - 1)} \quad = 0.0465\ kg/s$$

The fire power within the control volume can be calculated from enthalpy and temperature relation.

$$\dot{Q}_{cv} = \dot{m}_A\ (h_{amb} - h_H)$$

$$= \dot{m}_A \int_{T_{amb}}^{T_H} C_p(T)dT$$

$$= \dot{m}_A\ C_{p,avg}(T_H - T_{amb})$$

= 0.0465 * 1.089 *(1200-300) = 45.57 kW

The mass flow rate of the fuel, $\dot{m}_F$

$$\dot{m}_F = \frac{\dot{Q}_{in}}{HV} = \frac{45.57}{18000} = 0.0025\ kg/s$$

The air fuel ratio from the flow rate, can be calculated:

Air Fuel Ratio (AFR) = $\frac{\dot{m}_A}{\dot{m}_F}$ = = $\frac{0.0465}{0.0025}$ = 18.6

$$\varphi = \frac{AFR_{Stoich}}{AFR} = \frac{7.21}{18.6} = 0.38$$

% of excess air ratio = $\frac{(1 - \varphi) * 100\%}{\varphi}$

Appendix B

B1.Sample Experiment Data

Data recorded during WBT to investigate heat loss through the wall of the stove as well as by flue gas through chimney.

Table B1.1 On the first day collected data table (cold start)

description	Starting time at 8:01(local time)									Original water Temperature =19 0C			
	Time interval		8:35	8:50	9:05	9:20	9:35	9:50	10:05	10:20	10:35	10:50	11:05	11:30
circumference of the stove	Testing position	01	102.1	68.3	68.3	88.4	105.1	113.1	37	41.9	48.7	35.8	33.3	39.4
		02	31.1	54.3	51	63.4	73.4	79.1	79	95.9	109.7	109.7	108.3	119.4
		03	121.1	109.3	114.3	128.4	129.4	105.1	149	163.9	160.7	135.8	164.3	173.4
		04	173.1	116.3	83.3	73.4	103.1	191.1	137	148.9	130.7	115.8	140.3	201.4
From the chimney		05	95.1	83.3	88.3	112.4	115.1	113.1	89	150.9	126.7	132.8	135.3	166.4
		06	282.1	80.3	80.3	99.4	110.1	113.1	117	131.9	118.7	130.8	145.3	139.4
Bottom of the vessel		07	574.1	213.3	250.3	473.4	377.1	420.1	406	544.9	537	510.8	564.3	533.4
		08	Damaged position											
Fire Bed		09	476.1	433.3	407.3	851.4	580.4	603.1	665	218.9	170.7	103.8	111.3	110.4
	Tamb.		26.1	26.3	26.3	26.4	27.1	27.1	27	26.9	28.7	25.8	25.3	24.4
Boiled at 11:41 (local time)													

Table B1.2 On the second day collected data table (cold start)

description		*Starting time at 4:02(local time)*				Original water Temperature =19 ℃				
	Time interval	4:25	4:40	4:55	5:10	5:25	5:40	5:55	6:10	6:25
circumference of the stove 01 - 04	Testing position 01	31.1	87.6	89.8	51	131.4	118.2	116.7	163.1	190.4
	02	38.1	51.6	58.8	59	98.4	108.2	116.7	131.1	141.4
	03	183.1	177.6	185.8	128	226.4	219.2	222.7	270.1	153.4
	04	279.1	235.6	207.8	59	134.4	99.2	227.7	355.1	203.4
From chimney 05 & 06	05	102.1	126.6	148.8	151	186.4	184.2	194.7	207.1	215.4
	06	73.1	87.6	104.8	112	119.4	125.2	157.7	143.1	150.4
Bottom of the vessel 07 & 08	07	411.1	373.6	590.8	549	633.4	592.2	658.7	716.1	699.4
	08	Damaged position								
Fire Bed	09	978.1								
	Tamb.	23.1	23.6	23.8	24	24.4	25.2	25.7	26.1	26.4
Boiled at 6:34										

Table B1.3 On the second day collected data (hot start)

description		Starting time at 6:45(local time)			Original water Temperature =19 ℃			
	Time interval	7:10	7:25	7:40	7:55	8:10	8:25	8:40
circumference of the stove 01 - 04	Testing Position 01	47.1	43.8	51.9	70.9	69.8	42.7	60.3
	02	55.1	60.8	85.9	87.9	139.8	216.7	147.3
	03	204.1	205.8	235.9	275.9	240.8	280.7	291.3
	04	189.1	197.8	130.9	232.9	129.8	201.7	271.3
From chimney 05&06	05	166.1	162.8	180.9	210.9	203.2	226.7	217.3
	06	110.1	114.8	123.9	157.9	129.8	139.7	192.3
Bottom of the vessel 07&08	07	660.1	730.8	804.9	873.9	852.8	859.7	833.3
	08	Damaged position						
Fire Bed	09							
	Tamb.	27.1	28.8	28.9	28.9	29.8	29.7	30.3

	Humidity	41	39	36	34	34	33	31
Boiled at 8:41								

Table B1.4 On the third day collected data table of surface temperature (cold start)

		Test # 4 cold start outer surface loss EMF in millivolt		Initial water temp. = 20 Oc starting time = 4:31 Boiled at =6:57		
T_{amb}	RH	fuel inlet side	Opp. Side of fuel inlet	chimney Base	Chimney	Time
24.1	58	0.2	0.1	0.5	0.4	4:50
25.2	41	0.3	0.1	0.9	0.8	5:30
25.7	39	0.8	0.1	2.3	0.9	6:20
26.4	36	1.1	0.2	1.5	1.1	6:50
Temperature in ^oC						
24.1	58	28.1	26.1	34.1	32.1	4:50
25.2	41	31.2	27.2	43.2	41.2	5:30
25.7	39	41.7	27.7	69.7	43.7	6:20
26.4	36	48.4	30.4	56.4	48.4	6:50

B2 Experiment Results

Table B1.3 On the fourth day collected data (hot start)

Temperature in °C				Start at 3:02 (local time)		
Reference: J-Type thermocouple						
position		3:30	4:00	4:20	4:30	ave.
circumference of the stove 01 – 04	1	240	247	222	276	246.25
	2	73	211	216	307	201.75
	3	129	140	184	111	141
	4	125	146	146	143	140
Chimney (at base and top surface)	5	222	288	290	298	274.5
	6	122	169	169	169	157.25
Tamb.		21	23	23	25	23
Boiled at 4:36 (local time						

The result obtained at different time were illustrated in the following table

Table B2.1 average temperature (With inner insulation)

Test no	Average Temp.	circumference of the stove				chimney		bottom of the vessel,7	Ambient temp.
		1	2	3	4	base,5	surface,6		
1	T_{ave}	58.53	81.2	137.89	134.53	117.36	111.78	450.39	26.45
2	T_{ave}	108.81	89.25	196.25	200.14	168.48	119.25	580.48	24.7
3	T_{ave}	85.21	113.35	247.78	193.35	195.41	138.35	802.21	29.07
Tave.		84.2	94.6	194	176	160	123.13	611	26.74

Table B2.2 average temperature (Without inner insulation)

Test no	Average Temp.	circumference of the stove				chimney		Ambient Temp.
		1	2	3	4	base,5	surface,6	
1	T_{ave}	82.4	112.2	147.4	119.4	141.6	86.8	23.6
2	T_{ave}	144.2	145.8	167.2	141.4	172.2	107.2	25
3	T_{ave}	96	201.75	141	140	274.5	157.25	23
Tave		107.5	153.25	151.9	169	196.1	117.08	23.8

Table B2.3 Summary of WBT result with inner insulation

WATER BOILING TEST - VERSION 4.2. **TEST #**

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

Stove type/model	Institutional Stove
Location	Jimma University, Ethiopia
Fuel description	Eucalyptus Tree
Wind conditions	Moderate wind; Moderate wind; Moderate wind
Ambient temperature	24; 25; 25

1. HIGH POWER TEST (COLD START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	220	146	-	183	-	
Temp-corrected time to boil Pot # 1	min	219	144	-	181.311	-	
Burning rate	g/min	51	53	-	51.9231	-	
Thermal efficiency	%	38%	56%		0.4714042		
Specific fuel consumption	g/liter	57	40	-	48.352089	-	
Temp-corrected specific consumption	g/liter	57	39	-	47.902435	-	
Temp-corrected specific energy cons.	kJ/liter	986	679	-	832.54432	-	
Firepower	watts	14,755	15,325	-	15040	-	

2. HIGH POWER TEST (HOT START)	units	Test 1	Test 2	Test 3	Average	St Dev	COV
Time to boil Pot # 1	min	152	112	-	132	-	
Temp-corrected time to boil Pot # 1	min	151	111	-	130.75985	-	
Burning rate	g/min	72	79	-	75.800282	-	
Thermal efficiency	%	39%	42%		0.4058968		
Specific fuel consumption	g/liter	56	46	-	50.773414	-	
Temp-corrected specific consumption	g/liter	56	45	-	50.288462	-	
Temp-corrected specific energy cons.	kJ/liter	968	781	-	874.01346	-	
Firepower	watts	20,963	22,951	-	21956.815	-	

Table B2.4 Summary of WBT result without inner insulation

WATER BOILING TEST - VERSION 4.2.2	**TEST #**
All cells are linked to data worksheets, no entries are required	
Stove type/model	Institutional Stove
Location	Jimma University, Ethiopia
Fuel description	Eucalyptus Tree
Wind conditions	Moderate wind; Moderate wind; Moderate wind
Ambient temperature	24; 25; 25

1. HIGH POWER TEST (COLD START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	171	100	-	135.5	-	
Temp-corrected time to boil Pot # 1	min	169	99	-	133.71711	-	
Burning rate	g/min	48	80	-	63.577702	-	
Thermal efficiency	%	53%	54%		0.5359438		
Specific fuel consumption	g/liter	42	41	-	41.255358	-	
Temp-corrected specific consumption	g/liter	41	40	-	40.712524	-	
Temp-corrected specific energy cons.	kJ/liter	715	700	-	707.58367	-	
Firepower	watts	13,765	23,067	-	18416	-	

2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time to boil Pot # 1	min	154	94	-	124	-	
Temp-corrected time to boil Pot # 1	min	154	93	-	123.38158	-	
Burning rate	g/min	53	85	-	68.7395	-	
Thermal efficiency	%	52%	54%		0.5329996		
Specific fuel consumption	g/liter	42	41	-	41.253846	-	
Temp-corrected specific consumption	g/liter	42	40	-	40.985189	-	
Temp-corrected specific energy cons.	kJ/liter	724	700	-	712.32258	-	
Firepower	watts	15,285	24,538	-	19911.542	-	