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"Geometrical Optimization of Biomass Cook Stove for Efficient Utilization of Energy" (In case of Tikikil Stove)

A thesis research submitted in Partial Fulfillment of the Requirement for

The Degree of Masters of Science in Thermal Engineering

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ID/No- GSR/0711/06

Date –October /2016

ABSTRACT

The traditional three-stone fire is used in many households in rural areas of developing countries. These open fires are very inefficient at converting energy into heat for cooking. In order to improve energy security in developing countries modern cooking fuels and cook stove technologies are introduced and people are encouraged to switch to modern cooking technologies. Tikikil stove is one of improved cook stove which is currently used for cooking and heating needs in Ethiopia. Even though there are several factors that can be considered to improve the efficiency of these cook stove, this thesis enhance the impact or effect that geometry of the stoves has on its heat transfer efficiency.

In this work, SOLID WORK 2012 is used to model various geometries of the biomass cook stoves and a computational fluid dynamics (CFD) analysis has also been carried out for the different geometries of stove to analyze the flow behavior of gas, heat transfer behavior during the cooking period using Autodesk Simulation CFD 2012. For Tikikil stove the computational results were compared and validated with the experimental data. From experimental data thermal efficiency result is 27%, analytically using surface temperature measured the contributions of each mode of heat transfers are calculated also thermal efficiency is computed and value gained is 21.7%, finally using CFD analysis thermal efficiency obtained is 30.1%. Based on CFD simulation results of the different new geometry models, a cook stove geometry that gives significant improvement on performance is suggested which gives 50.1% of thermal efficiency by computing CFD output parameter.

Nomenclature

Symbol	
A	*Area*
E	*Energy*
m	*Mass*
T	*Temperature*
C_p	*Specific heat*
d	*Diameter*
t	*Time*
V	*Velocity*
T	*Temperature*
K	*Thermal conductivity*
f	*friction factor*
J	*View factor*
Q	*Heat transfer*
LHV	*Lower heating value of wood*
HHV	*Higher heating value of char*
h	*Heat transfer coefficient*
h_{fg}	*Enthalpy of vaporization of water*
ΔT	*Change in temperature from initial to final*
LHV	*Net calorific value of char*
L	Thickness
P1	*Dry mass of empty pot*
T_∞	*Ambient Fluid (air) Temperature*
Nu	*Nusselt number*

P	*Static Pressure*
Pr	*Prandtl number*
Re	*Reynolds number*
R	*Resistance*

Greek letters

σ	*Stefan-Boltzmann constant*
α	*Absorbtivity*
ε	*Emissivity*
μ	*Viscosity*
ρ	*Density*

Subscripts

i	*Initial*
f	*Final*
x, y, z	*Direction vectors*
a	*Ambient*
b	*boiling point*
s	*surface*
Char	*char*
e	*evaporated*

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CHAPTER ONE

1. INTRODUCTION

1.1 Background

Since very early times an open fire has been the method of choice when preparing food both in East Africa and in the rest of the world, and globally, more than 2.7 billion people still cook with wood or charcoal [Legros *et al.*, 2009]. Like many other sub-Saharan African countries, Ethiopia is highly dependent on biomass energy sources, such as fuel wood, charcoal, animal dung and crop residues. These biomass energy sources account for more than 90% of total domestic energy demand, according to Ethiopian Environmental Protection Agency (EEPA, 2004). The Ethiopian environmental protection further reports about 95% of the total population in Ethiopia uses biomass fuels for their main source of energy. Even though urban households have better access to modern energy than the rural population, the difference in biomass use is not large – approximately 99% of rural households compared to 94% of urban households.

The traditional three-stone fire is used in many households in rural areas of developing countries. These open fires are very inefficient at converting energy into heat for cooking the amount of biomass fuel needed each year for basic cooking can reach up to 2 tons per family [2]. In addition, collecting this fuel sometimes can take an hour a day on average. Furthermore, these open fires and primitive cook stoves emit a significant amount of smoke, which fills the home; this indoor cooking smoke has been associated with a number of diseases, the most serious of which are chronic and acute respiratory illnesses, such as bronchitis and pneumonia. There is evidence that biomass fuels burned in traditional ways contribute to a buildup of greenhouse gases (GHGs) (Venkataraman et al. 2010), as well as other climate forcers, including black carbon (BC), in the atmosphere (Ramanathan and Carmichael 2008). Those gases cause pollution on the environment which has an impact on health of the citizen. The World Health Organization (WHO, 2002) estimates that fumes from indoor biomass cook stoves kill 1.6 million women and children in developing countries, each year, and that the global burden of disease associated with biomass fuel use is 3%.

Since most of Ethiopian citizens use biomass fuel for their heating and cooking needs the figures for Ethiopia, are proportionately worse. In order to improve energy security in developing countries especially in rural areas are promoting more efficient and sustainable use of traditional bio- mass; and encouraging people to switch to modern cooking fuels and technologies. For many households, switching from traditional biomass to modern and clean biomass may not be feasible in the short term because of high capital cost coupled with high poverty levels [3]. Therefore, improving the biomass cooking stove in a way that the stove will be more efficient in terms of Energy expenditure, cost effective that everybody can afford to buy, friendly to the Environment and Safe to use(In terms of health of the user) is very essential. this research work is intended to optimize the impact or effect of geometry/configuration of the stove has on its heat transfer efficiency because, if heat transfer between the pot surface and hot gases from the fire is optimized, then overall thermal efficiency of the cooking operation is improved simply by modeling new geometry which is more efficient in utilization of energy also has a contribution in proper utilization of biomass energy by decreasing emission that is caused due to incomplete combustion.

Currently different types improved biomass cook stoves are being introduced and distributed for people living in rural and urban city in Ethiopia by governmental and nongovernmental organizations. For example, Charcoal stove, Lakech stove, Metal stove and Tikikil stove for heating and cooking needs and biomass Injera stoves like; Mirt stove and Gounziye stove**.** In this paper work the performance and heat transfer analysis will be carried out on one which is widely used type Tikikil stove. The aim of this research is to do the geometrical optimization of tikikil stove and analyzing the heat transfer history by using Fluent also performing experiment that helps to understand the performance and efficiency of that stove. This leads to recommend an optimized geometry of improved efficiency.

1.2 Objective

The overall objective of this research activity is studying Performance and Heat transfer analysis of existing biomass cook stove in Ethiopia (Tikikil stove) and improving the heat transfer efficiency by optimizing the geometry of stove.

The specific objectives are to study the effect of geometry on performance of the stove, to perform experiment and measure different parameters which are related to cook stove performance in order to calculate thermal efficiency, to identify major surface which is exposed to heat loss and also heat gain surface to do the energy balance of the stove and recommend how to recover energy lost. Simulation of the temperature distribution is done with CFD coded fluent software.

1.3 Methodology

A CFD coded software called FLUENT is chosen for this project because the development of such a computational model which uses detailed simulation using computational fluid dynamics (CFD) to predict the performance of the actual stove, and obtain the model equations that relate design and performance parameters and would also be useful in carrying out design optimization of a given type of biomass stove for a given fuel and also the heat transfer through the cooker will be analyzed using this software. The development of the computational model involves the development and validation of sub-models of buoyancy- induced fluid flow and heat transfer.

A natural draft, shielded-fire wood-burning cook stove is selected to develop a detailed computational zonal model of the heat transfer and fluid flow processes, and also experimental analysis is conducted on this stove to calculate energy balance in the stove. The basic equations used for mathematical modeling will be first law of thermodynamics to perform a mass and energy balance. A fundamental equation that demonstrates the interdependency between mass flow rate, temperature and heat transfer in and out of the stove will be modeled. Due to the different losses that occur in the stove study of different heat transfer processes is very important and necessary to understand the mechanism of heat transfer in a cook stove. And finally after identifying major heat loss area the geometry of existing stove will be modified for better utilization of energy.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

Biomass is the oldest energy sources in the world; it is also the most well-established. Biomass can be defined as the conversion of stored energy in plants into some energy that we can use. Biomasses are different than fossil fuels. In fact, first they do not have the same properties. “A major difference is the high content of volatile matter in biomass materials (up to 80 percent), whereas coal has less than 20 percent (anthracite coal sometimes even has a negligible volatile content.” Biomass differs to the fossil fuels by the fact that it is a renewable energy source. Renewable energy developments are generally considered to be environmentally beneficial by providing clean energy from resources that are continually replaced. There are different types of biomass; there is wood such as trees, shrubs, wood residue Sawdust, bark, etc. Then, there are wastes such as paper, food, and tires, livestock waste and process waste. There are also aquatic plants such as algae or water weed which are biomasses as well. The use of biomass has some advantages according to Energy matters: biomass are theoretically inexhaustible fuel sources, it is a renewable energy , Fuels produced by biomass are efficient, viable, and relatively clean-burning, they are available sources throughout the world.

2.2 Biomass Energy Utilization and Environmental Impacts

The application of the biomass is to work as a fuel. In developing countries, firewood is the only source of fuel for cooking for over a billion people. In fact 90% of the world’s fuel wood is produced & used in the developing countries [7]. The most common method of cooking in these countries, particularly in the rural areas is on an open fire (three stones) stove which involves building a fire directly on the ground, and placing a pot or pan atop three stones that surround the fire. The use of wood as fuel source for heating and cooking is as old as civilization itself. Almost all African countries still rely on wood to meet basic energy need. Wood fuels account for 90-98% of residential energy consumption in most sub-Saharan Africa.

Ethiopia consumed 0.566 million m^3 of wood accounting for 9.1% of total African cooking and heating wood consumption [6]. Biomass fuels (firewood, agricultural residues, animal wastes and charcoal) account for up to 90 percent of the energy supply of Ethiopia. [In general, average energy consumption of African households is significant. The average per capita firewood consumption in some African countries for families of 2-6 members was estimated at 1.14-1.36tons. Families with seven and greater members consume on average 1.12 tons per capita with the annual to total consumption for an average family of 4-7 persons being 6-4tons[4].

Different types of improved cook stoves introduced and widely used by the people living in urban and rural areas of Ethiopia are also inefficient in transferring heat therefore they consume high rate of biomass energy and due to the incomplete combustion occur in the stove there will be a harmful smoke. This inefficiency of cooking methods coupled with a high population growth rate of the developing countries has led to an extensive deforestation, which brings harmful effects such as global warming, climate change, greenhouse gas emissions, soil erosion, landslides, loss of biodiversity and lesser rainfall causing desertification. Biomass smoke from combustion contained a wide range of pollutants which could prove to be extremely health damaging due to continuous exposure. The most common pollutant produced from the combustion of biomass fuels are particulate matter, carbon monoxide, hydrocarbons, nitrogen oxides and sulfur oxides [1].Commonly everything leads to the disturbance to normal atmosphere. Emissions of organic compounds are due to an incomplete combustion or to the recombination of partly oxidized compounds in the combustion process. The composition of the pollutants emitted during the combustion of biomass fuel depends on several factors: original compositions of the fuel, ambient and combustion temperatures, air flow into the fire, mode of burning and type of stove [1].

2.3 Biomass Cook Stove Technology

The history of cook stove had started with the invention of fire and from archeological excavations at Chou Kutien in China. It had been shown that the Homo erectus Pekingnensis used the fire for heating during the first ice age of about 400,000 years ago [6]. However, the human civilization had started by making the use of refined stones, the mastery of fire, and the domestication of several animals and cultivation of plants [1].

From the open fires of prehistoric times [2] and three-stone fires, cook stove designs evolved into shielded fires [7], that paved way to development of improved cook stoves. The three-stone fires have continued to be used for cooking and heating purposes, mainly due to their simplicity. They are easy to build and virtually free. They can be adapted to different forms quite easily placed on waist-high platforms for more convenience for the user. There are more sophisticated types of traditional stoves, ranging from mud stoves to heavy brick stoves to metal ones. Most sources cite the fuel-efficiency of traditional stoves as 5-10% [1]. All the cook stoves developed during early time (i.e. before 17th century) were called as 'traditional cook stoves because their thermal efficiencies were very low and the material of construction was also very poor besides, they emitted a very high level of smoke.

2.3.1 History of Improved Cook Stove

Stoves with improved efficiency have been introduced in developing countries since1970. Improved cook stoves are cooking stoves that use biomass (charcoal, wood, paper or vegetable matter) and are designed to maximize thermal and fuel efficiency, operate safely and minimize emissions harmful to human health. The objectives have been to reduce deforestation, save cooking time, reduce health impacts through reduction in environmental emissions, save money and improve cooking satisfaction. Since nearly three billion people in the world use traditional stoves to cook their meals, efforts to improve the efficiency of cook stoves have been increasingly popular in the developing world [1]. Improved stoves come in different forms & sizes. Improved cook stoves can be designed & built in various ways, depending on the local conditions.

At their simplest, improved stoves rely on providing an enclosure for the fire to cut down on the loss of radiant heat & protect it against the wind. In addition, attention can be given to devising methods of controlling the upward flow of the combustion gases, to increase the transfer of heat to the cooking pot [1]. Cook stoves with chimneys and closed combustion chambers were usually considered “improved.”

The number of households using these relatively inexpensive, improved cook stoves totals roughly 166 million, with 116 million in China, more than 13 million in the rest of East Asia, nearly 22 million in South Asia, about 7 million in Sub-Saharan Africa, and over 8 million in Latin America and the Caribbean (where there is extensive use of petroleum fuel). Out of every four developing-country households dependent on solid fuels for cooking, only one uses a stove with a chimney or smoke hood [2]. To increase the combustion and heat transfer efficiencies of cook stove through different mechanisms, few components such as, grate, pot skirt, dampers, etc. were developed and introduced by number of authors.

The latest trends in cook stove modeling involve use of CFD for thermal analysis and use of finite element analysis for studying the structural strength of the cook stove material. For example Kohli, carried out CFD simulation of buoyancy-induced fluid flow and heat transfer for the simplified geometry of a sawdust stove with a pot, Varunkumar etal, reported both experimental and computational studies on a gasified cook stove using ANSYS CFX software. It was estimated that the radiation heat transfer from char bed was responsible for 6%of the total flaming mode efficiency of the stove. It was found both experimentally as well as computationally that the stove efficiency increases with increase in pot size exposed to flame, Urbanetal, reported use of commercial CFD software for locating the baffles in Plancha stove for its optimum performance. The flow and heat transfer were simulated using CFD and the heat transfer to the pan was optimized using a genetic algorithm, working in tandem with the CFD model and so on.

2.3.2 Benefit of Improved Cook Stove

In most countries, cooking is mainly considered the responsibility of women, who spend a significant amount of their time preparing food for their families. Cooking practices can be made easier by using more modern fuels (e.g., kerosene or LPG), improving the quality of charcoal production, and using electric appliances. The role of cook stoves in reducing emissions, eliminating drudgery, and improving overall quality of life is visible.

The pervasive use of biomass energy explains why the quality of the cook stoves used by developing - country households is so important. For the 2.7 billion people who rely on biomass energy. Collecting biomass for cooking is a frequent, arduous task. Improving the efficiency of a stove thus requires attention to a number of different factors.

- Increasing combustion efficiency is important so that as much of the energy stored in the combustible is released as heat and reduce the pollution caused by incomplete combustion gases.
- Heat transfer efficiency: so that as much of the heat generated as possible is actually transferred to the content of the pot. This includes conductive, convective, and radiation heat transfer processes.
- Control efficiency: so that only as much heat as is needed to cook the food is generated.
- Internal benefits or in the household include: reduce concentrations of smoke and indoor air pollution; money and time saved in acquiring fuel. Reduce work load for women, who are predominantly responsible for cooking and collecting fuel wood.
- External benefits include: less pressure on forest and energy resources; reduced GHG; and skill development and job creation in the community [8].

2.4 Stove Development in Ethiopia

The vast majority of rural people who are also dependent on traditional fuels use primitive and inefficient technologies. The improved stoves are more efficient than traditional stove they are best alternative to decrease fire wood consumption. Generally in Ethiopia the most widely used energy is biomass so it needs good efficient biomass conversion method to modernize and upgrade energy production.

There are different types of biomass cook stoves which have been developed and widely used in Ethiopia for cooking and heating needs. The improved cook stoves, namely: “Lakech” charcoal stove, “Mirt” fuel wood stove for making Injera (a large, flat bread (pancake) common diet in Ethiopia), and the “Gonzye” multi-purpose wood stove used for baking, cooking also boiling and tikikil stove for cooking.

2.4.1 Traditional three stone cooking stoves

In an open fire stove three medium sized stones are used to put the “Mitad” or the cooking pot. It is open except the spaces occupied by the stones. This kind of traditional house hold stove widely used throughout the country and high amount of Firewood use leads to deforestation and erosion, while smoke from traditional cooking cause’s health problem.

2.4.2 Lakech Stove

Lakech stove was adopted from the Kenyan Ceramic Jocko (KCJ), by the EREDPC of the Ministry of Mines & Energy in 1990 under the Cooking Efficiency Improvement & New Fuels Marketing Project. The stove was optimized by thinning the metal cladding of KCJ to suit with the Ethiopian cooking habits & reduces construction cost. It has the shape double conic fitted with ceramic liner above its waist. A half liner combined with the bell-bottom shape provides stability to the stove, with a low cost and low weight as compared to full liners [6]. Materials needed to produce the stove are metal, clay, cement, sand and water. Metal and clay are the major raw materials to produce the stove.

All the joints in the casing are either riveted/ folded and no welding, soldering or brazing is required. The recommended thickness of sheet steel for casing is between 0.5 – 0.8mm. It uses charcoal or briquette as fuel which is continuously fed into the upper part of stove**.** Charcoal stoves are the most widely used for “Wat” cooking, water boiling, coffee making and other related activities in urban and semi urban area of Ethiopia. The use of these stoves increases with the rapid growth of urban population of the country. From an energy point of view, charcoal is not a positive conversion of wood. Even though traditional charcoal stoves are usually more efficient than traditional three-stone stoves,

2.4.3 Tikikil Stove

The Tikikil stove is an improved wood-fuelled cooking stove of the ‘rocket stove’ design. The stove is manufactured in a small back-yard business described in a recent report by Freere (2011).

Tikikil stove is used for cooking. It uses firewood as fuel which is continuously fed into the combustion chamber**.** Scrap galvanized sheet metal is made into the cladding while the ceramic liner is made of clay mixture

2.4.4 Gounzie Stove

The Ethiopian Rural Energy Development and Promotion Center develop Gonzie stove in 1994, which serve as cooking and baking to make available affordable fuel saving stoves to the rural areas. Gonzie stove is made with mold but with no groves rather each closing another component.

Thus the Gonzie has a maximum diameter, to the size of the mold, does not have a minimum diameter. It can be reduced to suit the purpose or size of the stove. The Gonzie multi-purpose stove attains an efficiency of 23%. It has fuel saving potential of 54% for baking, 42% for cooking compared with traditional practices [4].

2.4.5 Mirt Stove

Mirt is an enclosed Injera stove designed by the former Ethiopian Energy studies and Research center of the Ministry of Mines and Energy. The name Mirt means best. The basic design of Mirt is adopted from those of the Ambo and Burayu enclosed Injera stoves by optimizing to handle different types of fuels. The stove has six parts. Four arcs which fit together to form the circular combustion chamber & two-U-shapes that form circular pot rest. The four arcs of the combustion champers enable the stoves to avoid cracks due to thermal stresses & also help to handle & transport the stove easily. The U-shape part is used for pot rest & chimney purposes. The components of Mirt stove energy saving stove mold are side mold, exit smock mold, wood intern mold and mold for dish.

	**Tradition three stone** open fire cook stove which uses wood as fuel.
	**Lakech stove** uses charcoal or briquette as fuel. Fuel is fed on upper part of stove
	**Tikikil stove** which uses wood as fuel and the fuel is fed on bottom part of the stove
	**Gounzie Stove** it uses wood as a fuel and serves both for cooking and baking.
	**Mirt stove** is an enclosed Injera stove which uses wood as fuel

Table 2.1 cooking stoves which are mostly used in Ethiopia

2.5 History on Thermal and Emission Characteristics of the Stoves

- **Mirt** and **Gonzie** consumed **67.15%** and **79.56%** of the wood consumed by **traditional stove**. Mirt burned only **84.40%** of the amount of wood consumed by Gonzie stove. (Amare, *et al.2015).* The length of time the stoves gave energy sufficient to bake additional 'Injera' was 1.63 and 1.5 times the length of traditional stove burned, for Mirt and Gonzie respectively. Mirt gave a burning time of 0.08 times longer than Gonzie.
    - The local stove for Injera baking has no charcoal extract. The weight of charcoal extracted from Mirt stove was averagely higher than that of Gonzie. Open fire or local stove damage to what would have been saved as a by-product (charcoal) to be used for stew and coffee making.
- **Tikikil stoves efficiency-**Thermal efficiency of 28% has been obtained in laboratory tests. This efficiency translates to a fuel saving potential of up to 50% compared with a three-stone stove.
    - Wood saving potentials of energy efficient stoves are gauged by the percentage of fuel wood that can be saved as a result of employing these stoves.
    - The calculation is based on efficiency evaluations and testing data of the Ministry of Water and Energy as well as donor organisations active in the promotion of efficient stoves (e.g., GIZ).

CHAPTER THREE

3. EXAMINING TIKIKIL STOVE BY EXPERIMENT AND COMPUTATIONAL FLUID DYNAMICS

Introduction

In this chapter the performance of Tikikil stove is studied by conducting experimental analysis which is water boiling test and by means of computer-based CFD simulation. The main work under taken in experimental analysis is experiments specific to stove, namely water boiling tests, durability test and emission test. The lifetime or durability test of this Ethiopian tikikil stove is done by GIZ organization, but the main focus of this chapter is on Water boil test (WBT).

The heat transfer characteristics of Tikikil cook stove is modeled in fluent using the considerations; 3D, incompressible and laminar flow. It is also assumed to be steady where the flow variables become independent of time.

This chapter includes;

- The necessary governing equations that FLUENT uses to solve the flow in the biomass cook stove (tikikil stove) along with the method of numerical computation of the flow variables which describes the numerical approach to solve the flow variables during CFD simulation. Such as;
    - Energy equation, First law of thermodynamics and laminar flow can be modeled to solve numerical value of the parameters such as; the temperature and velocity profiles, location and magnitude of losses, and the heat transfer contributions through various modes.
- The geometry of biomass tikikil stove which is modeled by solid work and its detail component
- The major steps involved in the simulation analysis including boundary conditions used for simulation of fluid flow and heat transfer
- The steps used when conducting water boiling test.

3.1 Experimental Analysis

The goal of experimental work is to determine the location and magnitude of heat losses from the series of stoves so that greatest losses can eventually be minimized in design. Ideally, with 100% efficiency, the energy input from the wood should equal the energy transferred to the water. In reality, however, about 90% of this energy input from open fires is lost to the environment. For the rocket stove, this is reduced to about 70% [1]. These losses can be quantified in several main areas: energy lost in the combustion gases, convection and radiation losses from the stove, convection and radiation losses from the pot, energy stored in the stove, and energy stored in the pot. There will also be some other losses not accounted for in the model.

Concerns over these issues have led research teams to develop new models of stoves to provide improved heat transfer to the pans and more complete combustion of the fuel. While use of these stoves has shown considerable improvement over traditional stoves and open fires, there is still room for additional improvement. Several important stove design parameters were varied for efficiency and loss comparisons. First, the stove inlet diameter was an important factor to the amount of wood fed into the stove. Second, the chimney height had a drastic impact on the heat radiation from the flames to the pan. Third, the gap between the top of the stove and the bottom of the pot influenced how much heat from the flue gasses and flames was transferred to the pot. Fourth, the amount of insulation in the stove influenced how long it took to heat up the stove and thus affected the efficiency. Finally, use of a skirt around the pan increased heat transfer around the perimeter of the pan. These factors were varied from a baseline setup to examine their effects on stove performance.

To optimize geometry of Tikikil stove major energy loss area of the stove has to be identified. Therefore in order to measure parameters and record important data the WBT test is a good option, because it is cheap and available test type.

3.1.2 Components and Property of Tikikil Stove

The stove is made up of six components. Figure below shows the disassembled stove, the six components are: outer shield, inner shield, main metal casing (with wooden handles), grate, cylindrical ceramic liner, and circular ceramic base plate. GIZ SUN Energy (Sustainable Utilization of Natural Resources) has been lately working with local potters and metal artisans for local manufacturing of a household rocket stove which would be affordable for low income households. “Tikikil” is tailor made and optimized to accommodate a 25 cm diameter of pot size which is typical size used in households. The stove’s inner clay liner for the combustion chamber is cladded with sheet metal on the outside. The clay liner is produced by local potters while the metal cladding is done by metal artisans. The stove has non-removable skirt. The wood shelf is made up of 5mm radius round metal bar. At present the retail price of the stove is estimated to be about USD 8.50 (ETB 178). Diameter of outer shield 342 mm, diameter of inner shield 292 mm, height of shield 85mm, diameter of main casing 203 mm, total height from the floor 390 mm, clearance base floor 16 mm, grate width 154mm , grate length 317mm.

Figure 3.1 Component of tikikil stove

3.1.3 Thermal Characteristics Stove

Stove characteristics are burning rate, firepower, turn-down ratio and the measure stoves commonly uses are Efficiency and performance measures which include time to boil, specific fuel consumption, thermal efficiency and Emission measures like emissions per fuel burned, emissions per MJ, emissions per task

- Burning Rate – A measure of the average grams of wood burned per minute during the test.
- Firepower – Firepower is a measure of how quickly fuel was burning, reported in Watts (Joules per second). It is affected by both the stove (size of fuel entrance/combustion chamber) and user operation (rate of fuel feeding). Generally it is a useful measure of the stove's heat output.
- Turn-Down Ratio – Turn-Down ratio indicates how much the user adjusted the heat between high power and low power phases. A higher value indicates a higher ratio of high power to low power, and could signal a greater range of power control in the stove. However, this value reflects only the amount of power control that was actually used.

Thermal Efficiency;

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. So a higher thermal efficiency indicates a greater ability to transfer the heat produced into the pot. While thermal efficiency is a well-known measure of stove performance, a better indicator may be specific consumption, especially during the low power phase of the WBT. This is because a stove that is very slow to boil may have very good looking temperature efficiency (TE) because a great deal of water was evaporated. However the fuel used per water remaining may be too high since so much water was evaporated and so much time was taken while bringing the pot to a boil Efficiency is one of the most common metrics taken from the Water Boiling Test. The test is supposed to help stove designers understand how well energy is transferred from the fuel to the cooking pot. However, the measurement of energy transfer is incomplete, leading to a misrepresentation of thermal efficiency. The energy transferred to the water is actually the sum of the latent heat, sensible heat, and the heat transferred away from the pot via convection, conduction, and radiation.

3.1.4 Testing Performance of Biomass Cook Stove

The performance of a biomass cook stove can be characterized in two categories thermal performance and emission performance. Thermal performance is measured in terms of fire power or input power of the cook stove, specific fuel consumption, efficiency and turn down ratio, while emission performance is measured mainly in terms of emission ratio so emission factors of pollutants. Performance of biomass stoves shows a strong dependence on operation parameters, characteristics of the fuel used, sizes and types of pots used, the type of cooking process, ambient conditions, the ventilation levels, etc. This gives rise to the need for precise definition of the various performance parameters on one hand, and on the other, it necessitates reporting of the operating conditions precisely, while presenting the experimental results.

3.1.4.1 Water Boiling Test (WBT)

The Water Boiling Test (WBT) is a simplified simulation of the cooking process. It is intended to measure **how efficiently a stove uses fuel to heat water in a cooking pot.** The Water Boiling Test was developed to assess stove performance in a controlled manner and In order to confirm desired impacts (whether it is fuel conservation, smoke reduction, or other impacts), stoves must be measured under real conditions of use. The type and characteristics of fuel you will use. The type, size and moisture content of fuel have a large effect on the outcome of stove performance tests. An excellent stove will have good measures of efficiency, emissions, and other performance such as time-to-boil. Intermediate stoves may not perform as well in one of these categories.

The WBT data calculation sheet developed consists of three phases which are known as cold start, hot start and simmer test procedures also the equation or formula used to calculate thermal efficiency, burn rate, and specific fuel consumption, time to boil and also fire power are discussed in detail. The calculation excel data work sheet for WBT is shown on appendix-1 of this paper

- The three phases conducted in water boiling test. This combination of tests is intended to measure the stove’s performance at both high and low power outputs, which are important indicators of the stove’s ability to conserve fuel.

1) In the first phase, the tester begins with the stove at room temperature and uses a pre-weighed bundle of wood to boil a measured quantity of water in a standard pot. The tester then replaces the boiled water with a fresh pot of cold water to perform the second phase of the test. Known as cold start phase

2) In the second phase, water is boiled beginning with a hot stove in order to identify differences in performance between a stove when it is cold and when it is hot. its known as hot start phase

3) Lastly, the tester again boils a measured amount of water and then, using a pre-weighed bundle of wood, simmers the water at just below boiling for a measured period of time (45 minutes).

- **Variables which are constant**

HHV - Gross calorific value (dry wood) (kJ/kg) Higher heating value (also called gross calorific value). This is the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel if it is completely combusted and the combustion products are cooled to room temperature such that the water produced by the reaction of the fuel-bound hydrogen is condensed to the liquid phase.

HHV of wood used for this analysis = 19,500kJ/kg

LHV - Net calorific value (dry wood) (kJ/kg); Lower heating value (also called net heating value).This is the theoretical maximum amount of energy that can be extracted from the combustion of the moisture-free fuel if it is completely combusted and the combustion products are cooled to room temperature but the water produced by the reaction of the fuel-bound hydrogen remains in the gas phase.

LHV of biomass wood used for this analysis = 18,595kJ/kg

MC - Wood moisture content (% - wet basis); this is the % wood moisture content on a wet basis, defined by the following formula:

$$MC = \frac{\text{mass of wet fuel} - \text{mass of dry fuel}}{\text{mass of wet fuel}} \ldots\ldots\ldots\ldots\ldots\ldots \quad (3.1)$$

MC is a decimal fraction which is formatted in the WBT spreadsheet as a percentage. Therefore, if the spreadsheet shows that MC = 15%, a value of MC=0.15 is used for the calculations.

- **Variables which are calculated from the measured result and constant parameters**

F $_{c\,m}$ – The **fuel consumed (moist)** is the mass of wood used to bring the water to a boil, found by taking the difference of the pre-weighed bundle of wood and the wood remaining at the end of the test phase:

$$F_{cm} = f_{ci} - f_{cf} \ldots\ldots (3.2)$$

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

W $_{c\,v}$ – The **mass of water vaporized** is a measure of the water lost through evaporation during the test. It is calculated by subtracting the initial weight of pot and water minus final weight of pot and water.

$$W_{cv} = P_{wi} - P_{wf} \ldots\ldots (3.3)$$

W $_{c\,r}$ – The **effective mass of water boiled** is the water remaining at end of the test. It is a measure of the amount of water heated to boiling. It is calculated by simple subtraction of final weight of pot and water minus the weight of the pot.

$$W_{cr} = P_{wf} - P_{wi} = 5\mathrm{k} \ldots\ldots (3.4)$$

Δt c - The **time to boil pot;** is the difference between start and finish times:

$$\Delta t_c = t_{cf} - t_{ci} \ldots\ldots (3.5)$$

F $_{c\,d}$ – The **equivalent dry fuel consumed** adjusts the amount of dry fuel that was burned in order to account for two factors: (1) the energy that was needed to remove the moisture in the fuel and (2) the amount of char remaining unburned. The mass of dry fuel consumed is the moist fuel consumed minus the mass of water in the fuel:

$$Dry\ fuel = f_{cm}(1 - MC) \ldots\ldots (3.6)$$

The energy that was needed to remove the moisture in the fuel ($\Delta \mathbf{E}_{\mathbf{H2o},\,c}$) is the mass of water in the fuel multiplied by the change in specific enthalpy of water.

$$\Delta E_{H2o,c} = \Delta m_{H2o,c}(C_p(T_b - T_{fuel,initial}) + \Delta h_{H20,fg}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.7)$$

$C_p \approx 4.186$ kJ/kg K $\Delta h_{\mathbf{H2o},\,fg} \approx 2{,}257$ kJ/kg $T_{fuel,\,initial} \approx T_a$

The mass of water in the fuel is; $m_{\mathbf{H2o},\,c} = f_{\mathbf{c\,m}}\ MC$

Therefore equation (3.7) will be rewritten; $\Delta E_{\mathbf{H2o},\,c} = f_{\mathbf{c\,m}}\ MC\ (4.186\ (T_b - T_a) + 2{,}257)$

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

$$\text{Fuel to evaporate water} = \frac{\Delta E_{H2o,c}}{LHV} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.8)$$

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

$$\text{Fuel}_{\text{ in char}} = \frac{\Delta Echar,c}{LHV} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.9)$$

Putting it together we will have;

$$f_{c\,d} = \text{dry fuel} - \text{fuel to evaporate water} - \text{fuel in char}$$

$$f_{c\,d} = fc\ m(1 - MC)\,\frac{fcm\ MC\ (4.186(Tb - Ta)\ +2.257}{LHV} - \frac{\Delta Cc\ LHVchar}{LHV}$$

$$f_{c\,d} = \frac{fcm(LHV\ (1 - MC)\ -MC\ \ (4.186(Tb - Ta)\ +2.257)) - \Delta Cc\ LHVchar}{LHV} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3.10)$$

***η* – Thermal efficiency**: This is a ratio of the work done by heating and evaporating water to the energy consumed by burning fuel. It is an estimate of the total energy produced by the fire that is used to heat the water in the pot. It is calculated in the following way:

$$\eta = \frac{\Delta E_{H2o,heat} + \Delta E_{H20,evaported}}{E_{released,c}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.11)$$

The energy to heat the water is the mass of water time’s specific heat capacity time’s change in temperature:

$$\Delta E_{H2o,\,heat} = m_{H2o}\, C_p\, \Delta T \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.12)$$

The specific heat capacity can be approximated as;

$$C_p \sim 4.186 \frac{KJ}{KgK}$$

$$\Delta E_{H2o,\,heat} = (P1_{Ci} - P1)\ 4.186(T1_{Cf} - T1_{Ci}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.13)$$

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

$$\Delta E_{H2o,\,evaporated} = W_{c\,v}\, \Delta h_{H2o,\,f\,g} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.14)$$

As explained in the EHV equation above, the specific enthalpy of vaporization can be approximated as:

$\Delta h_{H2o,\,f\,g} \approx 2{,}260$ kJ/kg and

$$\Delta E_{H2o,\,evaporated} = W_{c\,v}\, 2{,}260\ kJ/kg$$

The energy consumed is the equivalent mass of dry fuel consumed multiplied by the heating value: $E_{released,\,c} = f_{c\,d}\, LHV$

Putting all together thermal efficiency on equation (2.11) will be;

$$\eta = \frac{4.186\left(T_{1cf} - T_{1ci}\right)\left(P_{1ci} - P_1\right) + 2260 w_{cv}}{f_{cd}\ LHV}$$

The thermal efficiency is actually a unit less decimal fraction but it is formatted in Excel as a percentage.

$R_{c\,b}$ – Burning rate: This is a measure of the rate of fuel consumption while bringing water to a boil. It is calculated by dividing the equivalent dry fuel consumed by the time of the test.

$$R_{c\,b} = \frac{F_{cd}}{\Delta t_c} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.15)$$

SC_{cold}- Specific fuel consumption: Specific consumption can be defined for any number of cooking tasks and should be considered "the fuel required to produce a unit output" whether the output is boiled water, cooked beans, or loaves of bread. In the case of the 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. It is calculated as:

$$SC_c = \frac{F_{cd}}{W_{cr}} \quad \ldots\ldots (3.16)$$

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

$$\mathbf{FP}_{\mathbf{c}} = \frac{F_{cd}\,\text{LHV}}{\Delta tc\; 60} \quad \ldots\ldots (3.16)$$

Note, by using $F_{c\,d}$ in this calculation, we have accounted for both the remaining char and the fuel moisture content:

3.1.4.2 Instruments Used For the Experimental Procedure

1. Digital Thermometer, accurate to 0.5 degree C, with thermocouple probe suitable for immersion in liquids
2. Wood moisture meter or oven for drying wood and scale for weighing (moisture meter is less accurate, especially for very wet wood)
3. Timer
4. Tape measure for measuring wood and stove (cm)
5. Standard pots: pots that are used in the region of interest have a volume of about 7 liters (for 5-L tests) or 3.5 liters (for 2.5-L tests). For each size, they should choose a standard shape (height and circumference)
6. Small shovel/spatula to remove charcoal from stove
7. Metal tray to hold charcoal for weighing

1. Mass balance 2. Thermocouple 3. Infrared thermometer

4. Cook pot 5. Wood

Figure 3.2 Instruments used for this experimental procedure

3.1.4.3 Procedure of the Experiment

1. Determining the type and characteristics of fuel used. The type, size and moisture content of fuel have a large effect on the outcome of stove performance tests. Therefore solid fuel should be well dried and uniform in size. Fuel between1.5 x 1.5 cm to 3 x 3 cm is suggested.
2. To ensure the safety and health of the tester, a breathing mask and eye protection should be used.
3. The type of pot used, and record its size and shape.
4. For water boil test general condition to be considered are air temperature (^{0}C), air relative humidity (%), local boiling point of water.
5. Place the pot on the stove. Using thermocouple water temperature will be measured in the center also measure initial temperature of water and Start the fire in a reproducible manner according to local practices. Once the fire has caught, start the timer and record the starting time. Bring the pot rapidly to a boil without being excessively wasteful of fuel using wood from the pre-weighed bundle. Control the fire with the means commonly used locally. Time, Start (hr: min)
6. The temperature of the water and infrared thermometer reading of various metal temperatures were recorded roughly. The average rate of temperature rise in the water

was calculated and reported; this gives an indication of the power which is one surrogate for the thermal stress placed on the stove.

The water was assumed to be fully boiling when a rolling boil occurred. The infrared thermometers were moved to various metal or ceramic components of the stove between test cycles. Metal surfaces expected to be particularly hot were preferentially selected, although some cooler surfaces were also measured.

7. When the water in the pot reaches the pre-determined local boiling temperature as shown by the digital thermometer, rapidly do steps a and b.
   a. Record the time at which the water in the pot first reaches the local boiling temperature. Record this temperature also. Time, Finish Water temperature, Finish hr: min °C
   b. Remove all wood from the stove and extinguish the flames. Flames can be extinguished by blowing on the ends of the sticks or placing them in a bucket of ash or sand; do not use water – it will affect the weight of the wood. Knock all loose charcoal from the ends of the wood into the container for weighing charcoal. Weigh the unburned wood removed from the stove together with the remaining wood from the pre-weighed bundle. Extract all remaining charcoal from the stove. Weigh this remaining charcoal with the charcoal that was knocked off the sticks. Weight of fuel, Finish Weight of charcoal+ container, Finish

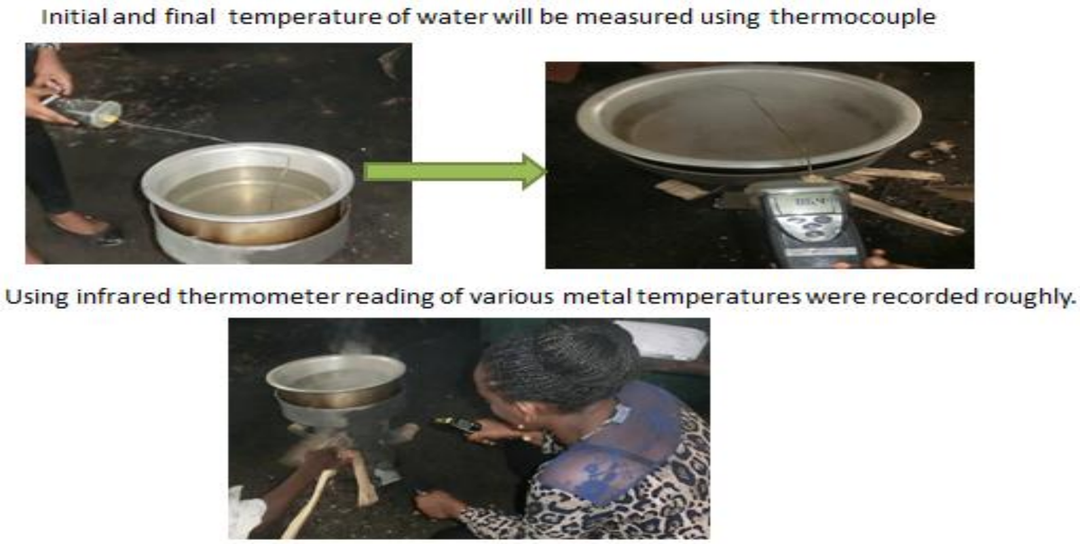


Figure 3.3 some procedure of the experiment

3.1.5 Result of the Experiment

- The test typically lasted about 30 to 60 minutes at which point excess wood was removed but the water was allowed to simmer for a further 45 minutes drawing on the heat from the burning charcoal.
- The average water heating rate (5L water) for all tests was 4.22^0C/min.
- The average fuel required to bring 5L of water to the boil was 0.625kg. There was not a statistically significant difference between wood species the cold start tests used about 25% more wood than the hot start tests. Reduced fuel use for hot-start tests was more pronounced for the dense, dry hardwood.
- The stove performed slightly better when a centimeter or so of ash was left in the base of the combustion chamber. This meant slightly less air passing up through the grate which seemed to improve combustion and ease of lighting.
- During the light-up stage sometimes large quantities of smoke were produced but once the stove warmed up there was little visible smoke.

No	Measured surfaces	Average temperature (^{0}C)
1	Temperature of Pot surface	95.5
2	Temperature of base plate	309
3	Flue gas temperature	563
4	Temperature of ceramic cylindrical body (inner part)	524
5	Temperature of sides of pot skirt ;	170
6	Temperature of inner part of pot skirt	220
7	Temperature of drip pan (top plate cone surface)	300

Table 3.1 the measured data for energy balance calculation

The data collected from the experiment will be inserted in WBT work sheet to get the numerical value of the thermal efficiency, burn rate, specific fuel consumption and firepower used to boil 5Litre of water by using this biomass cook stove. Also the energy balance of the stove will be calculated by measured surface temperature values of this experiment and the detail analysis of the energy balance will be discussed in the next chapter of this paper.

No	Parameters	Test -1		Test -2		Test -3	
		Cold start	Hot start	Cold start	Hot start	Cold start	Hot start
1	Time to boil the water	42 min	22 min	64 min	26 min	42 min	22min
2	Burn rate	12g/min	17g/min	10g/min	16g/min	11g/min	17g/min
3	Fire power	3765W	5484W	3407W	5220W	3649W	5617W
4	Thermal efficiency	26%	28%	20%	29%	29%	31%

Table 3.2 -Test result of WBT

- The average thermal efficiency obtained from experimental investigation is 27%.
- The average time required to oil 5L of water is 36minute.

3.2 Computational Fluid Dynamics

Computational Fluid Dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and etc. by means of computer-based simulations. And FLUENT is a CFD package for modeling fluid flow and heat transfer. FLUENT provides CAD/GUI based facility packages for generating unstructured meshes to solve flow problems in complex geometries.

All modes of heat transfer (conduction, convection – forced and natural, radiation, phase change) can be modeled in Fluent. The heat transfer characteristics in the analysis of tikikil cook stove is modeled in fluent using the considerations; 3D, incompressible and laminar flow. It is also assumed to be steady where the flow variables become independent of time. The appropriate physical flow model, which is available in FLUENT, will then be specified, based on these flow characteristics of the stove.

3.2.1 Governing Equations

To determine the temperature distribution, the eight equations must be solved simultaneously for the eight unknowns. The unknown variables are 8: enthalpy h (or internal energy, u), velocity v, pressure p, viscosity μ, density ρ, and thermal conductivity k. Thus the velocity and temperature fields are coupled. For incompressible flows density has a known constant value.

The fluid flow model for cook stove include governing equations such as; conservation of mass (continuity) equation, conservation of momentum (Navier- stokes equation) and conservation of energy (energy equation).

3.2.1.1 First Law of Thermodynamics

It is the law that relates the various forms of energies for system of different types. First law of thermodynamics is simply the expression of the conservation of energy principle. Based on experimental observations, the first law of thermodynamics states that “Energy can be neither created nor destroyed during a process; it can only change forms.” The first law of thermodynamics requires all energy within a system to be conserved, even if it changes forms. In cook stoves, combustion transforms stored chemical energy of the fuel into thermal energy.

Part of this thermal energy takes on the form of flow energy which is responsible for the buoyant flow of hot combustion gases through the stove and past the surface of the pot.

Properly applying the first law to a cook stove leads to a better understanding of the principles governing its operation. The conservation of mass and the conservation of energy principles for open systems or control volumes apply to systems having mass crossing the system boundary or control surface. In addition to the heat transfer and work crossing the system boundaries, mass carries energy with it as it crosses the system boundaries. A cook stove represents an open system since it is characterized by fluid flowing across the boundary of a fixed volume, referred to as a control volume.

The control volume in this case is bounded by the walls of the combustion chamber with the mouth of the stove acting as the inlet and the annulus formed by the pot and stove interface acting as the outlet, as shown in Figure below.

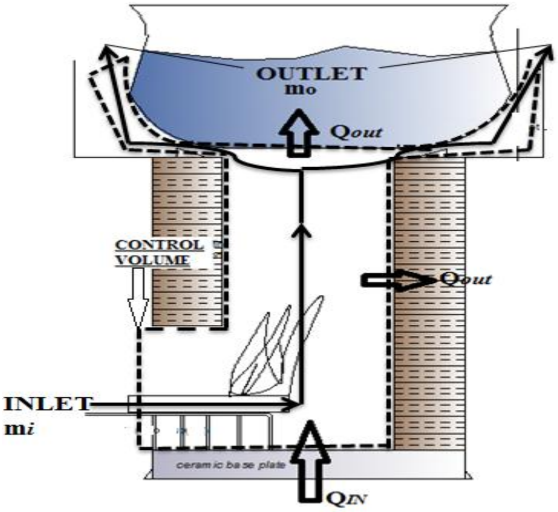


Figure 3.4; Cook stove control volume schematic

If heat transfer efficiency of existing cook stoves is to be accurately assessed and improved upon, then all energy involved in the combustion process must be accounted for. A control volume establishes a finite system boundary to analyze the balance of energy transferred between heat, work, and mass flow.

- ***Heat Transfer***, (Q) Heat transfer to a system (heat gain) increases the energy of the molecules and thus the internal energy of the system and heat transfer from a system (heat loss) decreases.
- ***Work Transfer***, (W) Work transfer to a system (i.e., work done on a system) increases the energy of the system, and work transfer from a system (i.e., work done by the system) decreases.
- ***Mass Flow***, (m) When mass enters a system, the energy of the system increases because mass carries energy with it (in fact, mass has energy). Likewise, when some mass leaves the system, the energy contained within the system decreases.

The rate of mass flow energy transfer to or from a system is represented by equation below

$$rate\ of\ energy\ flow = \dot{m} \times \theta$$

Where $\dot{m}$ -- is bulk mass flow rate of fluid

θ -- is total energy of a flowing fluid per unit mass

The total energy of a flowing fluid per unit mass can be broken down further into its fundamental components as

$$\theta = Pv + (u+ke+pe)$$

$$\theta = h + ke + pe$$

Where: Pv– flow energy of moving fluid

P – Pressure difference at the location

V– Specific volume of the fluid

U– Internal energy

Ke– kinetic energy

Pe– potential energy

h – enthalpy

Thermodynamic processes involving control volumes can be considered in two groups: steady-flow processes and unsteady-flow processes. A cook stove is evaluated assuming isobaric steady-flow conditions where bulk mass flow rate remains constant. These assumptions ignore transient effects since these add significant complexity to the energy balance calculations with minimal gains in accuracy. Additionally, most of the time users spend cooking typically when the stove past the "warm up" stage and steady state assumptions are valid. Other simplifying assumptions include constant kinetic and potential energy between the inlet and outlet of the control volume, zero mechanical work, and ideal gas behavior.

Based on these assumptions, the energy balance of a cook stove is evaluated through the following relationships;

$$\dot{E}_i = \dot{E}_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots (3.17)$$

$$\dot{Q}_i + \dot{W}_i + \sum_i \dot{m}i\,\theta = \dot{Q}_o + \dot{W}_o + \sum_i \dot{m}o\theta$$

$$\dot{Q}_i - \dot{Q}_o = \dot{m}\,(\theta_o - \theta_i)$$

$$\dot{Q}_i - \dot{Q}_o = \dot{m}\,(h_o - h_i)$$

$$\dot{Q}_i - \dot{Q}_o = \dot{m}_{Cp,avg}(T_o - T_i)$$

Where: Subscripts i and o – inlet and outlet variables, respectively.

$\dot{Q}$ – rate of heat transfer

$\dot{W}$ – rate of work transfer

$\dot{m}_{Cp,}$ – average constant pressure specific heat of air between T_i and T_o

T – Gas temperature

3.2.1.2 Energy Equation

The first law of thermodynamics requires that the energy of a system be conserved. This means that the amount of energy entering a system must equal the amount of energy leaving the system. The 3-dimensional energy equation for fluid flow is provided below in equation

$$\frac{\partial}{\partial t}\left(\rho C_p T\right) + \frac{\partial}{\partial x}\left(\rho v_x C_p T\right) + \frac{\partial}{\partial y}\left(\rho v_y C_p T\right) + \frac{\partial}{\partial z}(\rho v_z\ C_p T) = \frac{\partial}{\partial x}\left(k_{xx}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_{yy}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_{zz}\frac{\partial T}{\partial z}\right) + Q_v \quad \text{……} (3.18)$$

3.2.1.3 Laminar Flow Model

To identify the type of flow inside cylinder Reynolds number has been calculated in chapter four of this paper as result the flow is laminar. Because for fully developed internal flow Reynolds number ($Re < 2300$) is laminar flow. Therefore use of laminar model is necessary.

A variety of correlations are in use for predicting heat transfer rates in laminar flow. From dimensional analysis, the correlations are usually written in the form

Nu = f (Re, Pr, …) Where $Nu = \frac{hD}{K}$ is Nusselt Number, *f* is some of function and ………(3.19)

$Pr = \frac{\mu_{gas}\, c_{p\_gas}}{K_{gas}} = \frac{v}{\alpha}$ is Prandtl number. ……………………………………..………….. (3.20)

Here *h* is heat transfer coefficient, k is thermal conductivity of the fluid and C_p specific heat of fluid at constant pressure. The Prandtl number can be written as the ratio of the kinematic viscosity v to the thermal diffusivity of the fluid α.

Efficient heat transfer in laminar flow occurs in the thermal entrance region. A reasonable correlation for the Nusselt number was provided by Sieder and Tate.

$$Nu = 1.86\, Re^{1/3}\, Pr^{1/3} (\frac{D}{L})^{1/3} (\frac{\mu_b}{\mu_w})^{0.14} \text{……} (3.21)$$

As the length of the tube increases, the Nusselt number decreases as $L^{1/3}$. This does not, however, imply that the Nusselt number approaches zero as the length becomes large. This is because the Sieder-Tate correlation only applies in the thermal entrance region. In long tubes, where in most of the heat transfer occurs in the thermally fully-developed region, the Nusselt number is nearly a constant independent of any of the above parameters. When the boundary condition at the wall is that of uniform wall temperature Nu = 3.66. If instead the flux of heat at the wall is uniform, Nu = 4.36, but in this case we already know the heat flux and a heat transfer coefficient is not needed. Remember that the purpose of using a heat transfer coefficient is to calculate the heat flux between the wall and the fluid. In the case of uniform wall flux, we can use an energy balance directly to infer the way in which the bulk average temperature of the fluid changes with distance along the axial direction.

Notice that a ratio $\frac{\mu_b}{\mu_w}$ appears in the above laminar flow heat transfer correlation. We have defined μ as the viscosity of the fluid. The subscripts "*b*" and "*w*" stand for "bulk" and "wall," respectively. We know that the bulk temperature of the fluid will change along the tube. The wall temperature may be constant, or it may vary along the length of the tube. In all cases, we can use an arithmetic value of the average between the extreme values that occur in the system.

Because the exponent (0.14) is small, the effect of this term on the Nusselt number is not large it is only a small correction, and this averaging is quite justified. In fact, for all the other physical properties such as density, thermal conductivity, and specific heat, we should estimate values at the average temperature of the fluid between the inlet and outlet.

The Reynolds and Pradntl numbers are raised to the same power in the laminar flow correlation. Therefore, we can write the correlation as;

$$\mathrm{Nu} = 1.86\, Re^{1/3}\, Pr^{1/3} (\frac{D}{L})^{1/3}\ (\frac{\mu_b}{\mu_w})^{0.14}$$

3.2.2 Major Steps for CFD Analysis in FLUENT

This section provides detail about the simulation process from FLUENT 12.1. There are three major steps involved in the CFD analysis using FLUENT, namely Preprocessing, Processing and Post processing.

Preprocessing is the first step, which includes preparing of the geometrical model for the computation. It consists of creating geometry, mesh generation and set up of boundary zones and specifying physical flow models, fluid properties, boundary conditions, etc. in FLUENT.

Processing is the second step where the solution control and monitoring are carried on along with the actual computation process in FLUENT.

Post-processing is the activity of displaying of graphical results, reporting control variables and plotting of solution files for areas of interest in the flow field.

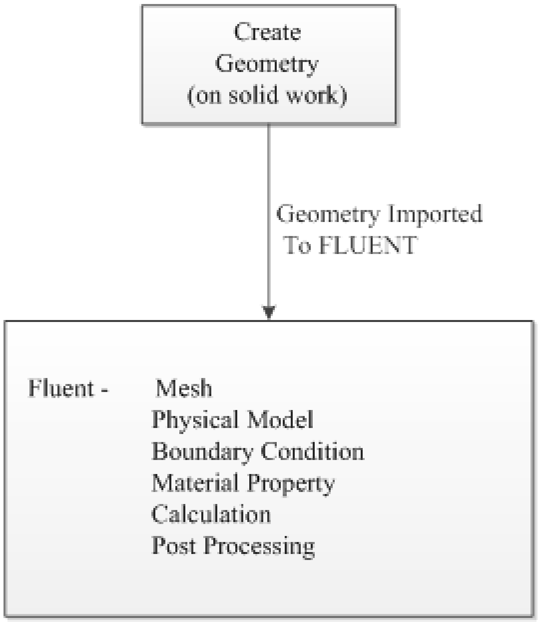


Figure 3.5 the basic procedural steps followed

3.2.2.1 Building Geometry of Tikikil Stove

Geometry of tikikil cook stove is modeled on SOLID work 2012 and imported to ANSYS FLUENT.

- ✓ Some of major assumption made in defining the geometry are;
  - In this simulation process only internal cylindrical part of stove body which is used as combustion chamber of the stove is modeled.
  - The model is developed for the case where there is no cooking pot place on the top of stove
  - Detail component such as metal sheet which covers the cylindrical body and pot skirt has not been included in the simulation process to reduce computational effort.
  - To reduce complexity of mesh the internal cylindrical body and baseplate are considered as one part

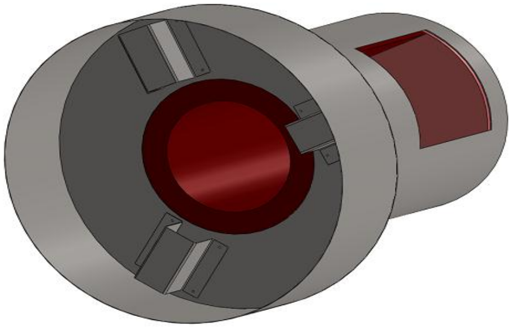
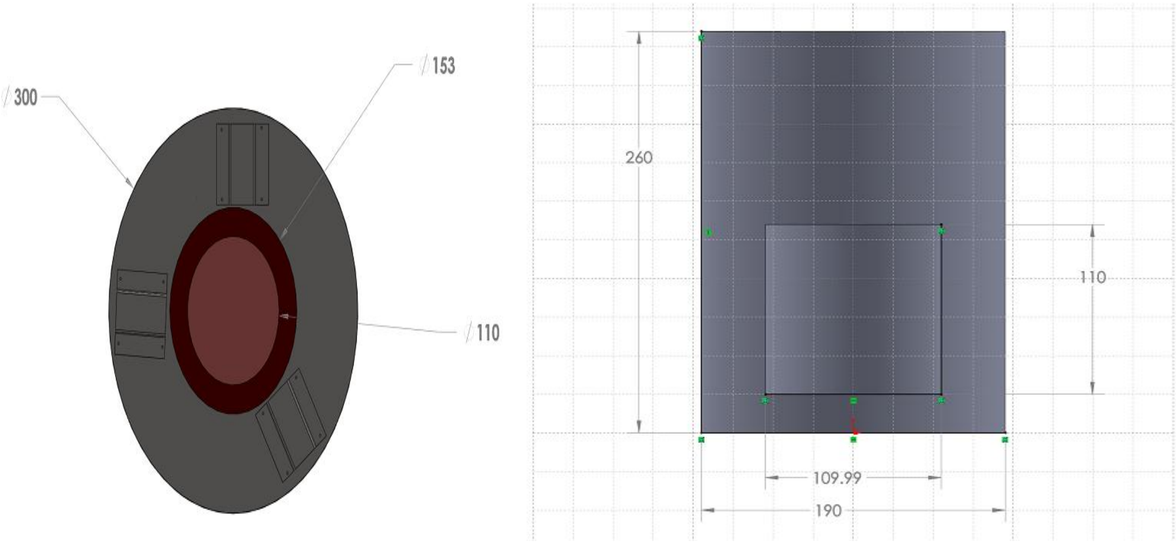


Figure 3.6, 3D View of Tikikil Stove the red color shows the internal part of stove which is made up of clay this component of stove is used as combustion chamber also its insulation for the flame produced by fire inside the chamber.



(a) (b)

Figure 3.7 Top and front view of stove with dimension

In figure 3.7 (a) Top view which includes dimensions such as outer diameter of pot skirt (Ǿ300mm), internal diameter of pot skirt (Ǿ153mm) and internal diameter of cylindrical body (Ǿ110mm) and on figure (b) length of cylindrical part (260mm), outer diameter of cylindrical part (Ǿ190mm) and opening of fuel inlet which has square cross section (110mm x 110mm).

- The heat transfer and fluid flow simulation will be optimized and modeled on internal cylindrical part of tikikil stove which is shown on figure (5.5) below

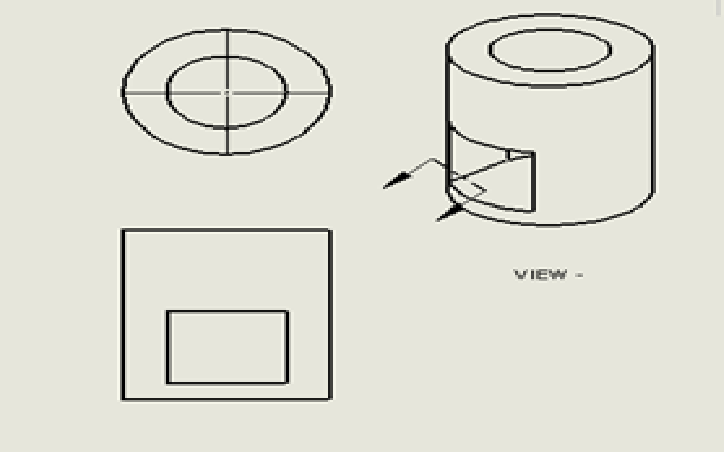
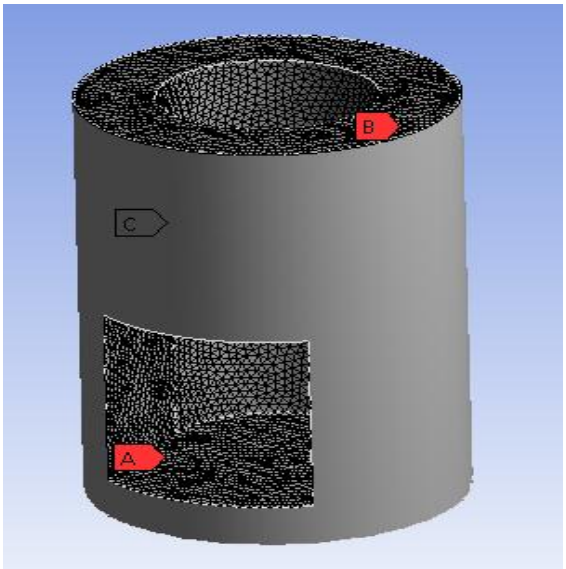
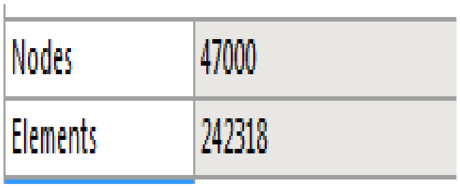


Figure 3.8 -Part Drawing and 3D View of Internal Clay Body Tikikil Stove.

3.2.2.2 Mesh

Solutions by numerical methods require physical discretization/meshing of the domain. A good solution is obtained if good meshes for the models are generated. The accuracy of the solutions depends on the sizes of the meshes.





Nodes	47000
Elements	242318

Figure 3.9 mesh and named selection which is used later as boundary condition in the process

3.2.2.3 Modeling Heat Transfer In Fluent

To model heat transfer the energy equation must be activated. Energy transport equation will be

$$\underbrace{\nabla[v(\rho\epsilon + p)]}_{\text{Convection}} = \nabla.[\underbrace{k_{eff}\,\nabla T}_{\text{Conduction}} - \underbrace{\textstyle\sum_j h_j J_j}_{\text{Species diffusion}} + \underbrace{\tau_{eff} v}_{\text{Viscous dissipatio}}] + \underbrace{S_h}_{\text{Enthalpy source sink}} \ldots\ldots\ldots\ldots (2.22)$$

Energy E per unit mass is defined as; $h - \frac{p}{\rho} + \frac{v^2}{2}$ pressure work and kinetic energy are always accounted for compressible flow or when using density-based solver. For pressure based solver they are omitted and can be added through text command.

- When fluid moves it carries heat with it and this is called convection heat transfer. Heat transfer can be tightly coupled to fluid flow solution. Energy + fluid flow is activated means convection computed.
- At walls the heat transfer coefficient is computed by turbulent thermal wall function

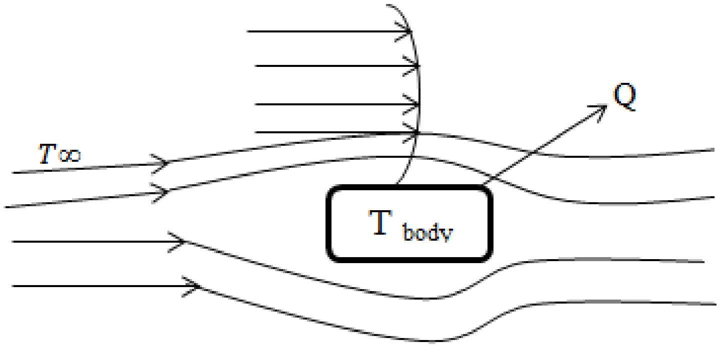


Figure 3.10 heat flow

Q = h ($T_{body} - T_{\infty}$) = h ΔT Where h = average heat transfer coefficient

- The general equation for heat flow is;

$q = UA\Delta T = \frac{A\Delta T}{R}$ Where q = rate of heat flow in watts

U = overall heat transfer coefficient in watts per square meter degree Celsius

A = surface area in square meters

ΔT = temperature difference causing flow in degree Celsius

R = 1/U the overall combined resistance

1. ***General***

FLUENT uses two numerical methods either pressure based or density based solver. Both of them solve the governing integral equations for the conservation of mass, momentum, energy and other scalars such as turbulence. Recently both methods have been extended and reformulated to solve and operate for a wide range of flow conditions beyond their traditional or original intent. In both methods the velocity field is obtained from the momentum equation

ANSYS CFD solvers are based on finite volume method basic technique used consists of:

- Domain is discretized into a finite set of control volumes.
- General conservation (transport) equations for mass, momentum, energy, species, etc. are solved on this set of control volumes
- Partial differential equations are discretized into a system of algebraic equations
- All algebraic equations are then solved numerically to render the solution field

For this CFD analysis the pressure-based solver system is used to analyze the heat transfer and fluid flow simulation of some biomass cook stoves which as different geometry to accurately predict temperature and velocity field above the fuel bed (to calculate heat transfer to the cook pot)**.**

∗ Pressure-Based Segregated Algorithm

The pressure-based approach was developed for low-speed incompressible flows, On the other hand, in the pressure-based approach; the pressure field is extracted by solving a pressure or pressure correction equation which is obtained by manipulating continuity and momentum equations.

In the pressure-based segregated algorithm governing equations are solved sequentially. The individual governing equations for the solution variables (e.g., u, v, w, p, T, k, e etc.) are solved one after another. Each governing equation, while being solved, is decoupled / segregated from other equations. With the segregated algorithm, the iteration consists of the steps shown below:

- Update fluid and solid properties because its fluid-solid conjugated heat transfer system (e.g., thermal conductivity, density, viscosity and specific heat capacity) on the current solution.

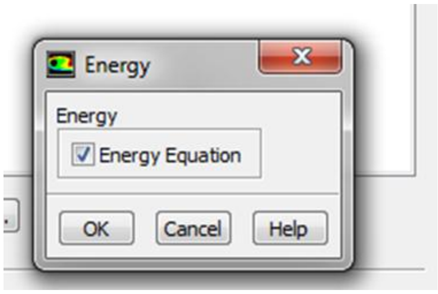
- Solve heat transfer rate and mass flow rate one after another depending on recently updated fluid and solid property also input temperature and input velocity introduced on inlet boundary condition.

∗ **Density based-solver**

The density-based approach was mainly used for high-speed compressible flows. In the density-based approach, the continuity equation is used to obtain the density field while the pressure field is determined from the equation of state."

2. Models

- Energy equation



- Radiation P-1 Model

Radiative transfer equation easy to solve with little CPU demand it includes effect of scattering. Effects of particles, droplets, and soot can be included. It Works reasonably well for applications where the optical thickness is large (e.g. combustion).

3. MATERIALS

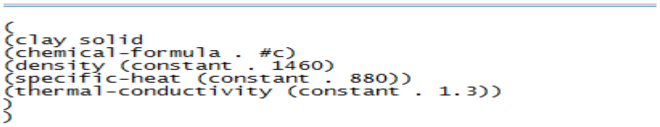
In this section, the materials specified for the different stove components and some of their important properties are stated.

∗ **Solid /Clay**

The internal cylindrical body and base plate are made of low lime, highly insulating clay which can withstand high temperatures and corrosion. Clay is not included in fluent material data base so introduced to the software by using user defined function. Some important properties of the tile are given in table 3.3.

No	Property	Value
At temperature of 300K		
1	Density	1460kg/m^3
2	Specific heat capacity	880J/kg. k
3	Thermal conductivity	1.3K[W/(m. K)]

Table 3.3 the material property of clay



```
(
(clay solid
(chemical-formula . #c)
(density (constant . 1460)
(specific-heat (constant . 880))
(thermal-conductivity (constant . 1.3))
)
)
```

Table 3.4 Defining clay property to fluent software

- **Fluid /Air**

Air is the material specified for the fluid phase occurring in the domain. Even the producer flame gas rising from the fuel bed is specified as air. The property of air which is available from the FLUENT materials library is used.

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

Table 3.5 the material property of air

4. *Boundary Condition*

Different boundary conditions used in this domain is shown on figure (5.8) below

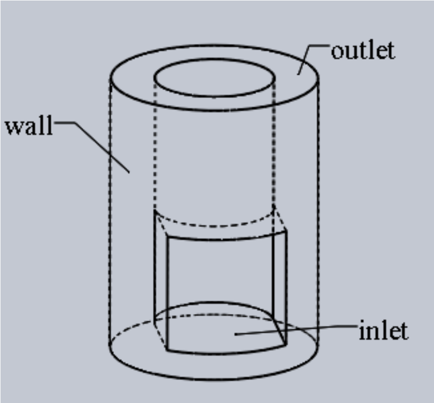


Figure 3.11 Boundary Conditions

- **Stove inlet**

It’s the part where air inters to combustion chamber, the flow property of the entering air is calculated from experimental result and also the following assumptions are taken for this velocity inlet boundary condition.

- Stagnation pressure is ambient pressure
- Neglect the viscous losses due to acceleration of fluid from the surrounding of stove inlet.
- The temperature at stove inlet is assumed to be temperature to burn wood = 227^0 C = 500k
- Fluid velocity at inlet = 0.55m/s

Using the flow velocity of air at this position the Reynolds number for fully developed internal flow through circular pipe will be calculated to identify the type of flow;

$$\mathrm{Re} = \frac{\rho_{gas}\, v_{inlet}\, d}{\mu_{gas}} = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots .. (3.23)$$

ρ – Density of the fluid, Kg/m3

v- Velocity of fluid through cylindrical, m/s

d- Diameter of the circular part, m

μ - Absolute viscosity air, 1atm and 237k, kg/m .s

Therefore Re =1047 which shows the flow is laminar flow

- **Stove Outlet**

This boundary condition is considered as pressure outlet and pressure value will be extrapolated from the flow in the interior. Also all other flow quantities are extrapolated from the interior

- Static pressure = ambient pressure
- Velocity outlet = velocity measured
- Fluid temperature extrapolated from upstream value

∗ At the solid wall

Flow inside the wall is surrounded by clay body which is considered as solid wall. The thermal boundary condition at walls includes:

- Heat flux, temperature, Convective heat transfer, External radiation and Combined external radiation and external convective heat transfer but for this simulation process temperature at wall is specified = 293k
- No slip condition
- On bottom cylindrical part heat changes are negligible but there is conduction heat loss to base plate

5. Computing the Solution

The last step in the CFD analysis of the fluid flow in tikikil stove is initializing the solution and performing calculation by setting number of iteration and the initial guess for starting the solution flow field. The convergence history of the process is displayed on window during iteration of the parameters.

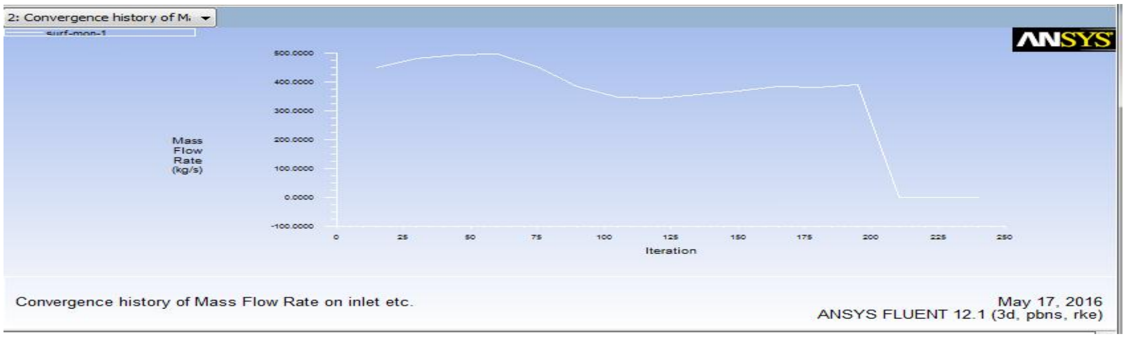
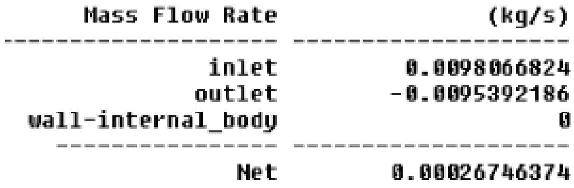


Figure 3.12 Convergence history of mass flow rate



```
           Mass Flow Rate                 (kg/s)
-------------------- --------------------
                inlet           0.0098066824
               outlet          -0.0095392186
   wall-internal_body                      0
     ---------------- --------------------
                  Net           0.00026746374
```

Table 3.6 value of mass flow rate with in domain of stove

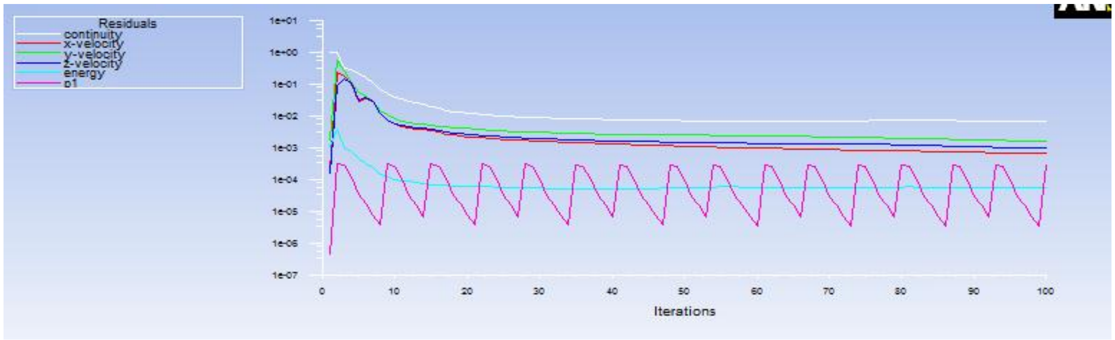


Figure 3.13 scaled residual at the end of iteration

6. **Examining the Result**

In post processing, the results are examined to review the solution and to extract useful data’s. It can be through graphical display or numerical report. In graphical display the overall flow pattern and determination of key flow features can be examined while in numerical reporting necessary integral quantities can be computed at boundaries of the flow domain. Amongst; the mass flow rate on boundaries, the heat transfer rate in the domain for selected wall zones and area-weighted average field variables on a surface in the domain are reported on chapter six of this paper.

3.2.3 Result of CFD Analysis

Heat transfer and fluid flow simulation on fluent assist the development of a simple model which can be used to predict the performance of a given stove. The results of the analysis in FLUENT can be shown by using graphical displays and numerical outputs. The outputs illustrated here are the graphical display and numerical output of Tikikil stove.

3.2.3.1 Graphical Display and Numerical Out Put

1. Graphical Display

Graphical displays allow us to easily view the velocity and temperature profile above fuel bed.

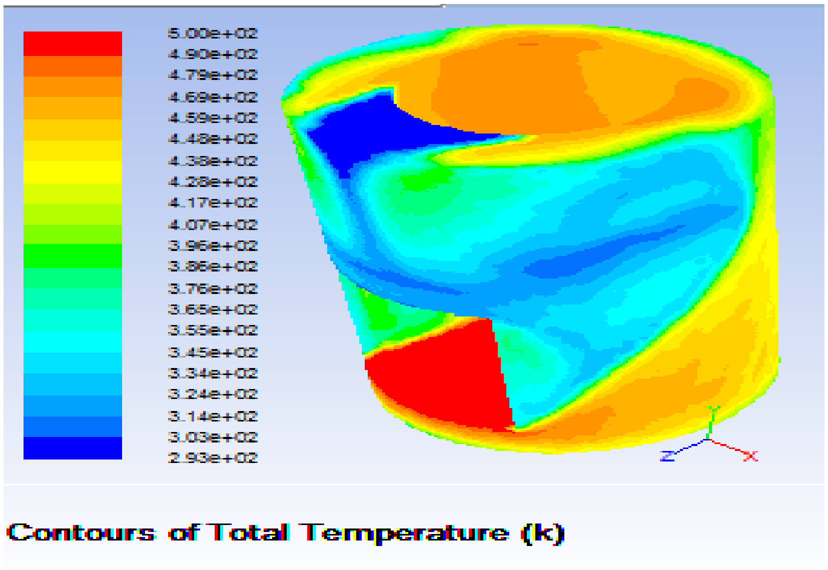


Figure 3.14 Temperature value and profile of tikikil stove

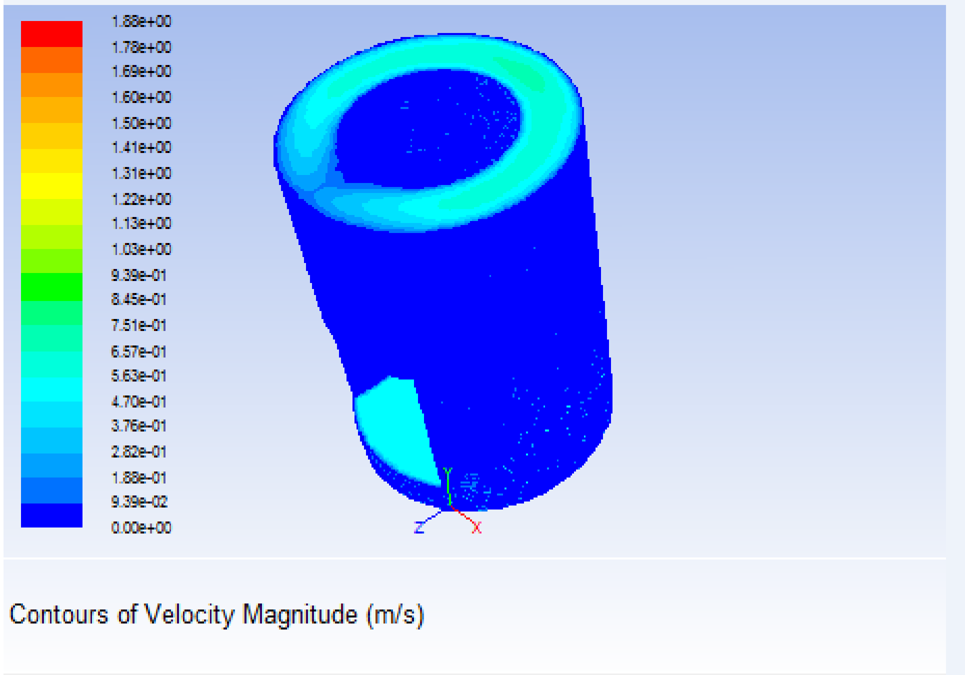


Figure 3.15 Velocity profile of tikikil stove

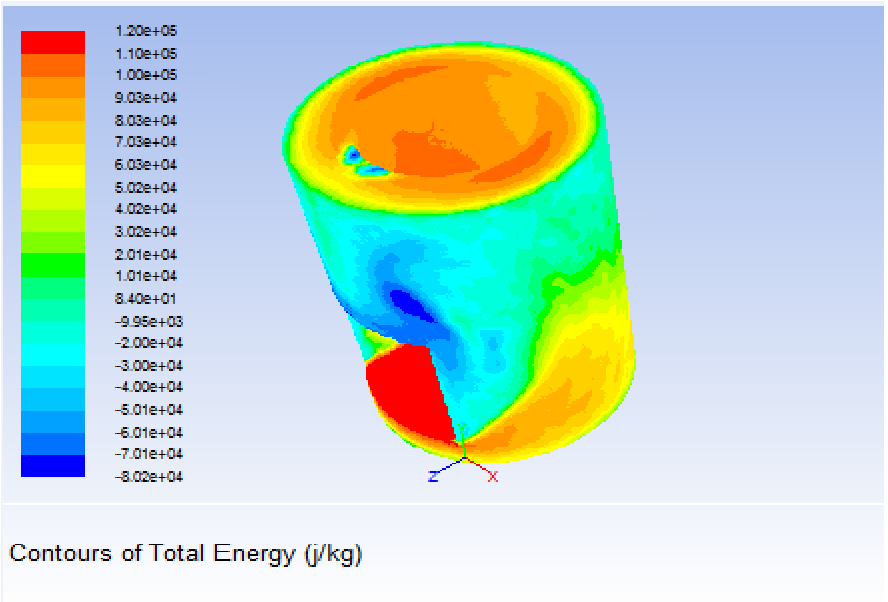
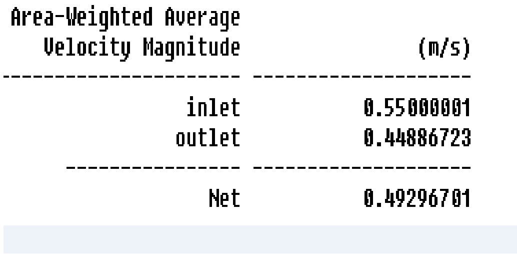


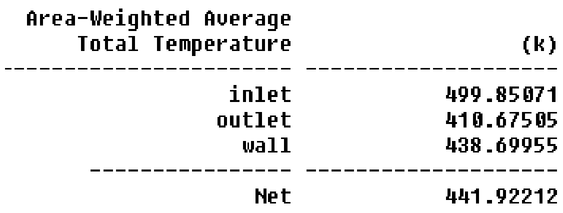
Figure 3.16 Energy contour of tikikil stove

2. Numerical output

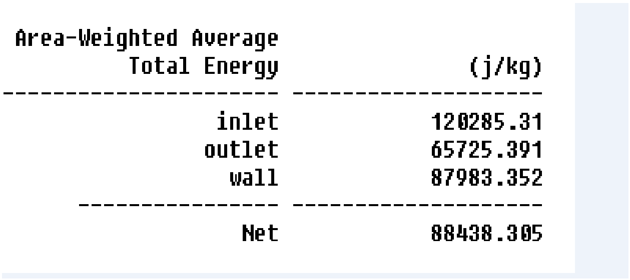
After convergence is reached printed quantitative results like heat transfer rate, velocity outlet, temperature distribution value at the wall and at outlet and surface integrated quantities are taken for the evaluation of design parameters. Reports of area-weighted average field variables on inlet and outlet surfaces, mass flow rate on inlet and outlet are illustrated below. Area-weighted average field variables are the average value of field variables on inlet and outlet surfaces. They are computed by dividing the summation of the product of the selected field variable and facet area by the total area of the surface.



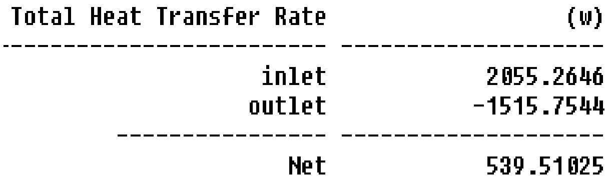
```
  Area-Weighted Average
     Velocity Magnitude                   (m/s)
-------------------------------- --------------------
                        inlet           0.55000001
                       outlet           0.44886723
         ---------------- --------------------
                          Net           0.49296701
```



```
Area-Weighted Average
    Total Temperature                    (k)
----------------------- --------------------
                inlet              499.85071
               outlet              410.67505
                 wall              438.69955
       ---------------- --------------------
                  Net              441.92212
```



```
Area-Weighted Average
         Total Energy                (j/kg)
--------------------- --------------------
                inlet            120285.31
               outlet            65725.391
                 wall            87983.352
      ---------------- --------------------
                  Net            88438.305
```



```
Total Heat Transfer Rate                  (w)
------------------------- --------------------
                    inlet           2055.2646
                   outlet          -1515.7544
         ---------------- --------------------
                      Net           539.51025
```

- In this ANSYS FLUENT software analysis of biomass cook stove, the model used to simulate the system is Energy model and fluid flow model which is used to compute heat transfer rate in the domain. Assuming the heat transfer rate at outlet as heat utilized in the system

Thermal efficiency ($\eta = \frac{Q_{utilized}}{Energy_{in\,fuel}}\, x\, 100$)……………………………………..…. (3.24)

Where;

- $Q_{utilized}$ = Heat utilized will be the heat transferred to the pot bottom. (From fluent output let assume heat transfer rate on the outlet is heat utilized by the system) = 1515.75W. Energy balance done in the chapter four of this paper indicates us from total heat energy generated in the system heat lost by convection and radiation is 21.8%. Therefore considering heat energy lost by convection and radiation of heat utilized will be $Q_{utilized}$ = 1185.6W

- Energy in the fuel = Energy consumed divided by time to boil the water

$$\text{Energy}_{\text{in fuel}} = \frac{LHVm_{wood}}{t_{boil}}$$

∗ Energy consumed = mass of dry fuel multiplied by heating value

Energy consumed = 1.828 x 10^7 J/Kg x 0.462kg = 84.536 x 10^5

Lower heating value of wood (dry basis) LHV = 1.828 x 10^7 J/Kg

Mass of wood (m_{wood}) = 462gm

$$\text{Energy}_{\text{in fuel}} = \frac{LHVm_{wood}}{t_{boil}} = 3.913 \text{ x } 10^3\text{W}$$

$$\eta = \frac{1185.6}{3913}\ x\ 100) = 31\ \%$$

3.3 Validation

The experiments conducted on tikikil biomass cook stove is used to distinguish the thermal efficiency of the stove using WBT EXCEL sheet prepared by GIZ organization (Detail explained in chapter 3) of these document. And also during this water boiling test surface temperatures at different location of the stove is measured to identify contribution of each mode of heat transfer (conduction, radiation and convection). The performance of the stove is compared in terms of experimental value with predicted CFD simulation data for validation purpose.

The performance and surface temperature of Tikikil biomass cook stove was tasted by conducting water boiling test. Inserting different measured parameters to WBT data calculation excel sheet the average thermal efficiency obtained from experimental analysis will be 27%. The value of tested data is used as boundary condition for CFD simulation purpose. Then simulation result gives thermal efficiency of 31% which has error 14% and close to tested data value. The mismatch may arise from the unidentified losses which are not considered during the simulation process also because the model in simulation is at steady-state, while the experimental procedures are not.

CHAPTER FOUR

4. ANALYTICAL INVESTIGATIONS ON TIKIKIL COOK STOVE

4.1 Introduction

If Heat transfer efficiency of existing cook stoves is accurately assessed it will be easy to improve the thermal and combustion efficiency of the stove. In order to increase the heat transfer to the pot, the overall heat transfer coefficient, h, area exposed to the flame and flue gases, A, and flame temperature, T, need to be increased. Overall heat transfer coefficient, h, is mainly composed of convective and radiative heat transfer coefficients. The physics that govern the behavior of cook stoves are rooted in thermodynamics, further explained using principles of heat transfer, and influenced by various stove geometries. To begin understanding the principles of heat transfer, a simple schematic in Figure 4.1 is used to represent the modes of heat transfer that play a role in stove performance.

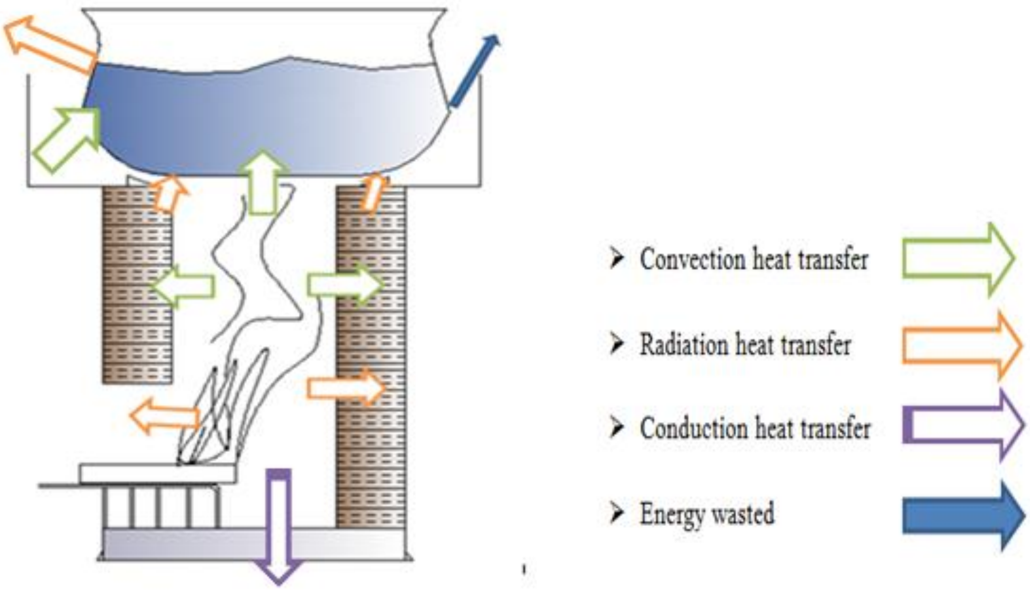


Figure 4.1, Stove Cross Section with Modes of Heat Transfer

This chapter contains detail discussion of steady state heat transfer model of natural draft, incompressible shielded biomass cook stove which is known tikikil wood stove.

In this chapter

- All modes of heat transfer such as conduction, convection and radiation is modeled depending on surface temperature measured during experimental analysis. The temperature and velocity profiles, location and magnitude of losses, and the heat transfer contributions through various modes also discussed
- Energy balance (energy loss and gain) is calculated and their result is discussed

4.2 Heat Transfer and Energy Balance

Thermal energy is related to the temperature of matter. Heat transfer is a study of the exchange of thermal energy through a body or between bodies which occurs when there is a temperature difference. When two bodies are at different temperatures, thermal energy transfers from the one with higher temperature to the one with lower temperature. Heat always transfers from hot to cold. Heat is typically given the symbol *Q*, and is expressed in joules (J) in SI units. The rate of heat transfer is measured in watts (W), equal to joules per second, and is denoted by *q*. The heat flux, or the rate of heat transfer per unit area, is measured in watts per area (W/m²), and uses Φ for the symbol.

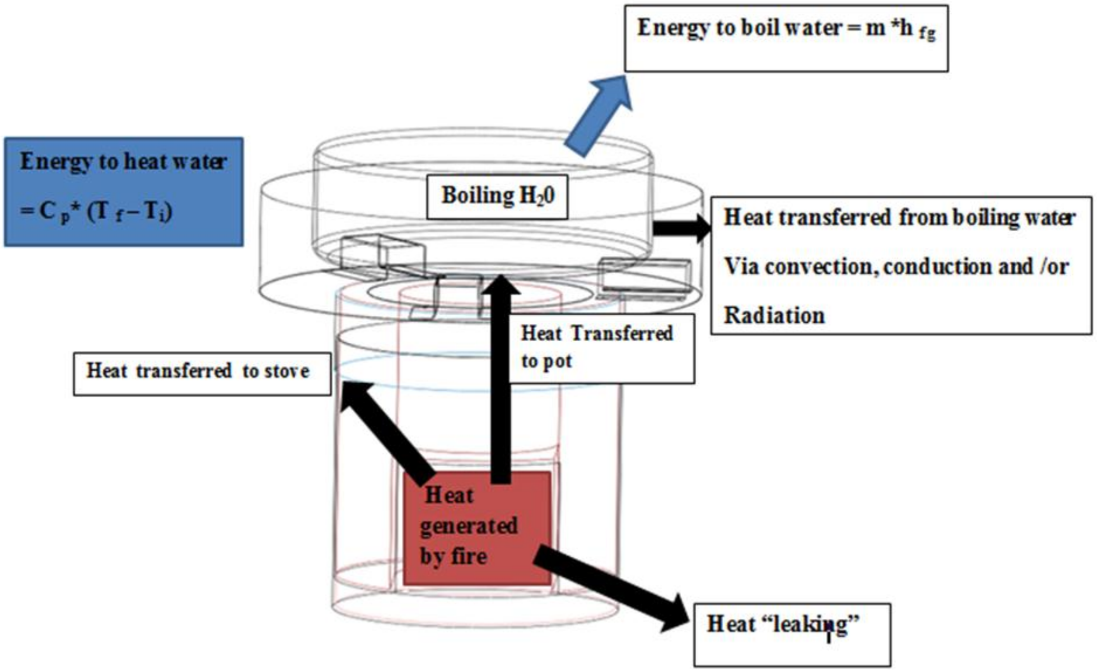


Figure 4.2; 3D Model of Tikikil stove with pot and its Energy balance

Since energy cannot be created or destroyed, it must change forms in the form of heat transfer. This is by three mechanisms: conduction, convection, and radiation. Any energy exchange between bodies occurs through one of these modes or a combination of them. Conduction is the transfer of heat through solids or stationery fluids. Convection uses the movement of fluids to transfer heat. Radiation does not require a medium for transferring heat; this mode uses the electromagnetic radiation emitted by an object for exchanging heat.

During those modes of transfer energy heat losses and gains will occur. Gains are associated with heat transferred to a pot and losses are associated with heat transfer into a body or out to ambient. Therefore conduction losses are negligible as they are accounted for in the change of energy of the stove. Convection and radiation losses may be calculated for both the stove and the pot based on their surface temperatures during combustion. Heat losses in different forms from different areas of a stove should be minimized in order to maximize the amount of heat transferred to the water.

4.2.1 Heat Transfer by Conduction

Conduction: In a solid material, heat is conducted by vibrating atoms and they speed up the vibration rate of more slowly moving neighbor atoms. In metals, heat is conducted by free electrons, which move with a high velocity from high temperature regions to lower temperature regions, where they collide and excite atoms. For a cook stove, the different areas in which the heat transfer through conduction takes place are: The heat losses through the stove wall, the heat storage from the flame to wood and the heat storage in the pot material and in the stove body. Larger the mass and specific heat of an object, the more energy it can store for a given change in temperature. Thus, a massive stove warms up slowly while a lightweight stove warms up rapidly.

Rate of heat transfer by conduction ($Q_{\text{conduction}}$) = $K\,A\,\frac{\Delta T}{L}$ …………………………… (4.1)

Where K = Thermal conductivity

A = Surface area

ΔT = Average temperature

L = Thickness of material

1. **Conduction heat loss to base plate**

$$Q_{cond} = \frac{A_{base\ plate}\ (T_{base\ plate} - T_{stove})}{R_{total}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

$A_{base\ plate} = 28352.87mm^2$	Area where flame of wood conducts to base plate
$K_{clay} = 1w/k.m$	Thermal conductivity of base plate
$L_{base\ plate} = 25mm$	Thickness of base plate
$R_{conductive} = \frac{L_{base\ plate}}{K_{clay}} = 0.025m$	Conductivity resistance from base plate
$T_{base\ plate} = 582k$	Temperature of exposed base plate surface
$T_{stove\ body} = 413k$	Steady state average temperature of stove body

- Total steady state rate of conduction heat transfer through stove baseplate will be;

$$Q_{cond\ loss\ to\ base\ plate} = \frac{A_{base\ plate}\ (T_{base\ plate} - T_{stove})}{R_{total}} = \frac{0.0283\ x\ (582-413)}{0.025}$$

$$Q_{cond\ loss\ to\ base\ plate} = 191.3W$$

4.2.2 Heat Transfer by Convection

Convection uses the motion of fluids to transfer heat. In a typical convective heat transfer, a hot surface heats the surrounding fluid, which is then carried away by fluid movement such as wind. The warm fluid is replaced by cooler fluid, which can draw more heat away from the surface. Since the heated fluid is constantly replaced by cooler fluid, the rate of heat transfer is enhanced. Convection coefficient, *h*, is the measure of how effectively a fluid transfers heat by convection. It is measured in W/m²K, and is determined by factors such as the fluid density, viscosity, and velocity.

- Convection is modeled by Newton's Law of Cooling

$$Q = h\ A\ (T_s - T_\infty) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.3)$$

Where; Q = heat transfer

h = convective Heat Transfer Coefficient

A = Surface Area

T_s = Surface Temperature

T_∞ = Ambient Fluid (air) Temperature

$m_{\text{flow rate}} = 2.129 \times 10^{-3}\ \frac{kg}{s}$

T_{gas} = 836k flue gas temperature

T_{pot} = 368.5k average pot surface temperature

$R_{\text{universal}} = 8.3143\ \frac{J}{K.mol}$ universal gas constant

$m_{\text{mass of air}} = 28.97\frac{gm}{mol}$ molecular mass of air P_{atm} = 76KPa

d_{stack} = 110mm diameter of combustion chamber

$R_{air} = \frac{R_{universal}}{m_{air}}$ $R_{air} = 289.997\frac{J}{K.Kg}$

$\rho_{gas} = \frac{P_{atm}}{R_{air}T_{gas}}$ $\rho_{gas} = \frac{1.01325 \times 10^5 pa}{289.997\frac{J}{K.Kg} \times 836k} = 0.4\ \frac{kg}{m^3}$

$A_{stack} = \frac{\pi d_{stack}^2}{4}$ $A_{stack} = \frac{\pi 110^2}{4} = 9.49 \times 10^{-3}\ m^2$

$V_{\text{gas stack}} = \frac{m_{\text{flow rate stove}}}{\rho_{gas}A_{stack}}$ $V_{\text{gas stack}} = 0.55$ m/s.

- Bernoulli's equation –basic form

$$\frac{P_1}{\rho} + \frac{1}{2}V^2 + gz_1 = \frac{P_2}{\rho} + \frac{1}{2}V^2 + gz^2$$

Bernoulli's equation reduced to fit boundary condition at stove inlet

$P_{gauge} = P_1 - P_2 = \rho\frac{1}{2}(V_2^2 - V_1^2)$ where $V_1 = 0$

Gauge pressure at stove inlet

$P_{gauge} = \rho\frac{1}{2}(V_{gas-stack}^2) = 0.155$ pa

Nominal absolute viscosity of air at 1atm and T_0 = 273K

$\mu_0 = 1.71.10^{-5}$ kg/m .s and $\mu_{gas} = \mu_0(\frac{T_{gas}}{T_0})^{0.7} = 2.1\text{x } 10^{-5}$ kg/m .s

- Reynolds number approximation for fully developed internal flow through circular pipe

$$Re_{stack} = \frac{\rho_{gas}\, v_{gas-stack}\, d_{stack}}{\mu_{gas}}$$

$$Re_{stack} = 1.047 \times 10^3$$

For fully developed internal flow Reynolds number less than 2300 (Re < 2300) are laminar flow.

1. **Convection heat loss from gases to upper combustion chamber (wall of inner cylindrical part of stove)**

$$Q_{conv\_chamber\ wall} = h_{chamber\ wall}\ A_{chamber\ wall}\ (T_{gas} - T_{chamber\ wall})$$

$D_{chamber\ -wall}$ = 110mm	Effective diameter of lower chamber if it were circular
$H_{chamber}$ = 235mm	Effective chamber length
A = 61924.27mm^2	Effective chamber surface area
T = 797k	Average upper chamber wall surface temperature

Friction factor between gases and walls of combustion chamber will be;

Assuming fully developed internal flow contained by smooth walls.

$$f = \frac{64}{Re_{stack}} = 0.061$$

Pradntl number (ration of thermal dissipation conduction)

$$Pr = \frac{\mu_{gas}\ c_{p\_gas}}{K_{gas}} = \frac{2.1\ x\ 1006.43}{10.5\ x\ 10^{-2}} = 2.01$$

Nusselt Number for flow in circular tube. The effects of wall roughness and laminar flow conditions (Re_D > 2300) may be considered by using the Gnielinski correlation: Nusselt Number represents a dimensionless temperature gradient at the surface. (Equation 8.57, INCROPERA)

$$Nu = 1.86\ Re^{1/3}\ Pr^{1/3} (\frac{D}{L})^{1/3}\ (\frac{\mu_b}{\mu_w})^{0.14} = 9.56$$

Convection coefficient through upper chamber (ceramic body of stove)

$$h_{chamber\ \_wall} = \frac{NuK_{gas}}{d_{up}} = \frac{9.56\ x\ 10.5\ x\ 10^{-2}}{0.11} = 9.1 \frac{w}{k\ .m^2}$$

$$Q_{conv\ \_chamber\ wall} = h_{chamber\ wall}\ A_{chamber\ wall}\ (T_{gas} - T_{chamber\ wall})$$

$$= (9.1)\ (0.0619)\ (836 - 797) = 21.957W$$

2. Convection heat transfer from gases to pot bottom

$Q_{conv\_pot} = h_{conv\_pot} A_{pot} (T_{gas} - T_{pot})$

Assume the space created by pot gap and stoves drip pan behaves like two parallel plates

$D_{pot} = 240mm$

$A_{pot\text{-}bottom} = \frac{d_{pot}^{2}\,\pi}{4} = 0.045m^{2}$

$L_{pot\text{-}gap} = 27.5mm$ height of air gap between pot and drip pan

$A_{pot\text{-}gap} = \pi d_{pot} L_{pot\text{-}gap} = 0.0207m^{2}$

Estimated gas velocity flowing through pot gap area

$V_{gas\text{-} pot\ gap} = \frac{m_{stove}}{\rho_{gas} A_{pot\ gap}} = 0.25$ m/s

Hydraulic diameter definition between two parallel plates $D_h = 2h_{pot\ gap} = 55mm$

$Re_{pot\ gap} = \frac{\rho_{gas}\, v_{gas-potgap}\, D_h}{\mu_{gas}} = 2.61 \times 10^{2}$ the flow through pot gap is less turbulent than in stack.

$C_{p\text{-}gas} = 0.624 \times 10^{3}\ \frac{J}{kg.K}$ specific heat capacity of air depending on average gas temperature

$K_{gas} = 10.5 \times 10^{-2}\ \frac{w}{K.m}$ Thermal conductivity of air (depending on gas temperature)

Pradntl number (ration of thermal dissipation conduction)

$Pr = \frac{\mu_{gas}\, c_{p\_gas}}{K_{gas}} = 0.124$

Stagnation Nusselt number for fully developed internal flow will be from (equation 8.57 INCROPERA text book)

$Nu_{D} = 1.86(\frac{Re_{D}\,Pr}{L/_{D}})^{\frac{1}{3}})(\frac{\mu}{\mu_{s}})^{0.14} =$

$Nu_{D} = 1.86(\frac{261\ x\ 0.124}{0.235/_{0.11}})^{\frac{1}{3}})(0.814)^{0.14} = 4.53$

Theoretical convective coefficient for isothermal non-combusting impinging flow upon pot bottom

$h_{conv\_pot} = \frac{Nu_{gas}\, K_{gas}}{d_{pot}} = 1.98\ \frac{w}{k\ .m^{2}}$

Accounting for combustion and therefore flame radiation can increase the magnitude of the convective heat transfer coefficient anywhere from 2.3x to 3.4x (Viskanta, R.)

This is more realistic expression of impinging flame jet flow exhibited in stove.

$h_{conv\_\ low\ flame} = 2.3\ h_{conv} = 1.98 \times 2.3 = 4.55\ \frac{w}{k\ .m^{2}}$

$h_{conv\_\ high\ flame} = 3.4\ h_{conv} = 1.98 \times 3.4 = 6.73\frac{w}{k\ .m^{2}}$

Assuming high flame $h_{conv\_ pot} = 6.73\frac{w}{k\ .m^2}$

Pot surface area, $A_{flame\ \_in} = \pi R^2_{flame\ \_in} = 0.0452m^2$ and temperature of pot, $T_{pot} = 368.5k$

Temperature of gas exposed to pot bottom will be calculated from the total heat loss to wall of combustion chamber before the hot gases make it to pot bottom ($Q_{stove\ \_\ losses}$)

$$Q_{stove\ \_\ losses} = m_{flow\ \_in\ stove}\ C_{p\_\ gas}\ (T_{gas} - T_{gas\ \_exposed\ to\ pot\ bottom})$$

$$Q_{stove\ \_\ losses} = Q_{conv\ \_\ chamber\ wall} + Q_{rad\ \_\ chamber\ wall} = 231.55W$$

$$T_{gas\ \_exposed\ to\ pot\ bottom} = T_{gas} - \frac{Q\ stove\ \_\ losses}{m_{flow\_in\ stove}\ c_{p\_gas}} = 727.8K$$

Then; $Q_{conv\ \_\ pot} = h_{conv\_\ pot}\ A_{pot}\ (T_{gas\_\ exposed\ to\ pot\ bottom} - T_{pot}) = 309.2W$

3. Convection heat transfer to side of the pot using pot skirt

$Q_{conv\ \_sides} = h_{conv\ \_sides}\ A_{sides}\ (T_{gas\_\ exposed\ to\ pot\ bottom} - T_{pot})$

Gas temperature as it exits the pot gap and travels up the sides of the pot.

$$Q_{pot\ \_losses} = m_{flow\ \_in\ stove}\ C_{p\_\ gas}\ (T_{gas} - T_{gas\ \_exposed\ to\ pot\ bottom}) = 233.4W$$

$$T_{gas\_\ 2} = T_{gas\ \_exposed\ to\ pot\ bottom} - \frac{Q\ pot\ \_losses}{m\ flow\ \_in\ stove\ C\ p\_\ gas} = 618.7k$$

$t_{skirt} = 60mm$	Thickness of the air gap between the pot skirt and pot
$h_{skirt} = 84mm$	Height of pot skirt from bottom of pot
$d_i = d_{pot} = 240mm$,	$d_0 = d_i + 2 \times t_{skirt} = 360mm$

$A_{side} = \pi d_{pot}\ h_{skirt} = 0.063m^2$

$T_{pot} = 368.5k$

Hydraulic diameter of circular tube annulus formed by pot skirt and pot

$$d_h = d_o - d_i = 120mm.$$

Nusselt number, assuming fully developed laminar flow, with outer wall of pot skirt perfectly insulated and side pot surface held at uniform temperature

$$h_{conv\ \_sides} = \frac{NuK_{gas}}{d_h} = 4.36$$

Assuming high flame $h_{conv\_\ sides} = 3.4h_{conv} = 14.8\frac{w}{k\ .m^2}$

$$Q_{conv\ \_sides} = h_{conv\ \_sides}\ A_{sides}\ (T_{gas\_2} - T_{pot}) = (14.8)\ (0.063)\ (618.7k - 368.5k) = 233.2W$$

Total convection heat transfer contribution

$Q_{conv\_total} = Q_{conv\_upper\ comb\ \_\ chamber} + Q_{conv\_gases\ pot\ bottom} + Q_{conv\ \_\ gases\ to\ side\ of\ pot} = 564.35W$

$Q_{conv\_\ loss} = Q_{conv\_upper\ comb\ \_\ chamber} = 21.95W$

$Q_{conv\_\ gain} = Q_{conv\_gases\ pot\ bottom} + Q_{conv\ \_\ gases\ to\ side\ of\ pot} = 542.4W$

4.2.3 Heat transfer by Radiation

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

- Radiation is modeled by the Stefan-Boltzmann Law,

$Q = \varepsilon \sigma T_s^4 - \alpha \sigma T_\infty^4$ or ………………………………………………. (4.4)

$Q = \varepsilon \sigma [T_s^4 - T_\infty^4]$

Where; Q= heat transfer

σ = Stefan-Boltzmann constant

α = Absorptivity

ε = Emissivity

T_s = Surface Temperature

T_∞ = Ambient Fluid (air) Temperature

- ✓ Estimated length of cylindrical enclosure (L) = 235mm
- ✓ Estimated effective perimeter of inner cylinder (P) = 912.84mm
- ✓ Estimated effective perimeter of outer cylinder (P) = 1415.5mm
- ✓ Effective radius of outer cylinder (R) = 95mm
- ✓ Effective radius of inner cylinder (R) = 55mm
- ✓ Surface area of inner cylinder (A) = 61924.27mm^2
- ✓ Surface area of ceramic base plate (A) = 28352.87mm^2

$T_{base\ plate} = 582k$ Average steady state surface temperature of base plate walls

$T_{inner\ cylinder} = 797k$ Average steady state surface temperature of inner cylinder

$\epsilon_{flame} = 0.72$ Estimated emissivity value of diffusion flame from literature

$\epsilon_{wood} = 0.85$	Estimated emissivity value of burning wood from literature
$\epsilon_{clay} = 0.75 = \epsilon_{inner\ cylinder}$	Estimated emissivity value of ceramic baseplate
$\epsilon_{metal} = 0.26$	Emissivity metal chamber
$A_{ceramic\ base\ plate} = 28352.87 mm^2$	Area of base plate exposed to radiation
$A_{metal\ chamber} = 110247.45 mm^2$	Area of metal chamber exposed to radiation

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

1. **Radiation loss to walls of combustion chamber which is inner cylindrical parts of the stove;** due to radiation heat transfer between the flame and inner part of cylinder there will be radiation loss to the wall of the ceramic part. This amount of steady state heat loss can be calculated as;

$$Q_{\text{radiation loss to wall of combustion chamber}} = \frac{\sigma_{stefan} A_{inner\ cylindrical\ boy} (T^4_{cylindrical\ body} - T^4_{average})}{\frac{1}{\varepsilon} + \frac{1-\varepsilon}{\varepsilon} \frac{R_{inner\ cylindrical\ body}}{R_{outer\ cylindrical\ body}}}$$

Average steady state surface temperature of flames and wood

$T_{average} = 0.6T_{flame} + 0.4T_{wood} = 0.6(836) + 0.4(353) = 642.8k$

$L_{cylindrical\ enclosure} = 235mm$

$R_{inner\ cylinder} = 55mm$

Perimeter of inner cylinder (P) = 912.84mm

$R_{outer\ cylinder} = 95mm$

$A_{inner\ cylinder} = 61924.27mm$

- Area weighted average emissivity for this region (i.e. metal and clay)

$$\epsilon = \frac{\epsilon_{clay} A_{clay} + \epsilon_{metal} A_{metal}}{A_{clay} + A_{metal}} = \frac{0.75(0.028) + 0.26(0.11)}{0.028 + 0.11} = 0.35 \text{ ……………... } (4.5)$$

- Steady state radiative heat loss to inner cylindrical body of the stove

$$Q_{\text{radiation loss to inner cylinder body}} = \frac{5.67 \times 10^{-8} (0.062)(797^4 - 642^4)}{\frac{1}{0.35} + \frac{1-0.35}{0.35} (\frac{0.055}{0.095})} = 209.6W$$

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

$$Q_{Rad\_flame\ to\ pot} = A_{flame} F_{flame} \sigma_{Stefan} (\epsilon_{flame} T_{flame\_a}^4 - T_{flame\_b}^4)$$

$T_{flame\_a} = 763k$ Average temperature of emitting area

$T_{flame\_b} = 338k$ Average temperature of pot surface

$R_{flame\_a} = 150mm$ radius of effective emitting flame area

$R_{flame\_b}=120mm$ radius of pot bottom

$L_{flame}= 27.5mm$ separation distance between two effective areas

$A_{flame\_b} = \pi R^2_{flame} = 0.0706m^2$ effective emitting flame area

$A_{flame\_a} = \pi R^2_{flame} = 0.0452m^2$ effective area intercepted by pot bottom

Variable simplification for view factor calculation

$$S_{flame\_view}=1+\frac{1+(\frac{R_{flame\_b}}{L_{flame}})^2}{(\frac{R_{flame\_a}}{L_{flame}})^2} = 2.647$$

View factor ($F_{flame\_ in\ out}$)

$$F_{flame\ in\_ out} = \frac{1}{2}\left[S_{flame\_view} - [S^2_{flame\_view} - 4(\frac{R_{flame\_in}}{R_{flame\_out}})^2)^{\frac{1}{2}}\right] = 0.269$$

Therefore radiation heat transferred to pot surface will be;

$$Q_{Rad\_flame\ to\ pot} = A_{flame}\ F_{flame}\ \sigma_{Stefan}\ (\epsilon_{flame}T_{flame\_a}^4 - T_{flame\_b}^4) = 151.83W$$

3. **Radiation reflected from drip pan to pot bottom;** the rate at which radiation leaves flames and is intercepted by drip pan. Rate at which radiation leaves drip pan and is intercepted by pot;

$$Q_{Rad\_from\ flames\ to\ drip\ pan} = A_{flame\_to\ drip\ pan}\ F_{flame\_to\ drip\ pan}\ J_{from\ flame\_\ to\ drip\ pan}$$

$R_{drip\_ pan\_ in} = 76.5mm$ inner surface of drip pan

$R_{drip\_ pan\_out} = 150mm$ outer surface of drip pan

$A_{drip\ pan\_in} = 0.018m^2$

$L_{pan\_pot} =27.5mm$

$\epsilon_{\text{drip pan}}$= 0.26 emissivity of drip pan assuming sheet metal surface

$\rho_{\text{drip pan}} = 1 - \varepsilon_{\text{pan}} = 0.74$

$J_{\text{flame \_drip pan}} = T^4_{\text{flame}} \text{ x } \varepsilon_{\text{flame}} \text{ x } \sigma_{\text{stefan}} = 19.92 \text{ x}10^3$

View factor from flame sheet to drip pan

$$F_{\text{flame \_ out}} = \frac{1}{2}[S_{flame\_out} - [S^2_{flame\_out} - 4(\frac{R_{flame\_in}}{R_{flame\_out}})^2)^{\frac{1}{2}}] = 0.436$$

$$S_{\text{flame \_out}} = 1 + \frac{1+(\frac{Rflame\_in}{L_{flame}})^2}{(\frac{R_{flame\ out}}{L_{flame}})^2} = 1.69$$

- For emission + reflected irradiation from flame to drip pan surface. Assume flames have negligible reflectivity.

$Q_{\text{Rad \_from flames to drip pan}} = A_{\text{flame}} F_{\text{flame \_to drip pan}} J_{\text{from flame \_ to drip pan}} = 156.56\text{W}$

Total radiation heat transfer contribution;

$Q_{\text{Total}} = Q_{\text{Rad \_from flames to drip pan}} + Q_{\text{Rad\_flame to pot}} + Q_{\text{radiation loss to inner cylinder body}} + Q_{\text{radiation loss to base plate}} = 517.96\text{W}$

$Q_{\text{radiation gain}} = Q_{\text{Rad \_from flames to drip pan}} + Q_{\text{Rad\_flame to pot}} = 308.36\text{W}$

$Q_{\text{radiation loss}} = Q_{\text{radiation loss to inner cylinder body}} = 209.6\text{W}$

4.2.4 Wasted heat out the top of the stove

$T_{\text{gas\_exit}} = T_{\text{gas \_ 2}} - \frac{Q_{\text{conv\_sides}}}{m_{\text{flow \_in stove}} C_{\text{p\_ gas}}} = 509.9\text{k}$ and $T_{\text{ambient}} = 291.1\text{k}$,

$C_{\text{p\_ gas\_ exit}} = 0.836 \text{ x}10^3$ (depending on temperature)

$Q_{\text{waste}} = m_{\text{flow \_in stove}} C_{\text{p\_ gas\_ exit}} (T_{\text{gas\_ exit}} - T_{\text{ambient}}) = 389.4\text{W}$

	Values Calculated For Tikikil Stove
Convection: To pot bottom To sides of pot	 309.2W 233.2W
Total convection to pot	**542.2W**
Radiation; Flame to pot bottom Drip pan to pot	 151.8W 156.56W
Total radiation to pot	**308.3W**
Total Heat Energy Gain	**850.5W**
Heat Losses Conduction – To base pate Convection – Flame to wall Radiation – Flame to wall Wasted heat	 191.3W 21.9W 209.6W 389.4W
Total Energy Loss	**812.2W**
Total Heat Energy Generated in The System = 1662.7W	

Table 4. 1 Values of Heat Transfer Modes

4.3 Total Energy Balance and Thermal Efficiency

1. Internal energy required to bring 5L of water to boil

$$U = m_i C_p (T_f - T_i) + (m_f - m_i) h_{fg} \quad \ldots\ldots (4.6)$$

$$U = 2.39 \times 10^3 \text{ kJ}$$

2. Rate of heat transfer from stove to 5L pot

$$Q_{total} = \frac{U}{t} \quad \ldots\ldots (4.7)$$

$$Q_{total} = 1.106 \times 10^3 \text{w}$$

3. For the stove, the energy input is based on the energy stored in the fuel wood according to the following:

$$E_{in} = m_f L_f - m_c H_c \quad \ldots\ldots (4.8)$$

$$E_{in} = 5\text{kg } (18{,}595\text{kJ/kg}) - 4.6\text{kg } (19{,}500\text{Kj/Kg})$$

$$E_{in} = 3.275 \times 10^3 \text{ kJ}$$

4. The energy out transferred to the water is modeled by:

$$E_{out} = m_w c_p \Delta T + m_e L \ldots\ldots (4.9)$$

E_{out} = 5kg x 4.185KJ/kg x 71.1k + 0.4kg x 2260kJ/kg

E_{out} = 1487.7kJ + 904kJ = 2.39 x 10^3 KJ

5. Energy balance will be

$$\text{Energy}_{balance} = \text{Energy}_{in\ fuel} - \text{Energy}_{combustion} - Q_{total} \ldots\ldots (4.10)$$

$$Q_{total} = Q_{rad\_total} + Q_{conduction} + Q_{conv\_total} + Q_{waste} = 1.662 \times 10^3 W \ldots\ldots (4.11)$$

- Energy consumed = mass of dry fuel multiplied by heating value

  Lower heating value of wood (dry basis) LHV = 1.828 x 10^7 J/Kg

  Mass of wood (m_{wood}) = 462gm

  Energy consumed = 1.828 x 10^7 J/Kg x 0.462kg = 84.536 x 10^5

- Energy in the fuel = Energy consumed divided by time to boil the water

$$\text{Energy}_{in\ fuel} = \frac{LHV m_{wood}}{t_{boil}}$$

$$\text{Energy}_{in\ fuel} = \frac{LHV m_{wood}}{t_{boil}} = 3.913 \times 10^3 W$$

$\eta_{Combustion}$ = 0.98

- Energy from fuel lost due to incomplete combustion will be

$$\text{Energy}_{combustion} = \text{Energy}_{fuel} (1 - \eta_{Combustion}) = 122.6W$$

Then energy balance in stove will be

$$\text{Energy}_{balance} = \text{Energy}_{in\ fuel} - \text{Energy}_{combustion} - Q_{total} = 2.127 \times 10^3 W$$

Contributions of modes of heat transfer

- Total radiation heat gain Q_{rad_gain} = 308.36W
- Total radiation heat lost to system Q_{rad_loss} = 209.6 W

  Q_{rad_total} = 517.9W

- Total convection heat gain Q_{conv_gain} = 542.4W
- Total convection heat lost to a system Q_{conv_loss} = 21.95W

  Q_{conv_total} = 564.35W

  $Q_{total} = Q_{rad\_total} + Q_{conv\_total}$ = 1082.5W

$$Q_{utilized} = Q_{rad\_gain} + Q_{conv\_gain} = 308.36 + 542.4 = 850.76W \ldots\ldots (4.12)$$

$$Q_{loss} = Q_{conv\_loss} + Q_{rad\_loss} = 21.95W + 209.6 = 231.5W \ldots\ldots (4.13)$$

From total heat generated by convection and radiation 78.62% is utilized heat while 21.38% is heat loss.

6. Thermal Efficiency

- Thermal efficiency is calculated per the sum of convective and radiative heat transfer into all regions of the pot divided by the firepower.

$$\eta = \frac{\text{Q rad\_ gain + Q conv\_ gain}}{Energy_{in\ fuel}}\ x\ 100 = \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \quad (4.14)$$

$$\eta = \frac{850.76}{3913} \text{ x } 100 = 22\%$$

CHAPTER FIVE

5. GEOMETRICAL OPTIMIZATION OF BIOMASS COOK STOVE

5.1 Introduction

Because stove performance vary with stove geometry modeling existing cook stove by solid work and analyzing its heat transfer history above its fuel bade by ANSYS FLUENT is very essential for design of new geometry. The key objective of this project is to model optimized geometry of biomass cook stove which is more efficient in utilization of energy. Since enhancing better stove geometry is by try and error in this section three different stove geometry is modeled and simulated by FLUENT to identify which has good temperature distribution also using numerical output from this software analysis such as fluxes (heat transfer rate and mass flow rate) also surface integrals (inlet temperature, outlet temperature, wall temperature, velocity magnitude, total energy, entropy, heat transfer coefficient)

Generally parameters related to heat transfer efficiency is compared with each other and also compared with output result of existing cook stove which is bench mark for this study. All the different geometry modeled is only the fire box zone which is also known as combustion chamber of the stove body.

In this chapter;

- Different geometry of biomass cook stove is modeled by solid work and FLUENT. And their geometry and performance is compared with the existing one which is tikikil stove.

5.2 Methodology Used and Result

The basic work of the model is done on SOLID WORK 2012. The approach for modeling different geometry will be;

- Changing shapes of geometry to acquire high flame velocity so that convective heat transfer rate to pot bottom is increased
- Modifying flame outlet diameter of stove to increase area of pot surface exposed to high flame means by increasing
- Altering shapes of cook stove and comparing the contour of total temperature and velocity magnitude with existing stove
- Altering bottom surface of combustion chamber and also window of fuel input surface to get sufficient air flow rate with in the stove to increase burn rate and decrease emission caused by incomplete combustion.
- But the height or length of stove from ground is not changed because increasing the height of chamber will decrease or reduce convective and radiative heat transfer to the pot even if it increases draft.

5.2.1 CFD Simulation Result

In this work FLUENT software is used for simulation. Main focus of this work is on heat transfer analysis of a cook stove for different geometries. In all the simulation procedure boundary condition used is similar to that of tikikil stove which was discussed in detail in section (5.3 (input, output and wall boundary conditions, the user defined thermal property of clay and property of air selected from fluent data base, governing equation used and solution methods are all the same. By completion of all the test runs in Fluent, several key performance indicators were studied to understand the heat transfer characteristics and trends for each configuration. To understand results we study Temperature based results and Velocity results in graphical mode ad also compare their numerical value.

5.2.1.1 Definitions of Parameters

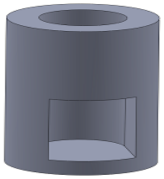
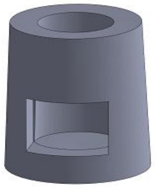
FLUENT output Parameters used to compare the performance characteristics of biomass cook stove geometry are; heat transferred to the pot (heat transfer at the outlet), heat transfer coefficient, velocity and the energy output of the stove. Thermal efficiency of different geometries is computed to compare their performance with each other.

Thermal efficiency ($\eta = \frac{Q_{utilized}}{Energy_{in\,fuel}}\, x\, 100$)

Where;

$Q_{utilized}$ = Heat utilized will be the heat transferred to the pot bottom. (From fluent output let assume heat transfer rate on the outlet is heat utilized by the system)

Energy $_{\text{In the fuel}}$ = Energy consumed is mass of dry fuel multiplied by heating value. (Which is calculated in chapter four of this paper = 3913W)

		Tikikil stove	**Geometry -1**	**Geometry -2**	**Geometry -3**
Geometric data's					
	1. Thickness = 0.04m (the same for all geometries) 2. Length = 0.26m (the same for all geometries) 3. Outer Diameter = 0.19m (the same for all geometries) 4. Inner Diameter = 0.11m (the same for all geometries)				
			Window of fuel inlet = 0.12 x 0.12 Lower combustion chamber; Outer diameter = 0.21m Inner diameter = 0.13m	Narrow region of combustion chamber; Outer diameter = 0.15m Inner diameter = 0.07m	Window of fuel inlet = 0.12m x 0.12m Upper combustion chamber Outer diameter = 0.18m Inner diameter = 0.10m Lower combustion chamber Outer diameter = 0.21m Inner diameter = 0.13m
Input Variables	Inlet	Velocity inlet = 0.55m/s (the same for all geometries) Temperature = 227^{0}C = 500K (the same for all geometries) Internal emissivity = 0.95 (the same for all geometries)			
	Outlet	Back flow total temperature =293k			
	Wall	No slip Stationary wall External emissivity = 0.75			
Fluid Property	Clay	Density = 1460Kg/m^3, Specific heat capacity = 880J/Kg. K , Thermal conductivity = 1.3			
	Air	Density = 1.225Kg/m^3, Specific heat capacity = 1006.43 J/Kg. K ,Thermal conductivity = 1.789 x 10^{-5}			

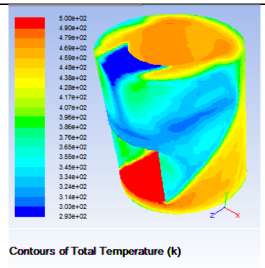
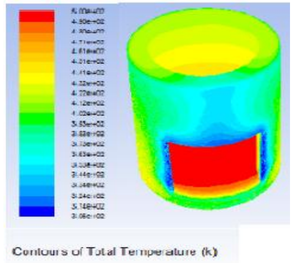
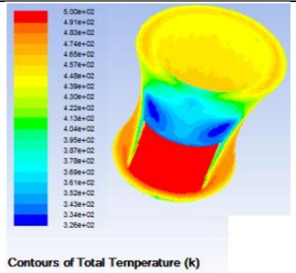
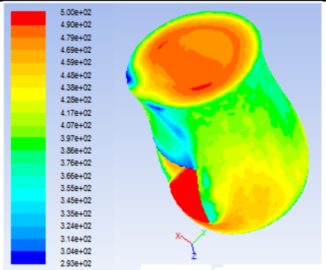
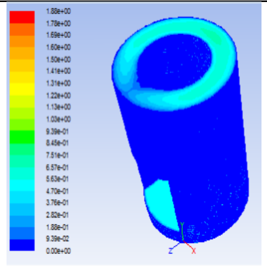
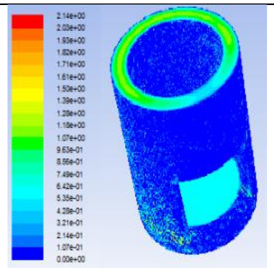
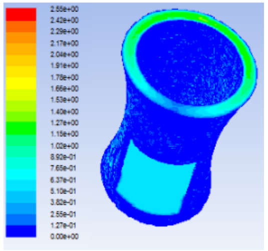
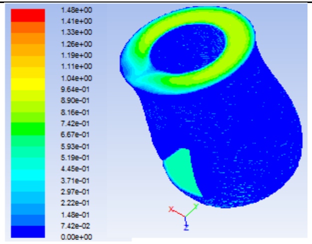
FLUENT Output Graphs	Contours of Total temperature					
	Contours of Velocity magnitude					
FLUENT Output Values	Temperature	Outlet	410 K	422K	435K	448K
		Wall	438 K	443K	457K	474K
	Velocity Outlet		0.44 m/s	0.56	0.61	0.65m/s
	Heat transfer rate (Q in Watt)	Inlet	2009.3W	2682.4W	2338.5W	2740W
		Outlet	1515.7W	2070W	1722.4W	2180W
	Mass flow rate (kg/s)	Inlet	0.009819949 Kg/s	0.013204572 Kg/s	0.01151194Kg/s	0.013364768Kg/s
		Outlet	0.0098199192 Kg/s	0.013201174 Kg/s	0.011516068 Kg/s	0.013360295Kg/s
	Energy (in kJ/kg)	Inlet	120.2 KJ/Kg	120.2W	120.2 KJ/Kg	120.3 KJ/Kg
		Outlet	65.72 KJ/Kg	71.6W	59.9 KJ/Kg	67.57 KJ/Kg
	Radiation heat transfer rate	Inlet	14W	18W	23W	25W
		Wall	22W	26W	48W	53W
	Heat transfer coefficient		4.73W/m^2 - K	5.53W/m^2 - K	6.42W/m^2 - K	8.0473W/m^2 - K
Computed Values	Thermal efficiency $\eta = \frac{Q_{utilized}}{Energy_{in\,fuel}}\ x\ 100$		30.1 %	41.3%	34.4%	43.5%

Table 5.1; How Stove Performance Vary With Geometry

This simulation analysis of biomass wood stove which has different shape shows how stove performance change with geometry. Therefore depending on the above results of simulation and numerical values the more efficient stove (geometry-3) is selected because, as we see the contour of temperature distribution and numerical results obtained from fluent analysis, the figure shows uniform temperature distribution across the domain and high heat transfer rate compared to other geometries. Also the outlet temperature value is higher than geometry tried and from the existing tikikil stove. Outlet velocity of selected geometry is higher than the others because of converged shape which results increase of convective heat transfer across the domain. The result of different parameters related to the stove performance compared to tikikil stove is discussed in detail on next chapter.

CHAPTER SIX

6. RESULT AND DISCUSSION

6.1 Introduction

As mentioned before, the purpose of this research is modifying geometry of cook stove for efficient utilization of energy. Therefore heat transfer and fluid flow simulation on fluent assist the development of a simple model which can be used to predict the performance of a given stove. This model could also be used to carry out a design optimization that gives the optimal dimensions of a given stove configuration for best efficiency and/or minimum emissions. Therefore Different modifications on the basic geometries were investigated to optimize the performance of the stove. The existing model of cook stove (Tikikil stove) is done by using geometric data' s from manual of production of Tikikil stove prepared by GIZ organization[4] and the performance analysis is done by conducting experiment which is water boil test (WBT). Those results serve as a reference for comparing the performance of the modified geometry.

An effort was made to solve the flow details using FLUENT. Each model undergoes through all simulation procedures; and evaluation is performed by using the output results and computed values from these output results.

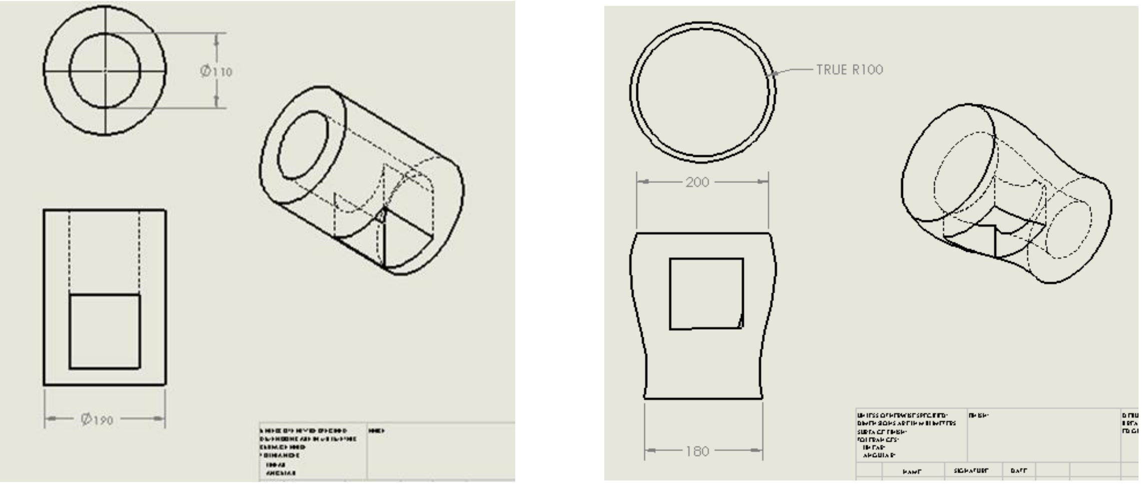
In this chapter:

- Plots and numerical outputs which shows the heat transfer and flow characteristics in the Tikikil stove and the modified one is presented and discussed
- The performance of modified geometry is analyzed and compared with existing one to check if improvements are obtained
- Heat transfer correlations specific to the flow and temperature regimes is validated

6.2 Modification Made and CFD Results

To improve the performance of the cook stove following modifications are made on the basic geometry.

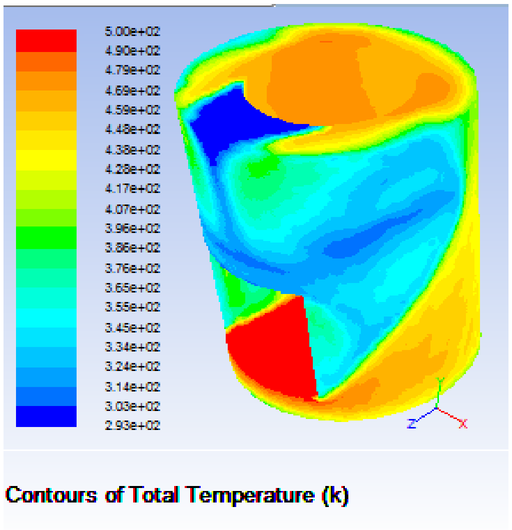
I. First using the same thickness and height only changing shape of existing geometry is done by increasing the diameter of bottom combustion chamber from 190mm to 200mm and also window of fuel inlet (110mm x110mm) is modified to (120mm x 120mm).

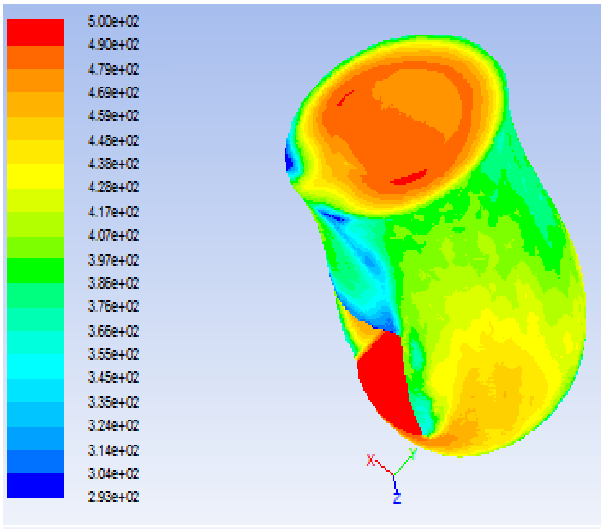


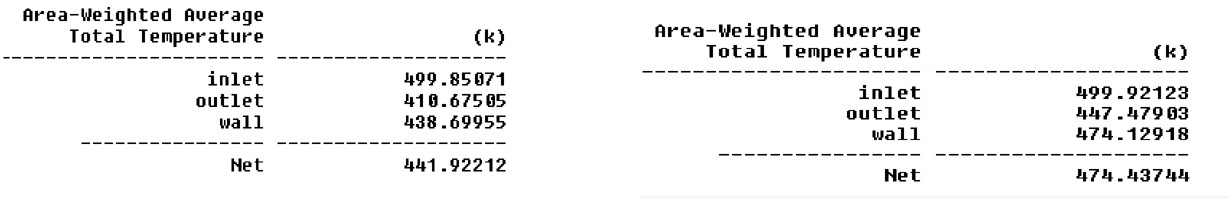
(a) Part drawing of tikikil stove (b) Part drawing of modified stove

Figure 6.1detail drawings of tikikil stove and the modified one

CFD Graphical display allows us to easily view the velocity and temperature profile above fuel bed.







```
  Area-Weighted Average
      Total Temperature                    (k)
------------------------ --------------------
                  inlet             499.85071
                 outlet             410.67505
                   wall             438.69955
       ----------------- --------------------
                    Net             441.92212
```

```
  Area-Weighted Average
      Total Temperature                    (k)
------------------------ --------------------
                  inlet             499.92123
                 outlet             447.47903
                   wall             474.12918
       ----------------- --------------------
                    Net             474.43744
```

a) Temperature value tikikil stove b) Temperature value of modified stove

Fig 6.2 temperature distribution across the domain of tikikil stove and modified geometry

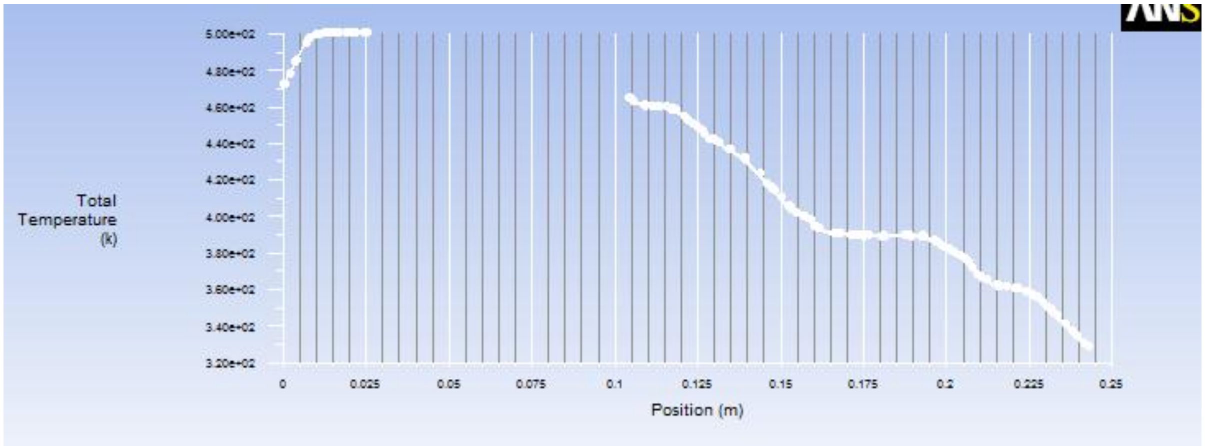
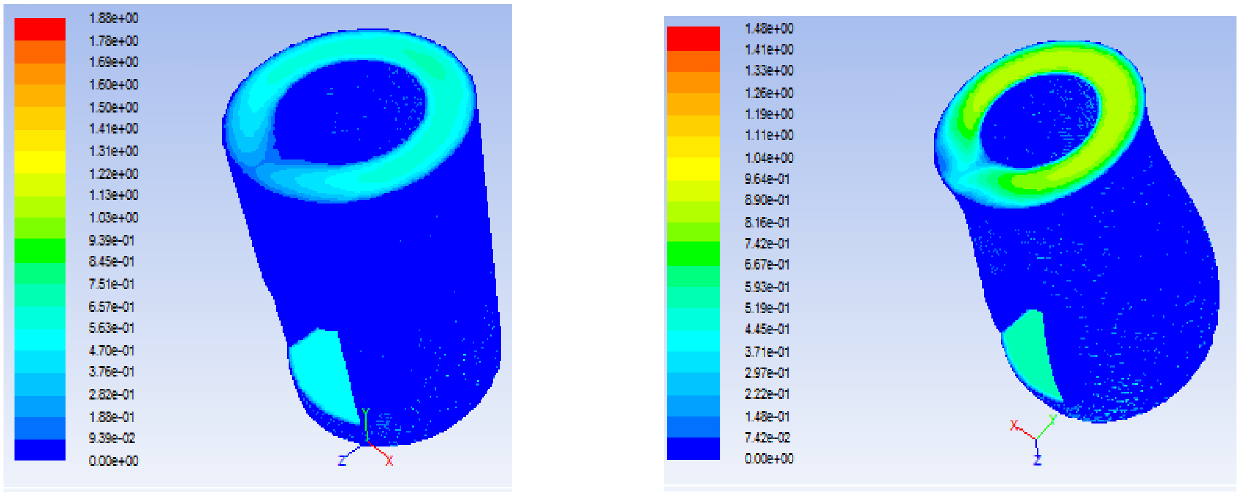


Fig 6.2 (c) Temperature versus distance from the flame zone (air inlet to the exit) for tikikil stove

a) As we see from the profile of Temperature distribution of tikikil stove in the flame zone or at the inlet air temperature is 500 °k at a pressure slightly higher than the atmospheric pressure. It is taken as the inlet stream for the simulation. The temperature decreases to about 410 °k where it touches the cook pot which is kept upon the stove.

b) Using the same inlet temperature 500^0 k for the modified geometry the stack air temperature that touches cook pot will be 447 ^{0} k. modified temperature distribution is achieved due to sufficient air which enters the fuel inlet window and convergent part stove that causes high velocity.

c) The plot on figure 6.2(c) shows how temperature flows from the hot area which is inlet zone to outlet to exit of the stove. As we from temperature contour of tikikil stove and also the x-y plot shown the average temperature that touches pot bottom is 410 ^{0}k and the minimum will temperature is 320 ^{0}k.



```
Area-Weighted Average
   Velocity Magnitude                (m/s)
---------------------- --------------------
                 inlet          0.55000001
                outlet          0.44886723
      ---------------- --------------------
                   Net          0.49296701
```

```
Area-Weighted Average
   Velocity Magnitude                (m/s)
---------------------- --------------------
                 inlet          0.55000001
                outlet          0.65045059
      ---------------- --------------------
                   Net          0.59761786
```

(a)

Velocity value and profile of tikikil stove

(b)

Velocity value and profile of modified stove

Figure 6.2 (d) Velocity value and velocity profile of tikikil stove and modified geometry

(d) the velocity magnitude shown in the above figure shows; due to convergent shape introduced to the upper part of the chamber high velocity is achieved at the outlet which result high turbulence or better heat transferred to the cook pot compared to the existing geometry.

II. The second design modification is carried out depending on the result obtained from modified geometry. It involves;
    a. Increasing diameter of lower combustion chamber, to decrease smoke due to incomplete combustion produced when starting the fire.
        Outer diameter = 210mm
        Inner diameter = 150mm
    b. Modifying the shape and internal diameter of upper part of combustion chamber, to increase bottom part of cook pot surface area exposed to flame region. And also to increase flue velocity across the domain.
        Outer diameter = 180mm
        Inner diameter = 120mm

c. Increasing fuel window to increase air entering the fuel bade.

Window of fuel inlet = 120mm x 120mm

d. Decreasing wall thickness to reduce heat loss to the wall of combustion chamber

Wall thickness = 30mm

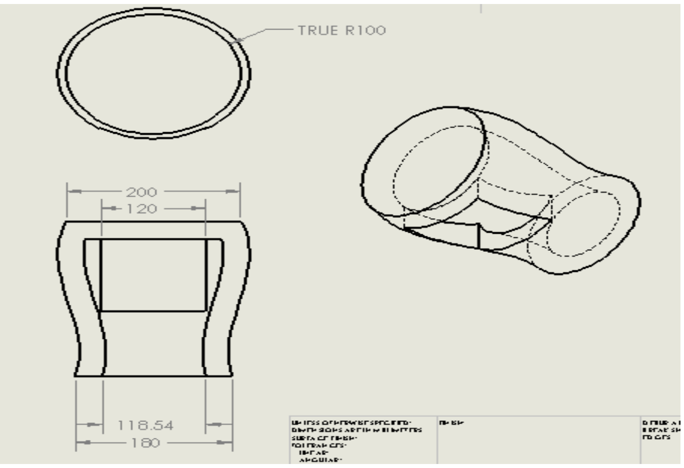
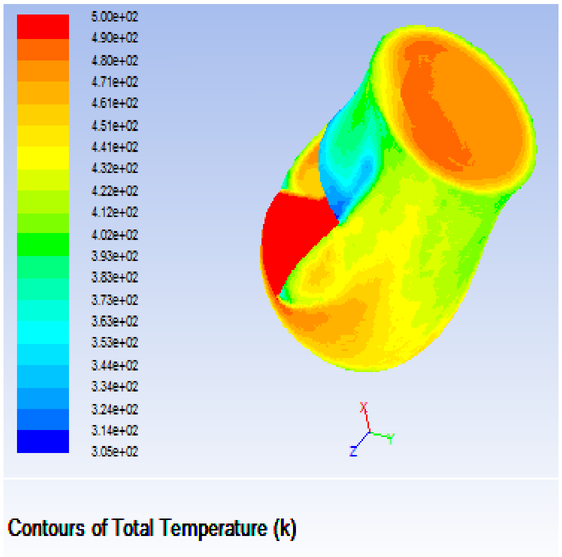


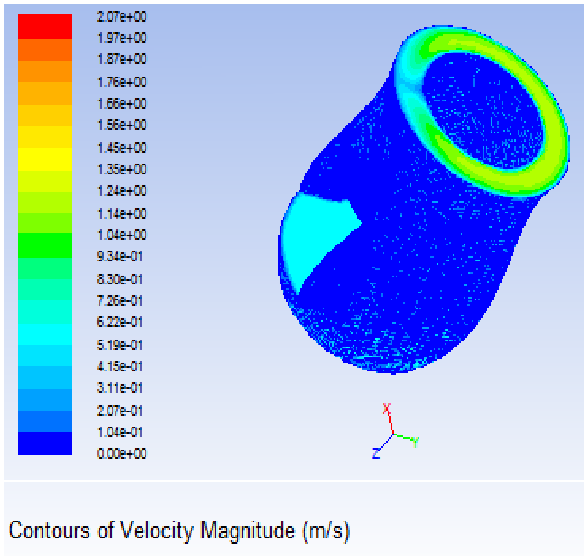
Figure 6.3 detail drawing of optimized geometry

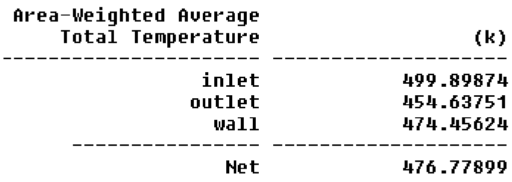
6.3 Optimized Geometry

To investigate the heat transfer and fluid flow characteristics in the domain of stove the results of the analysis in FLUENT can be shown by using graphical displays and numerical outputs.

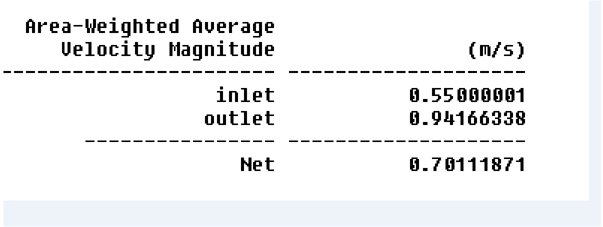
6.3.1 Graphical display and numerical value of optimized geometry







```
Area-Weighted Average
    Total Temperature                      (k)
---------------------- --------------------
                inlet            499.89874
               outlet            454.63751
                 wall            474.45624
      ---------------- --------------------
                  Net            476.77899
```



```
  Area-Weighted Average
     Velocity Magnitude                  (m/s)
----------------------- --------------------
                  inlet           0.55000001
                 outlet           0.94166338
       ---------------- --------------------
                    Net           0.70111871
```

(a) (b)

Figure 6.4 temperature and velocity contour of optimized geometry

a) According to the result shown in the contour the stove has better temperature distribution above fuel bade. The outlet temperature value that reaches cook pot bottom is higher than geometry tried (454 ^{0}k) and also from the existing tikikil stove.

b) Since convergent shape is introduced the heated air velocity will increase as it moves from inlet chamber to the outlet (0.94m/s). Increasing the flow velocity often leads to more turbulence which improves heat transfer efficiency compared against laminar flow behavior.

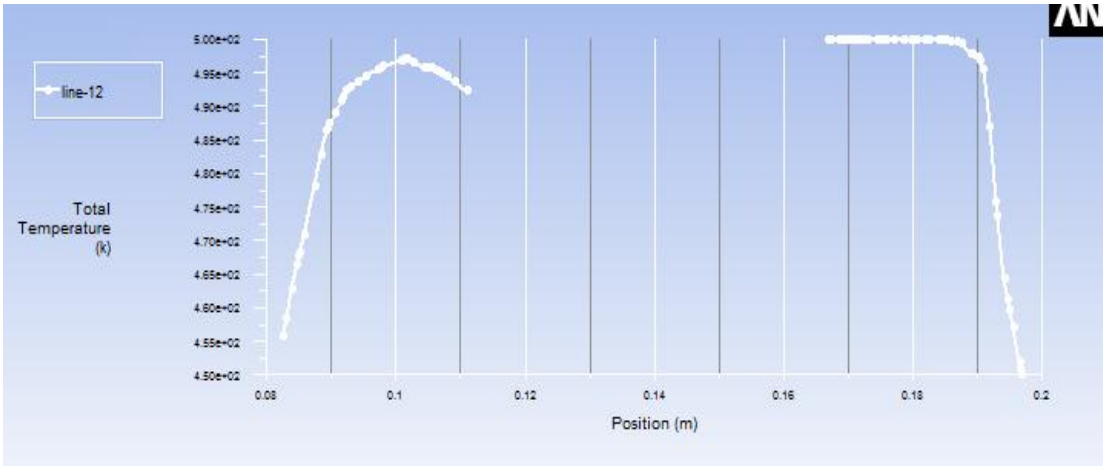
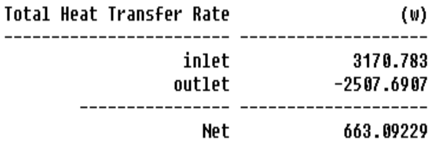


Fig 6.4 (c) Temperature versus distance from the flame zone (air inlet to the exit) for optimized stove

c) As we from temperature contour of tikikil stove and also the x-y plot on figure 6.4 (c) the average temperature that touches pot bottom is 454 ^{0}k and the minimum will temperature is 450 ^{0}k. Therefore the simulation result confirmation tells us the new modeled geometry is more efficient in utilization of energy compared to existing tikikil stove.

d) Heat transfer rate across the domain of the selected geometry is greater than other tried geometries and also from the existing tikikil stove, therefore heat transfer efficiency of this new optimized geometry will be calculated and compared to the others.



```
Total Heat Transfer Rate                  (w)
------------------------ --------------------
                   inlet             3170.783
                  outlet           -2507.6907
        ---------------- --------------------
                     Net            663.09229
```

In this ANSYS FLUENT software analysis of biomass cook stove, the model used to simulate the system is Energy model and fluid flow model which is used to compute heat transfer rate in the domain. Assuming the heat transfer rate at outlet as heat utilized in the system

Thermal efficiency ($\eta \;=\; \frac{Q_{utilized}}{Energy_{in\,fuel}}\; x\;100)$

Where;

- $Q_{utilized}$ = Heat utilized will be the heat transferred to the pot bottom. (From fluent output let assume heat transfer rate on the outlet is heat utilized by the system) = 2507.69W.
- Considering heat lost by convection and radiation as 21.8% of heat utilized the net heat transferred will be; $Q_{utilized}$ = 1961.1W
- Energy $_{\text{In the fuel}}$ = Energy consumed is mass of dry fuel multiplied by heating value. (which is calculated in chapter four of this paper = 3913W)

$$\eta \;=\; \frac{1961.1}{3913}\; x\;100) = 50.01\%$$

No	Geometry	Temperature at the Outlet (^{0}k)	Heat transferred to pot bottom (W)	Thermal efficiency (%)
1	Tikikil stove	410 ^{0}k	1563 W	30.1%
2	Modified shape	445 ^{0}k	2180 W	43.5%
3	Modified shape and optimized thickness	454 ^{0}k	2507.69 W	50.1%

Table 6.1 Evaluation of design parameters for geometries of cook stoves

The Numerical analysis or simulation result doesn’t consider the ambient conditions such as; humidity, moisture content of the biomass fuel, daily temperature condition and daily wind speed. Therefore by considering those factors the thermal efficiency result acquired from simulation will decrease from 5% to 10%.

CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATION

7.1 Introduction

Different biomass wood stove has been designed for Improving efficiency and decrease emission in Ethiopia by governmental and nongovernmental organization. And from those stoves Tikikil stove is one of improved biomass cook stove. This work focuses on geometrical optimization of the cook stove for better utilization of energy. To achieve the objective of the research effort; experimental analysis is conducted to examine the major heat loss and gain area and also an attempt is made to investigate flow characteristic and temperature profile using FLUENT on both Tikikil stove and the modified geometries.

7.2 Conclusions

The following conclusions are found from this work;

1. The geometry of tikikil cook stove was cylindrical and this work modified geometry by;
    - ∗ Increasing fuel window to get good air flow inside the fuel inlet of stove because as observed from experimental analysis there is a lot of smoke during warm up period and also it takes a lot of time to start the fire this happen because of the narrow size of fuel bed. Means increasing turbulence which helps to have good heat transfer efficiency.
    - ∗ Minimizing the diameter of stove above fuel bade or (Converging the shape of cylindrical part) means forcing the hot gases to flow through a narrow channel to increase flame velocity inside chamber.
    - ∗ The rim of the stove around the pot is extended to increase the cook pot bottom area exposed to convective heat transfer.
    - ∗ The wall thickness is also reduced to increase free stream flow in side combustion chamber.
2. Agreement between test data's and simulation values is observed and compared for Tikikil stove.

3. Using the output value of CFD fluent analysis the thermal efficiency of optimized geometry is computed and compared with the existing bench mark stove (Tikikil stove). therefore the efficiency of the new suggested geometry is 50.1% while tikikil stove has efficiency of 30.1% by simulation analysis

7.3 Recommendation

In this research work the geometrical optimization focuses on internal part of Tikikil biomass wood stove which is used as combustion chamber and it is made up of clay. This portion of cook stove has cylindrical geometry. This cook stove has circular sheet metal mounted above combustion chamber used as pot skirt, sheet metal covering the stove body used as insulation and three pot-supports the detail drawing of Tikikil stove is shown in Appendix three of this paper. Therefore to get more improved efficiency;

- The effect of pot skirt on heat transfer efficiency has to be analyzed by CFD and also the effect of gap between top part cone surface used to hold pot supports or mouth of flame outlet and pot bottom should be analyzed for this cook stove geometry.

The efficiency value gained from simulation analysis of new geometry has to be validated with experimental test result.

REFERENCE

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3. Rural Energy And Development. Technical Report, The World Bank, Washington DC. WB, (1996).
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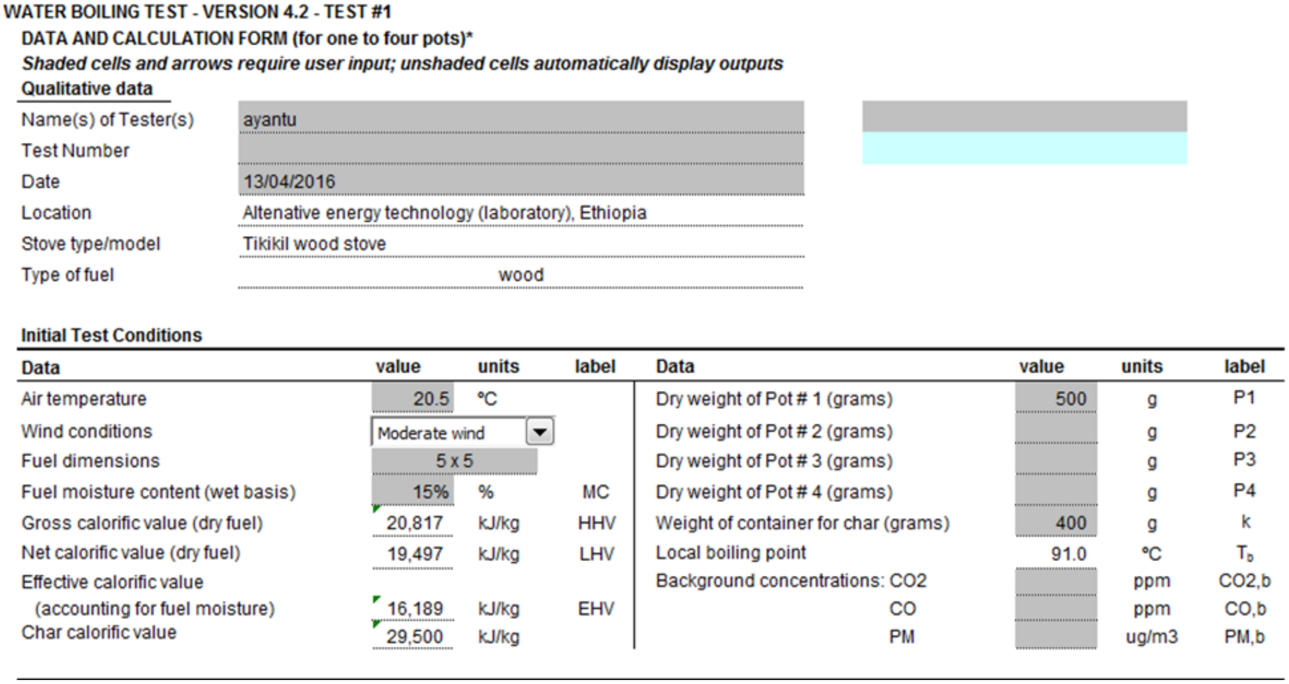
APPENDIX

Appendix 1 - Water boiling Test in Excel Sheet

1.1 Test 1

I. Input Parameters for the Excel



WATER BOILING TEST - VERSION 4.2 - TEST #1

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

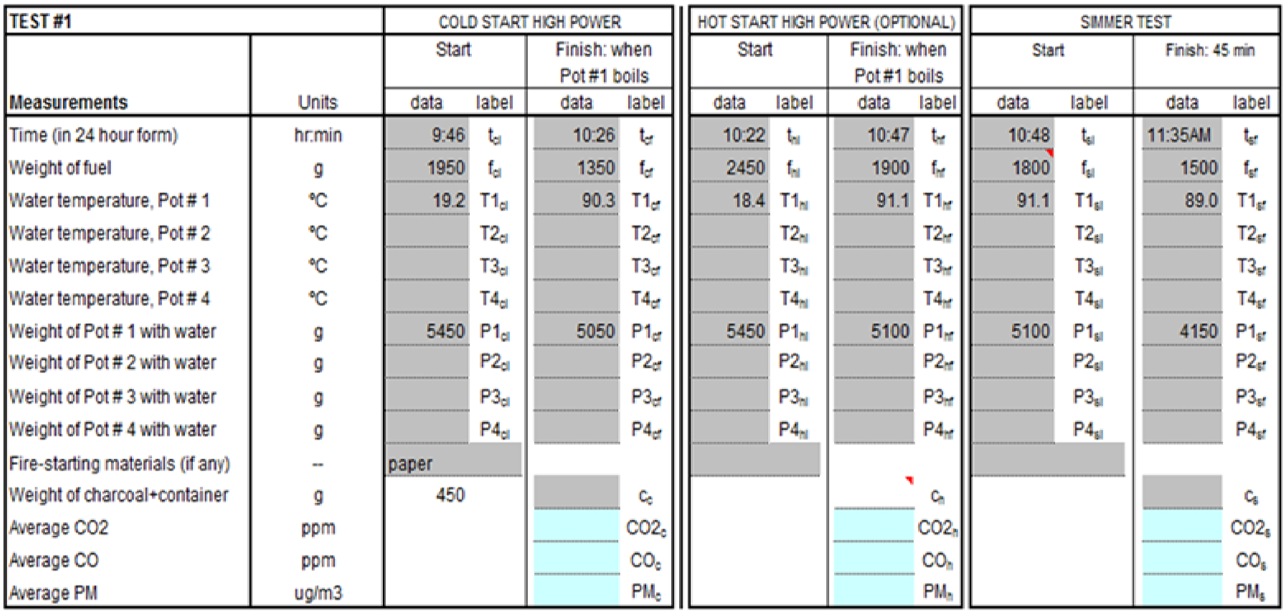
Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	ayantu
Test Number	
Date	13/04/2016
Location	Altenative energy technology (laboratory), Ethiopia
Stove type/model	Tikikil wood stove
Type of fuel	wood

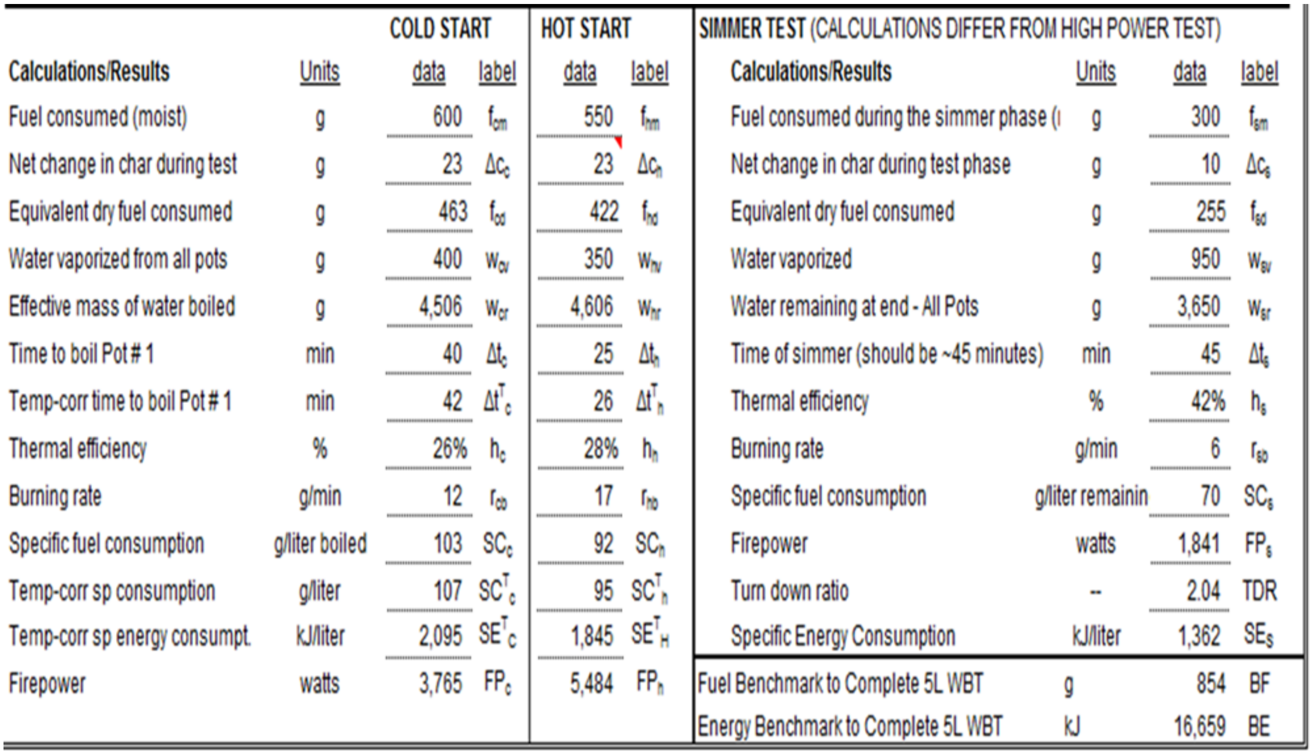
Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	20.5	°C		Dry weight of Pot # 1 (grams)	500	g	P1
Wind conditions	Moderate wind ▼			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	5 x 5			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	20,817	kJ/kg	HHV	Weight of container for char (grams)	400	g	k
Net calorific value (dry fuel)	19,497	kJ/kg	LHV	Local boiling point	91.0	°C	T_b
Effective calorific value (accounting for fuel moisture)	16,189	kJ/kg	EHV	Background concentrations: CO2		ppm	CO2,b
				CO		ppm	CO,b
Char calorific value	29,500	kJ/kg		PM		ug/m3	PM,b



TEST #1		COLD START HIGH POWER				HOT START HIGH POWER (OPTIONAL)				SIMMER TEST			
		Start		Finish: when Pot #1 boils		Start		Finish: when Pot #1 boils		Start		Finish: 45 min	
Measurements	Units	data	label	data	label	data	label	data	label	data	label	data	label
Time (in 24 hour form)	hr:min	9:46	t_{ci}	10:26	t_{cf}	10:22	t_{hi}	10:47	t_{hf}	10:48	t_{si}	11:35AM	t_{sf}
Weight of fuel	g	1950	f_{ci}	1350	f_{cf}	2450	f_{hi}	1900	f_{hf}	1800	f_{si}	1500	f_{sf}
Water temperature, Pot # 1	°C	19.2	$T1_{ci}$	90.3	$T1_{cf}$	18.4	$T1_{hi}$	91.1	$T1_{hf}$	91.1	$T1_{si}$	89.0	$T1_{sf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$		$T2_{hi}$		$T2_{hf}$		$T2_{si}$		$T2_{sf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$		$T3_{hi}$		$T3_{hf}$		$T3_{si}$		$T3_{sf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$		$T4_{hi}$		$T4_{hf}$		$T4_{si}$		$T4_{sf}$
Weight of Pot # 1 with water	g	5450	$P1_{ci}$	5050	$P1_{cf}$	5450	$P1_{hi}$	5100	$P1_{hf}$	5100	$P1_{si}$	4150	$P1_{sf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$		$P2_{hi}$		$P2_{hf}$		$P2_{si}$		$P2_{sf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$		$P3_{hi}$		$P3_{hf}$		$P3_{si}$		$P3_{sf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$		$P4_{hi}$		$P4_{hf}$		$P4_{si}$		$P4_{sf}$
Fire-starting materials (if any)	--	paper											
Weight of charcoal+container	g	450			c_c				c_h				c_s
Average CO2	ppm				$CO2_c$				$CO2_h$				$CO2_s$
Average CO	ppm				CO_c				CO_h				CO_s
Average PM	ug/m3				PM_c				PM_h				PM_s

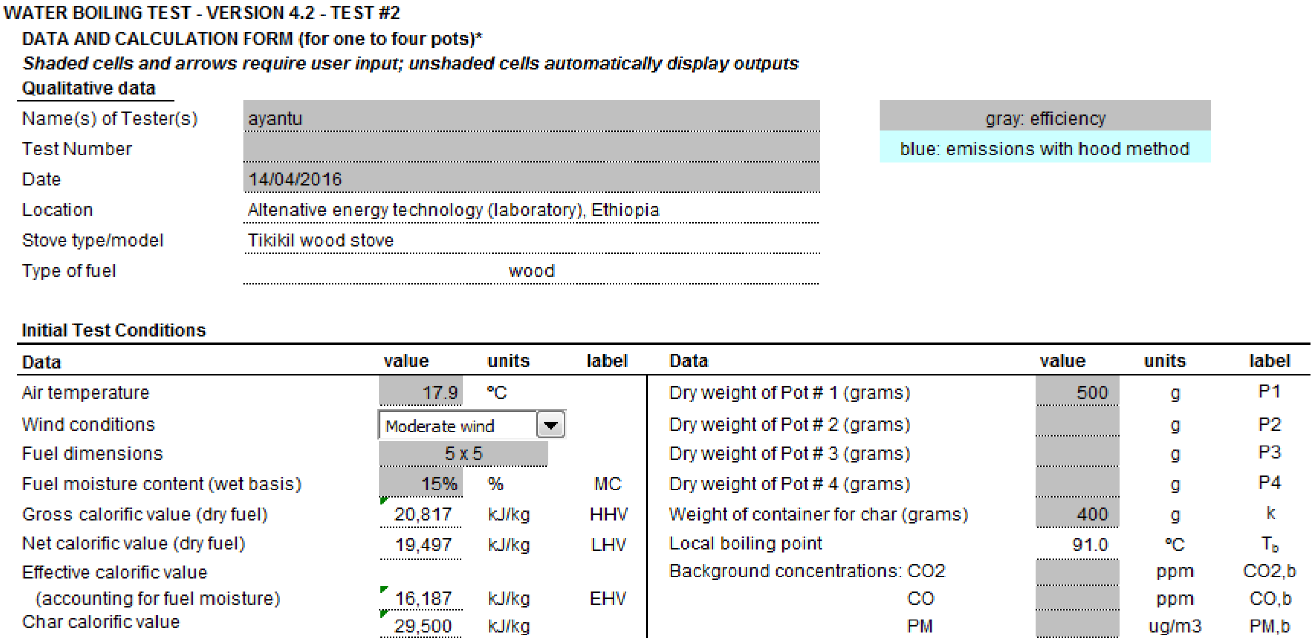
II. Result Obtained



		COLD START		HOT START		SIMMER TEST (CALCULATIONS DIFFER FROM HIGH POWER TEST)			
Calculations/Results	Units	data	label	data	label	Calculations/Results	Units	data	label
Fuel consumed (moist)	g	600	f_{cm}	550	f_{hm}	Fuel consumed during the simmer phase (i	g	300	f_{sm}
Net change in char during test	g	23	Δc_c	23	Δc_h	Net change in char during test phase	g	10	Δc_s
Equivalent dry fuel consumed	g	463	f_{cd}	422	f_{hd}	Equivalent dry fuel consumed	g	255	f_{sd}
Water vaporized from all pots	g	400	W_{cv}	350	W_{hv}	Water vaporized	g	950	W_{sv}
Effective mass of water boiled	g	4,506	W_{cr}	4,606	W_{hr}	Water remaining at end - All Pots	g	3,650	W_{sr}
Time to boil Pot # 1	min	40	Δt_c	25	Δt_h	Time of simmer (should be ~45 minutes)	min	45	Δt_s
Temp-corr time to boil Pot # 1	min	42	Δt^T_c	26	Δt^T_h	Thermal efficiency	%	42%	h_s
Thermal efficiency	%	26%	h_c	28%	h_h	Burning rate	g/min	6	r_{sb}
Burning rate	g/min	12	r_{cb}	17	r_{hb}	Specific fuel consumption	g/liter remainin	70	SC_s
Specific fuel consumption	g/liter boiled	103	SC_c	92	SC_h	Firepower	watts	1,841	FP_s
Temp-corr sp consumption	g/liter	107	SC^T_c	95	SC^T_h	Turn down ratio	--	2.04	TDR
Temp-corr sp energy consumpt.	kJ/liter	2,095	SE^T_c	1,845	SE^T_H	Specific Energy Consumption	kJ/liter	1,362	SE_S
Firepower	watts	3,765	FP_c	5,484	FP_h	Fuel Benchmark to Complete 5L WBT	g	854	BF
						Energy Benchmark to Complete 5L WBT	kJ	16,659	BE

1.2 Test -2

I. Input Parameters for the Excel



WATER BOILING TEST - VERSION 4.2 - TEST #2

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

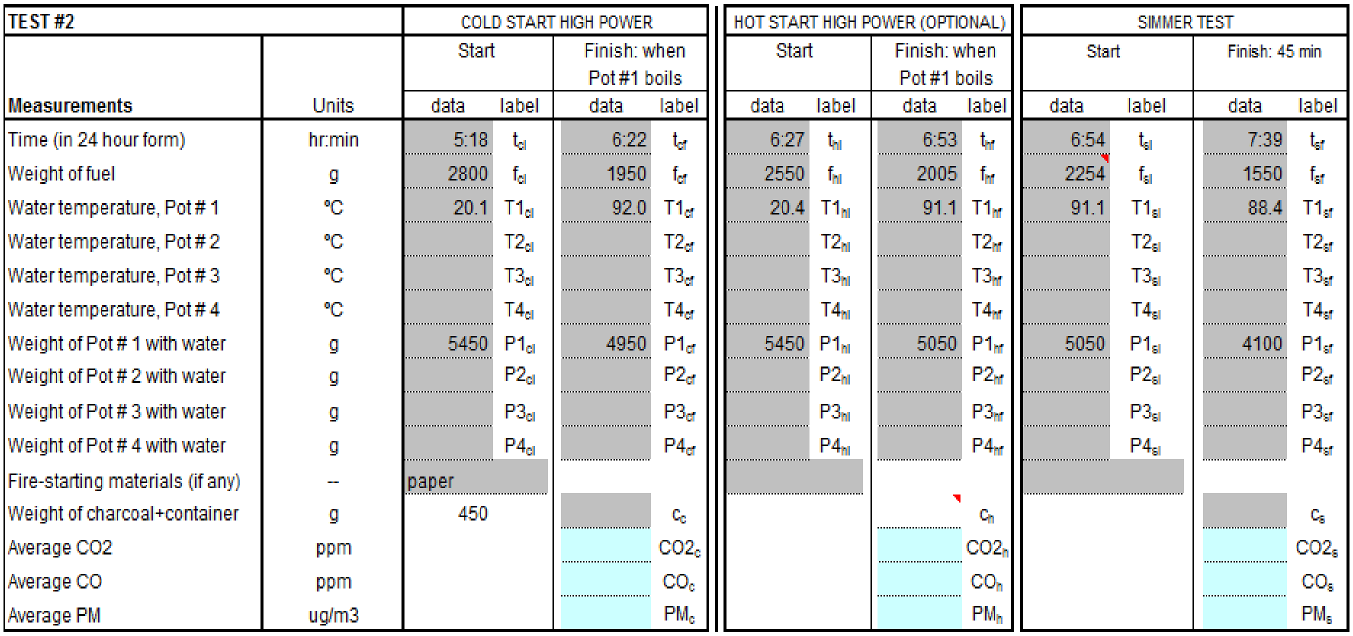
Shaded cells and arrows require user input; unshaded cells automatically display outputs

Qualitative data

Name(s) of Tester(s)	ayantu		gray: efficiency
Test Number			blue: emissions with hood method
Date	14/04/2016		
Location	Altenative energy technology (laboratory), Ethiopia		
Stove type/model	Tikikil wood stove		
Type of fuel	wood		

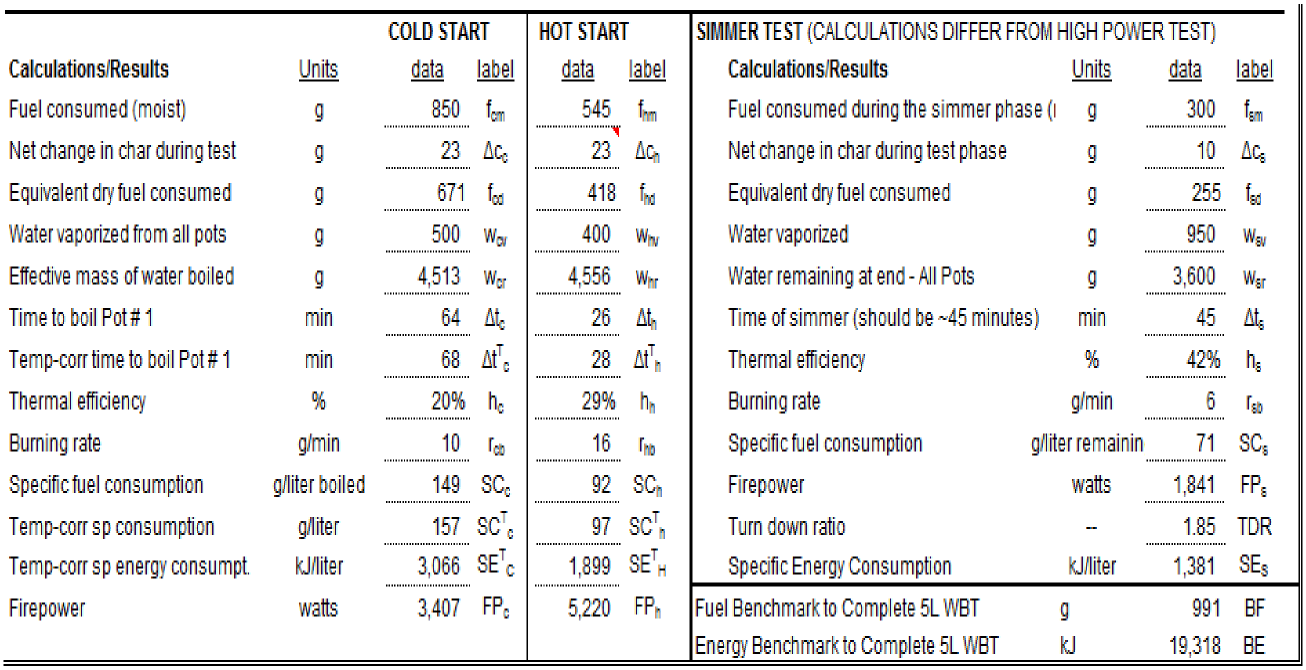
Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	17.9	°C		Dry weight of Pot # 1 (grams)	500	g	P1
Wind conditions	Moderate wind ▼			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	5 x 5			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	20,817	kJ/kg	HHV	Weight of container for char (grams)	400	g	k
Net calorific value (dry fuel)	19,497	kJ/kg	LHV	Local boiling point	91.0	°C	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	16,187	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	29,500	kJ/kg		PM		ug/m3	PM,b



TEST #2		COLD START HIGH POWER				HOT START HIGH POWER (OPTIONAL)				SIMMER TEST			
		Start		Finish: when Pot #1 boils		Start		Finish: when Pot #1 boils		Start		Finish: 45 min	
Measurements	Units	data	label	data	label	data	label	data	label	data	label	data	label
Time (in 24 hour form)	hr:min	5:18	t_{ci}	6:22	t_{cf}	6:27	t_{hi}	6:53	t_{hf}	6:54	t_{si}	7:39	t_{sf}
Weight of fuel	g	2800	f_{ci}	1950	f_{cf}	2550	f_{hi}	2005	f_{hf}	2254	f_{si}	1550	f_{sf}
Water temperature, Pot # 1	°C	20.1	$T1_{ci}$	92.0	$T1_{cf}$	20.4	$T1_{hi}$	91.1	$T1_{hf}$	91.1	$T1_{si}$	88.4	$T1_{sf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$		$T2_{hi}$		$T2_{hf}$		$T2_{si}$		$T2_{sf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$		$T3_{hi}$		$T3_{hf}$		$T3_{si}$		$T3_{sf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$		$T4_{hi}$		$T4_{hf}$		$T4_{si}$		$T4_{sf}$
Weight of Pot # 1 with water	g	5450	$P1_{ci}$	4950	$P1_{cf}$	5450	$P1_{hi}$	5050	$P1_{hf}$	5050	$P1_{si}$	4100	$P1_{sf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$		$P2_{hi}$		$P2_{hf}$		$P2_{si}$		$P2_{sf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$		$P3_{hi}$		$P3_{hf}$		$P3_{si}$		$P3_{sf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$		$P4_{hi}$		$P4_{hf}$		$P4_{si}$		$P4_{sf}$
Fire-starting materials (if any)	--	paper											
Weight of charcoal+container	g	450			c_c				c_h				c_s
Average CO2	ppm				$CO2_c$				$CO2_h$				$CO2_s$
Average CO	ppm				CO_c				CO_h				CO_s
Average PM	ug/m3				PM_c				PM_h				PM_s

II. Result Obtained

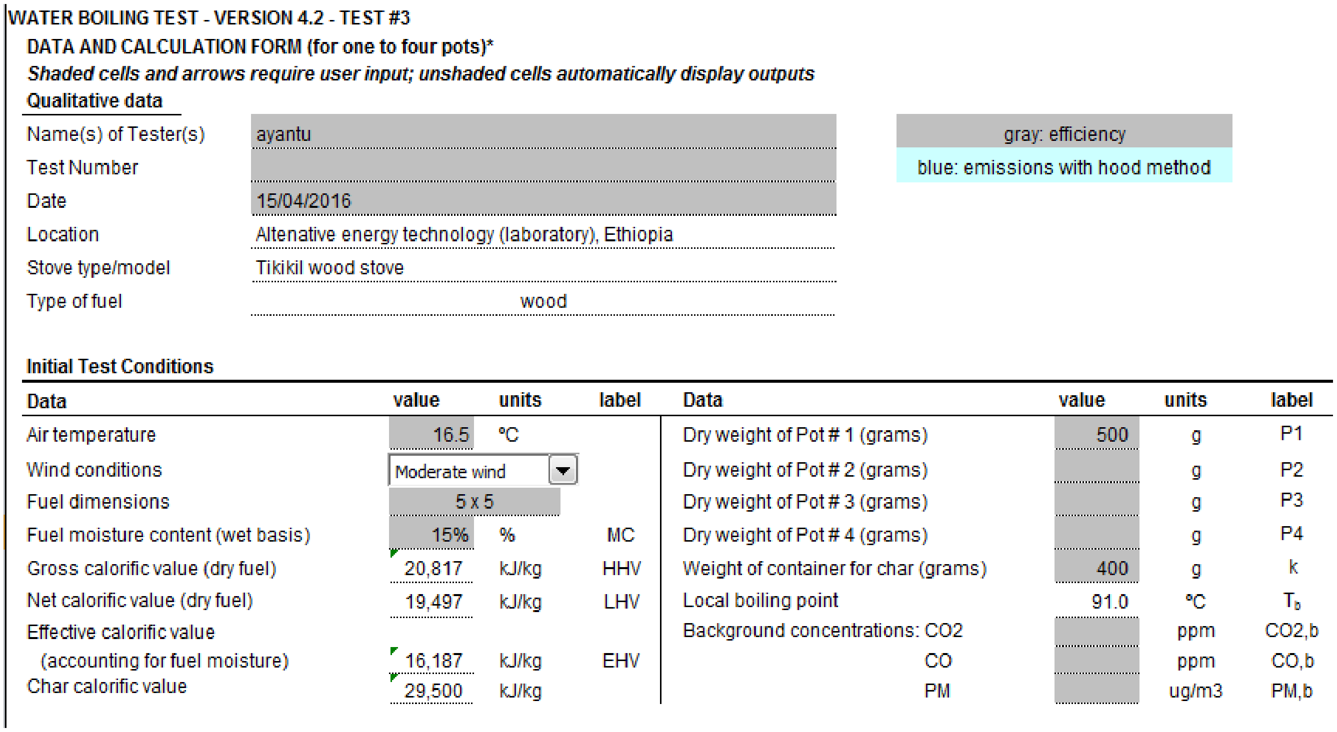


		COLD START		HOT START	
Calculations/Results	Units	data	label	data	label
Fuel consumed (moist)	g	850	f_{cm}	545	f_{hm}
Net change in char during test	g	23	Δc_c	23	Δc_h
Equivalent dry fuel consumed	g	671	f_{cd}	418	f_{hd}
Water vaporized from all pots	g	500	w_{cv}	400	w_{hv}
Effective mass of water boiled	g	4,513	w_{cr}	4,556	w_{hr}
Time to boil Pot # 1	min	64	Δt_c	26	Δt_h
Temp-corr time to boil Pot # 1	min	68	Δt^T_c	28	Δt^T_h
Thermal efficiency	%	20%	h_c	29%	h_h
Burning rate	g/min	10	r_{cb}	16	r_{hb}
Specific fuel consumption	g/liter boiled	149	SC_c	92	SC_h
Temp-corr sp consumption	g/liter	157	SC^T_c	97	SC^T_h
Temp-corr sp energy consumpt.	kJ/liter	3,066	SE^T_C	1,899	SE^T_H
Firepower	watts	3,407	FP_c	5,220	FP_h

SIMMER TEST (CALCULATIONS DIFFER FROM HIGH POWER TEST)			
Calculations/Results	Units	data	label
Fuel consumed during the simmer phase (I	g	300	f_{sm}
Net change in char during test phase	g	10	Δc_s
Equivalent dry fuel consumed	g	255	f_{sd}
Water vaporized	g	950	w_{sv}
Water remaining at end - All Pots	g	3,600	w_{sr}
Time of simmer (should be ~45 minutes)	min	45	Δt_s
Thermal efficiency	%	42%	h_s
Burning rate	g/min	6	r_{sb}
Specific fuel consumption	g/liter remainin	71	SC_s
Firepower	watts	1,841	FP_s
Turn down ratio	--	1.85	TDR
Specific Energy Consumption	kJ/liter	1,381	SE_s
Fuel Benchmark to Complete 5L WBT	g	991	BF
Energy Benchmark to Complete 5L WBT	kJ	19,318	BE

1.3 Test -3

I. Input Parameters for the Excel



WATER BOILING TEST - VERSION 4.2 - TEST #3

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

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

Qualitative data

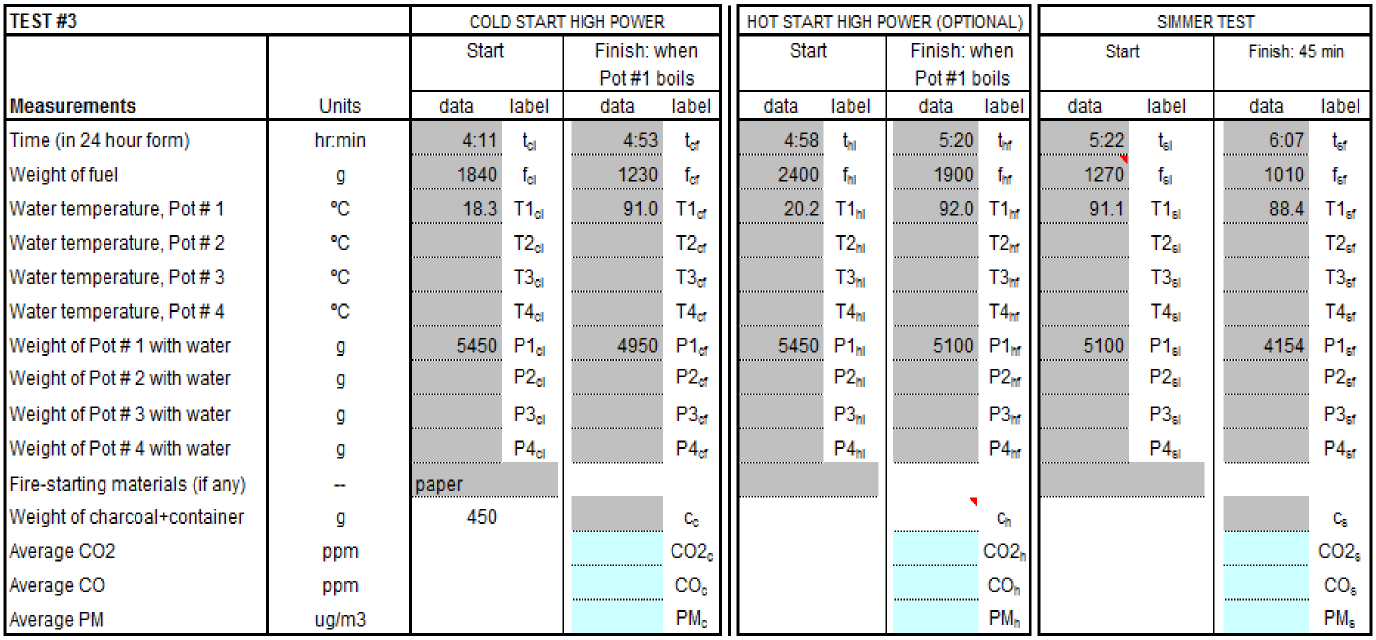
Name(s) of Tester(s)	ayantu
Test Number	
Date	15/04/2016
Location	Altenative energy technology (laboratory), Ethiopia
Stove type/model	Tikikil wood stove
Type of fuel	wood

gray: efficiency

blue: emissions with hood method

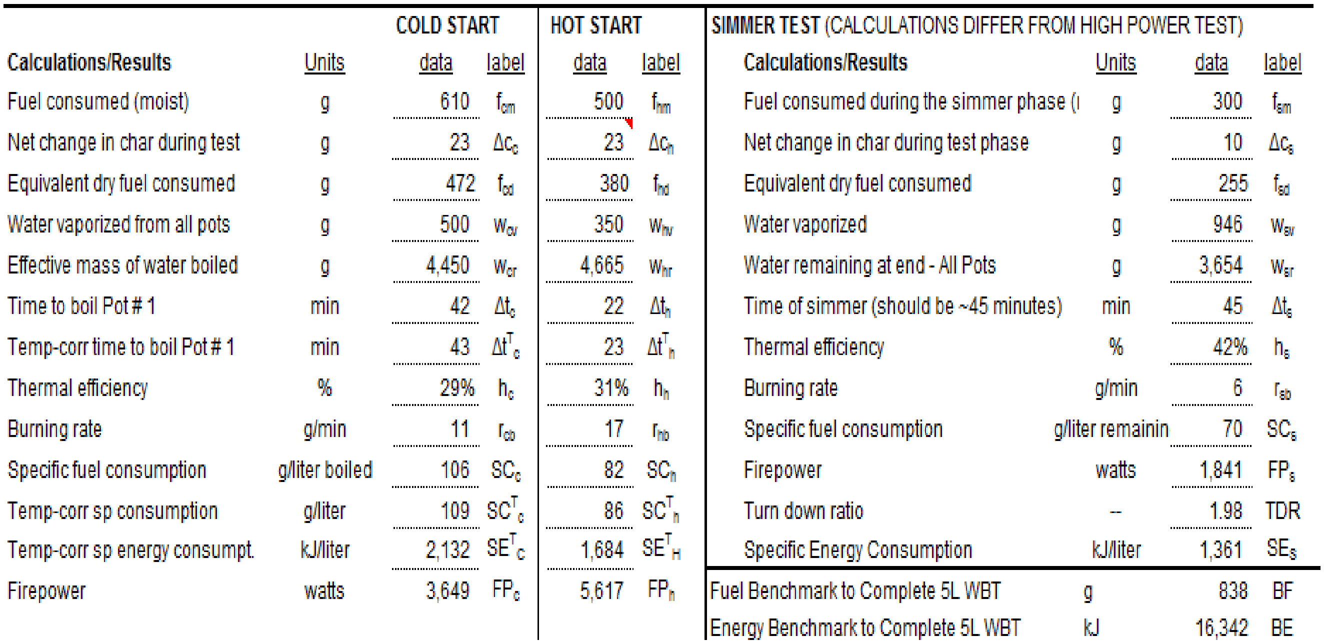
Initial Test Conditions

Data	value	units	label	Data	value	units	label
Air temperature	16.5	°C		Dry weight of Pot # 1 (grams)	500	g	P1
Wind conditions	Moderate wind ▼			Dry weight of Pot # 2 (grams)		g	P2
Fuel dimensions	5 x 5			Dry weight of Pot # 3 (grams)		g	P3
Fuel moisture content (wet basis)	15%	%	MC	Dry weight of Pot # 4 (grams)		g	P4
Gross calorific value (dry fuel)	20,817	kJ/kg	HHV	Weight of container for char (grams)	400	g	k
Net calorific value (dry fuel)	19,497	kJ/kg	LHV	Local boiling point	91.0	°C	T_b
Effective calorific value				Background concentrations: CO2		ppm	CO2,b
(accounting for fuel moisture)	16,187	kJ/kg	EHV	CO		ppm	CO,b
Char calorific value	29,500	kJ/kg		PM		ug/m3	PM,b



TEST #3		COLD START HIGH POWER				HOT START HIGH POWER (OPTIONAL)				SIMMER TEST			
		Start		Finish: when Pot #1 boils		Start		Finish: when Pot #1 boils		Start		Finish: 45 min	
Measurements	Units	data	label	data	label	data	label	data	label	data	label	data	label
Time (in 24 hour form)	hr:min	4:11	t_{ci}	4:53	t_{cf}	4:58	t_{hi}	5:20	t_{hf}	5:22	t_{si}	6:07	t_{sf}
Weight of fuel	g	1840	f_{ci}	1230	f_{cf}	2400	f_{hi}	1900	f_{hf}	1270	f_{si}	1010	f_{sf}
Water temperature, Pot # 1	°C	18.3	$T1_{ci}$	91.0	$T1_{cf}$	20.2	$T1_{hi}$	92.0	$T1_{hf}$	91.1	$T1_{si}$	88.4	$T1_{sf}$
Water temperature, Pot # 2	°C		$T2_{ci}$		$T2_{cf}$		$T2_{hi}$		$T2_{hf}$		$T2_{si}$		$T2_{sf}$
Water temperature, Pot # 3	°C		$T3_{ci}$		$T3_{cf}$		$T3_{hi}$		$T3_{hf}$		$T3_{si}$		$T3_{sf}$
Water temperature, Pot # 4	°C		$T4_{ci}$		$T4_{cf}$		$T4_{hi}$		$T4_{hf}$		$T4_{si}$		$T4_{sf}$
Weight of Pot # 1 with water	g	5450	$P1_{ci}$	4950	$P1_{cf}$	5450	$P1_{hi}$	5100	$P1_{hf}$	5100	$P1_{si}$	4154	$P1_{sf}$
Weight of Pot # 2 with water	g		$P2_{ci}$		$P2_{cf}$		$P2_{hi}$		$P2_{hf}$		$P2_{si}$		$P2_{sf}$
Weight of Pot # 3 with water	g		$P3_{ci}$		$P3_{cf}$		$P3_{hi}$		$P3_{hf}$		$P3_{si}$		$P3_{sf}$
Weight of Pot # 4 with water	g		$P4_{ci}$		$P4_{cf}$		$P4_{hi}$		$P4_{hf}$		$P4_{si}$		$P4_{sf}$
Fire-starting materials (if any)	--	paper											
Weight of charcoal+container	g	450			c_c				c_h				c_s
Average CO2	ppm				$CO2_c$				$CO2_h$				$CO2_s$
Average CO	ppm				CO_c				CO_h				CO_s
Average PM	ug/m3				PM_c				PM_h				PM_s

II. Result Obtained



		COLD START		HOT START	
Calculations/Results	Units	data	label	data	label
Fuel consumed (moist)	g	610	f_{cm}	500	f_{hm}
Net change in char during test	g	23	Δc_c	23	Δc_h
Equivalent dry fuel consumed	g	472	f_{cd}	380	f_{hd}
Water vaporized from all pots	g	500	w_{cv}	350	w_{hv}
Effective mass of water boiled	g	4,450	w_{cr}	4,665	w_{hr}
Time to boil Pot # 1	min	42	Δt_c	22	Δt_h
Temp-corr time to boil Pot # 1	min	43	$\Delta t^T{}_c$	23	$\Delta t^T{}_h$
Thermal efficiency	%	29%	h_c	31%	h_h
Burning rate	g/min	11	r_{cb}	17	r_{hb}
Specific fuel consumption	g/liter boiled	106	SC_c	82	SC_h
Temp-corr sp consumption	g/liter	109	$SC^T{}_c$	86	$SC^T{}_h$
Temp-corr sp energy consumpt.	kJ/liter	2,132	$SE^T{}_C$	1,684	$SE^T{}_H$
Firepower	watts	3,649	FP_c	5,617	FP_h

SIMMER TEST (CALCULATIONS DIFFER FROM HIGH POWER TEST)			
Calculations/Results	Units	data	label
Fuel consumed during the simmer phase (I	g	300	f_{sm}
Net change in char during test phase	g	10	Δc_s
Equivalent dry fuel consumed	g	255	f_{sd}
Water vaporized	g	946	w_{sv}
Water remaining at end - All Pots	g	3,654	w_{sr}
Time of simmer (should be ~45 minutes)	min	45	Δt_s
Thermal efficiency	%	42%	h_s
Burning rate	g/min	6	r_{sb}
Specific fuel consumption	g/liter remainin	70	SC_s
Firepower	watts	1,841	FP_s
Turn down ratio	--	1.98	TDR
Specific Energy Consumption	kJ/liter	1,361	SE_S
Fuel Benchmark to Complete 5L WBT	g	838	BF
Energy Benchmark to Complete 5L WBT	kJ	16,342	BE

Appendix 2 -Thermal Property

A thermal property is any characteristic of a material defining the substance and related to temperature.

1. **Heat capacity**; is a measurable physical quantity equal to the ratio of the heat added to (or removed from) an object to the resulting temperature change. It is the energy required to increase the unit mass a unit temperature. It depends on the path (although it is not a path but a state variable), and the thermal capacity at constant pressure is usually given; for condense substances the difference is negligible, but for gases it is not; e.g. the thermal capacity of air at constant pressure is C_p=1000 J/(kg·K). The most common technique to measure heat capacity is by calorimeter, i.e. letting the sample come into equilibrium with a bath at a different initial temperature and measuring the final temperature
2. **Density**; It is the mass of the unit volume
3. **Thermal conductivity**; It is the coefficient in Fourier's law of heat conduction (i.e. heat flux proportional to temperature gradient) When two metallic parts are in contact, the thermal joint resistance may drastically deteriorate the heat flow, and a thermal pad or thermal grease is applied to enhance thermal-joint-conductance. Fourier's will be stated or shown as $k = QL /(A\Delta T)$ where *A is* sample of area and *L,* thickness, while ΔT is maintained temperature difference between thermal blocks.
4. **Emissivity;** It is the energy radiated per unit area by a one-side surface in all directions and at all wavelengths (what is known as hemispherical bolometric emission, or infrared emission, since not-incandescent materials emit mainly in the infrared).
5. **Viscosity**;

No	Thermal Property	Materials	
		Solid /Clay	Fluid /air
1	Density	1464 kg/m^3	1.225kg/m^3
2	Thermal conductivity	1.3	0.0242
3	Specific heat capacity	880 J/kg .k	1006.43 J/kg. k
4	Emissivity	0.75	
5	Viscosity		1.789 x 10^{-5}kg/m-s

Table; 2.1 property of materials used in this research work

Appendix 3 - Components of Tikikil Stove

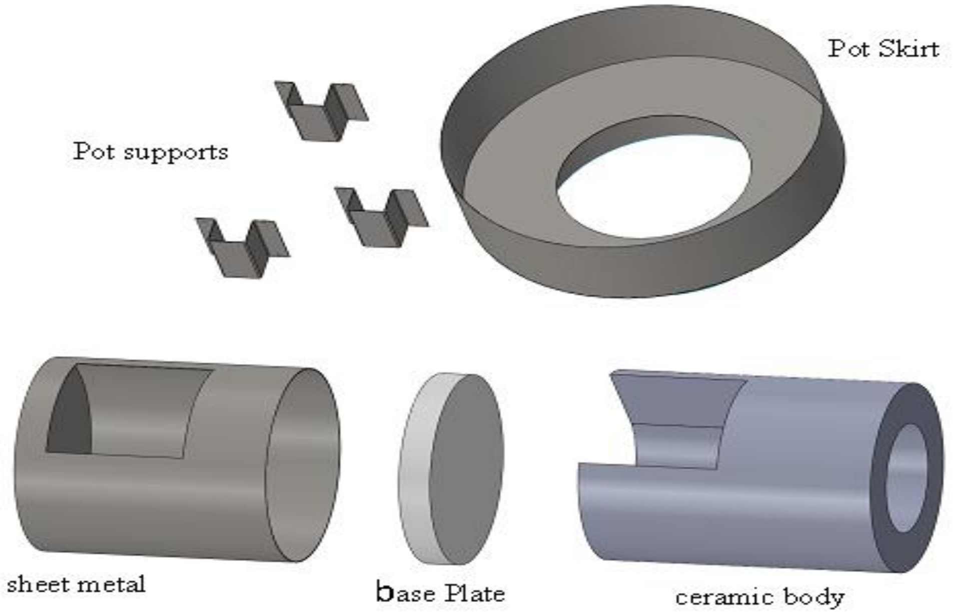


Figure1. Components of tikikil stove

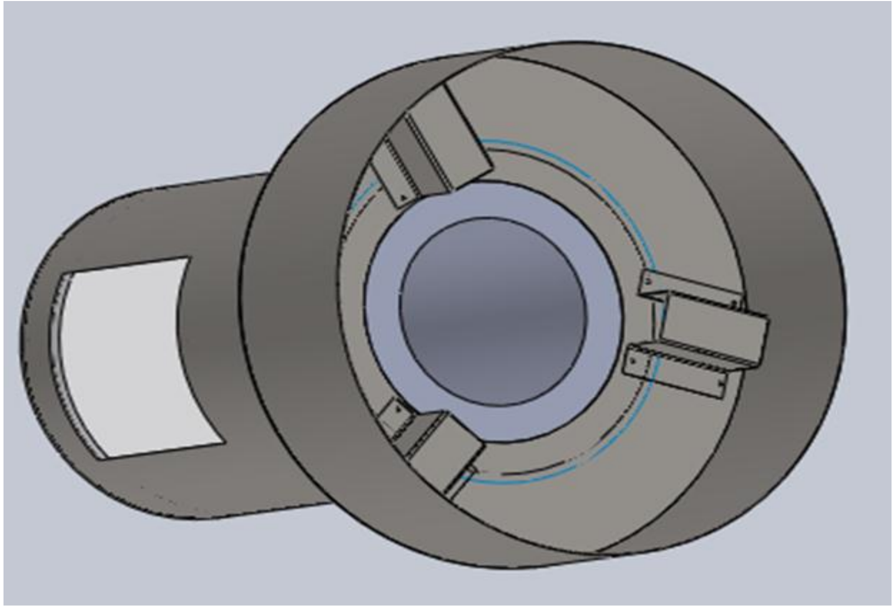


Figure2. 3D view of assembled tikikil stove

Appendix 4 – Geometry of Tikikil stove and Optimized Stove

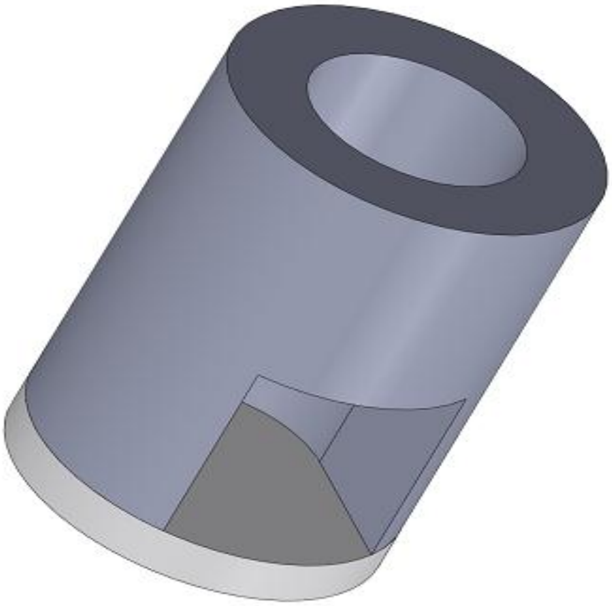


Figure1. Geometry of internal chamber of tikikil stove

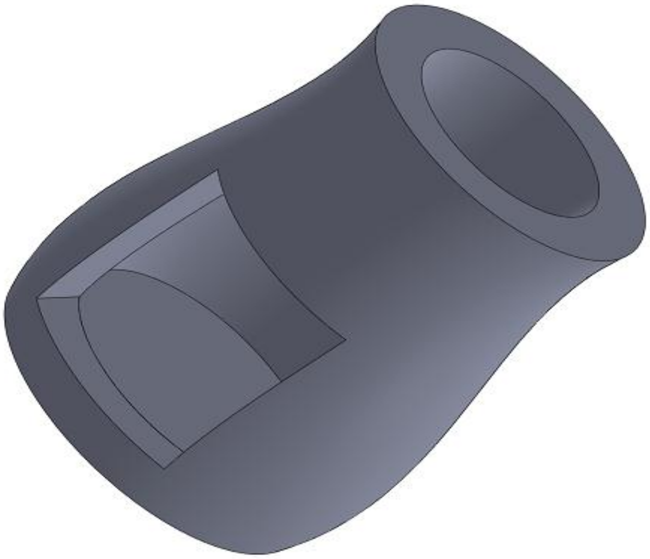


Figure2. Geometry of internal chamber of optimized stove