INVESTIGATION OF THE THERMAL PROPERTIES OF WOOD ASH AND CLAY-SAWDUST MIXTURE FOR USE AS INSULATION MATERIALS IN A ROCKET STOVE

BY

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DECLARATION

I declare that the work in this Dissertation entitled Investigation of The Thermal Properties of Wood Ash and Clay-sawdust mixture for use as Insulation Materials in a Rocket Stove, has been carried out by me in the Department of Mechanical Engineering. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this research was previously presented for another degree or diploma at this or any Institution.

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Name of Student	Signature	Date

CERTIFICATION

This Dissertation entitled INVESTIGATION OF THE THERMAL PROPERTIES OF WOOD ASH AND CLAY-SAWDUST MIXTURE FOR USE AS INSULATION MATERIALS IN A ROCKET STOVE by EMMANUEL OCHIMA EBIEGA meets the regulations governing the award of the degree of Master of Science in Mechanical Engineering of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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ABSTRACT

In recent years there has been an increased awareness to conserve energy through efficient use of fuels, energy saving devices and insulation against heat losses. Consequently, the construction of a rocket stove was undertaken in this research and the thermal property tests for ash and clay-sawdust insulation materials were carried out, after which the effect of these insulation materials on the thermal efficiency of the rocket stove was experimentally determined using cooking tests (water boiling test, control test and kitchen performance test). Both the ash and the clay-sawdust showed the ability to be used as insulators in the rocket stove; having low thermal conductivities (0.2W/mK and 0.16W/mK respectively), high specific heat (889J/kgK and 910J/kgK respectively) and low thermal diffusivity (3.67e-7/m^2s and 1.58e-7/m^2s respectively). When the ash and clay-sawdust were used in the rocket stove the thermal efficiency of the stove has a value of 21.6% and 22.28% respectively (for cold start), 46.34% and 44.06 % respectively (for hot start) and 20.00% and 23.91% respectively (simmering phase). This shows a great improvement when compared with the stove without insulation 10.86% (cold start), 17.70% (hot start) and 14.50% (simmering). The burning rate (5.30g/min, 5.24g/min for ash and clay-sawdust respectively, 10.72g/min for the stove without insulaion), firepower (2.36Watt and 2.34Watt for ash and clay-sawdust respectively, 5.25Watt for the stove without insulation) and specific fuel consumption (0.038 and 0.039 for ash and clay-sawdust respectively, 0.13 for the stove without insulation) all improved when there was insulation around the rocket stove. This shows that both ash and the clay-sawdust can be used as insulation material in the rocket stove and they improve the thermal efficiency of the rocket stove. The clay-sawdust insulated stove performed better than the ash insulated stove, having better thermal properties as shown above and gave better results when the water boiling tests were carried out.

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NOMENCLATURE

G_A; gap between the bottom of the pot and the top edge of the combustion chamber (m)

Gc; gap at the edge of the Pot (m)

G_D; gap between pot side and Stove body (m)

Q; chimney draft/flow rate (m^3/s)

C; discharge coefficient

g; acceleration due to gravity (m/s^2)

T; temperature (^0C)

K; thermal conductivity of the material (W/mK)

η_C; combustion efficiency (%)

η_{HT}; heat transfer efficiency (%)

C_W; specific heat capacity of water (kJ/kgK)

C_P; specific heat capacity of pot (kJ/kgK)

L_V; latent heat of evaporation of water (kJ/kg)

C_F; specific heat capacity of fuel wood (kJ/kgK)

C_c; specific heat capacity of charcoal (kJ/kgK)

H_C; calorific value of charcoal (kJ/kg)

α; thermal diffusivity (m^2/s)

WBT; water boiling test

CCT; control cooking test

PHU; percentage heat utilised (%)

SFC; specific fuel consumption (kg/kg)

BR; burning rate (g/min)

FR; firepower (W)

M_w; mass of water (kg)

M_p; mass of pot (kg)

M_v; mass of vapour (kg)

M_f; mass of fuel (kg)

M_c; mass of charcoal (kg)

CHAPTER ONE

INTRODUCTION

1.1 Background of Study

With a global human population exceeding six billion people, a lot of food is being cooked using a lot of energy. In the industrialised world, that energy usually takes the form of a stove that is heated by electricity or by burning a gaseous fuel such as natural gas or liquefied petroleum gas (Zube, 2010). While in the developing world, the cooking device is rarely powered by electricity, and is far more likely to be powered by burning liquefied petroleum gas, kerosene or biomass such as wood, dung, or charcoal. The large preference for wood as fuel is predicated upon the fact that apart from wood and coal the other primary non-renewable sources of energy such as petroleum, natural gas and liquefied natural gas are no longer easy to come-by in terms of cost and availability. The lifetime for these other alternatives is estimated to range from 15 years for natural gas to nearly 300 years for coal (Yawas, 2003). Estimate put the total number of people throughout the world who rely on solid biomass fuels at three billion, or roughly one-half of the world's human population (Desai *et al*., 2004). The problems that surround burning biomass for cooking purposes affect a very large number of people, and this number is not likely to be reduced significantly in the near future (Zube, 2010). Even in areas where governments are actively attempting to displace the use of biomass fuels by subsidising the cost of electricity, people continue to use biomass for cooking because it tends to be less expensive, and electricity is valued for its ability to power television sets and other devices that cannot be powered with wood (Madubansi and Shackleton, 2007).

Nearly 2.7 billion people use solid biomass fuels for household cooking and heating in open fires and simple stoves (Legros *et al*., 2009). The users of these stoves live almost entirely in the developing world, and the individual, community, and global impacts of these small biomass cook stoves is significant. It has been estimated that indoor air pollution from solid fuel use is responsible for nearly 4 million deaths annually and approximately 4% of the global burden of disease, representing the second leading cause of death for women globally (Lim *et al.*, 2012). The fine particulate matter, carbon monoxide, polycyclic aromatic hydrocarbons, and other emissions due to incomplete combustion within poorly ventilated spaces contribute to acute lower respiratory infections, pneumonia, and chronic obstructive lung disease; as well as adverse pregnancy outcomes and cataracts (Legros *et al.*, 2009). In many cases, the use of biomass fuel for household energy is exacerbated by deforestation and desertification around communities, leading to increased time and energy spent in gathering fuel, and it poses a significant opportunity cost to education, health, and income-generating activities, primarily for women and children (Rehfuess, 2006).

The ‘vicious circle’ of energy poverty and environmental deterioration, health degradation, and opportunity costs inhibits the capacity to move from the use of energy for simply meeting basic survival needs to productive or income-generating energy use. Poor families spend one-fifth or more of their income on wood and charcoal, devote one quarter of household labour collecting fuel wood, and then suffer the life-endangering pollution that results from inefficient combustion (Sovacool, 2012).

Stove dissemination programmes have been met with varying levels of success (Schreiner, 2011). As is true with any development initiative, the sustainability of an improved stove research is not driven by the technology alone. Social, cultural, and economic factors have a significant effect on stove use and adoption rates. The most successful improved stoves are easy to construct in local settings using existing techniques and materials and have clear advantages with respect to fuel economy, ease of use, durability, and cleanliness (Barnes, 1994).

The Rocket stove as first designed by Winiarski, introduced insulation around the fire to improve thermal efficiency of the stove (Bryden, 2010). Rocket Stove is a stove with flexible design that produces virtually no smoke and uses very little fuel. Rocket Stoves features "elbow" fuel magazines which produce cleaner, more complete combustion and insulated combustion chambers which maintain high cooking temperatures. Rocket stoves are small efficient stoves that can produce a hot flame with only a few small pieces of wood. The reason it is called a rocket stove is because when wood is added to the fire the flames create an internal draft. As the draft is created, the fire begins to produce a jet of fire coming through the stove pipe. The rocket stove has become widely recognized as the world leader in high efficiency, intermediate technology stove, (Scott, 2006). Insulators due to their low thermal conductivity are able to retard the flow of heat energy. There are varieties of insulating materials which come in various forms like loose fill, rigid boards, pipe and foam. Proper selection of the insulating material to be used is based on the thermal properties which include the thermal conductivity, specific heat capacity and thermal diffusivity.

1.2 Statement of Problem

With a large population of the world relying on woodstove for cooking, wood fuel will continue to be in high demand. Felling of trees harm the environment and there are many health challenges associated with cooking with wood. An open fire is often 90% efficient in turning wood into energy, but only a small proportion (10% to 40%) of the released energy makes it to the pot (heat exchanger) hence, more wood is burnt (Bryden, 2010). Hence, combustion efficiency does not appreciably help the stove use less fuel. Heat transfer is currently underutilised as a means of increasing stove thermal efficiency and opportunities exist that could change this. Hence, this is the area of research offering the greatest potential to enhance performance and provide more people with improved cooking procedures (Ebiega, 2012).

Also, most improved stoves have the problem of absorbing some of the heat produced into the stove body thereby reducing heat reaching the heat exchanger, even though they may have low specific fuel consumption.

1.3 Present Research

The present research investigated experimentally the thermal properties of wood ash and clay-sawdust mixture for use as insulators in a rocket stove, with the aim of improving heat transfer efficiency in the rocket stove and studied how they affect the thermal efficiency of the rocket stove, and the stove was tested under different conditions to ascertain the best condition for its usage.

1.4 Aim and Objectives

The aim of this research is to investigate experimentally the thermal properties of wood-ash and clay-sawdust mixture insulating materials and to determine their effect on the thermal efficiency of a rocket stove.

The specific objectives of this research work are to:

i. develop wood ash and clay-sawdust mixture insulating materials and test their thermal properties: thermal conductivity, specific heat capacity and thermal diffusivity.
ii. construct three prototypes of a designed rocket stove with wood ash and clay-sawdust mixture as insulation materials for the two stoves and one without insulation.

iii. determine experimentally the effects of each insulating material on the efficiency of the stoves.

iv. carry out control cooking tests on the stoves.

1.5 Justification

With over 2 billion of the world's population using biomass to cook every day, the possibility of improved stoves helping to mitigate climate change is generating increasing attention. Laboratory results have shown that some improved stoves with rocket-type combustion or fan assistance can reduce the overall warming impact from the products of incomplete combustion (PICs) by as much as 50-65% (Karekezi, 1992). The use of insulators is one way of improving heat transfer efficiency as heat loss to the stove body which is a major challenge in improved stoves is reduced greatly hence more heat gets to reach the heat exchanger. Hence if the stove performance can be improved using local materials like wood-ash and clay-sawdust mixture as insulatorsthen health, economic and environmental concerns will be greatly reduced in Nigeria

If it is ascertained that wood-ash and clay-sawdust mixture are good enough insulators for the rocket stove, this will be a boost economically, as people can go into stove manufacturing and both health and environmental challenges will be reduced eventually and there are large quantities of these materials (wood ash and the clay-sawdust).

1.6 Scope of Study

This present research is focused on constructing an already designed rocket stove. The thermal properties of the insulating materials were determined experimentally and water boiling test and cooking tests were carried out to find the effects of the thermal property of wood-ash and clay-sawdust mixture on the thermal efficiency of the rocket stove.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

The development of wood burning stoves is not a recent phenomenon. Within the last one hundred years, wood-burning stoves were adopted by middle and upper-income families when access to petroleum-based fuels was a problem, before then the open three stone fire have been in existence. Half of the world's population cook their food using various forms of biomass such as wood, charcoal, dung and crop residues. Burning each of these biomass fuels emits harmful chemicals and large amounts of particulates, each of which have adverse effects on human health, global climate and regional ecosystems from which the fuel is extracted. In the year 2000, it was estimated that the combustion of biomass fuels was responsible for 13 % of global energy consumption. A large majority of this consumption occurs in developing countries where 90% of rural households rely upon biomass as a means to provide for their heating and cooking needs (Bruce, 2000). Unfortunately, most of these people use very inefficient traditional cooking methods that cause excessive air pollution and use more fuel than necessary. Improved stoves are designed to increase fuel efficiency and reduce smoke and harmful emissions associated with the combustion of biomass fuels. Improved cook stoves are a promising measure for sustainable and efficient use of fuel wood (Foundation, 2008).

Improved stove designs seek to increase combustion efficiency though a number of design features; adequate draft and a proper air-to-fuel ratio ensure a more complete and efficient combustion process. Careful consideration of the size, geometry, and placement of the fuel inlet and combustion chamber provides increased control of airflow. A hotter fire is also more effective at consuming combustible gases. Proper insulation around the combustion chamber reduces heat loss, allowing the fire to burn at higher temperatures (Bryden, *et al*. 2005). Most challenges with improved stove is the issue of heat loss to the stove body, which ultimately reduces heat transfer and overall stove efficiency, but with rocket type stove, the heat loss to the stove body is reduced due to the insulation provided between the double wall cavity of the stove.

2.2 Types of Cook stoves

A traditional biomass cook stove consists of the air intake and transport system, a bed of fuel, a gas phase combustion zone, and a cooking pot. There are three primary types of traditional household biomass cook stoves based on the treatment of the combustion chamber (MacCarty, 2013)

1. Open cooking fires—these are traditional cooking fires in which a pot is held atop three stones or other similar support (Figure 2.1). The airflow is uncontrolled and the air is entrained in the system due to buoyancy. Generally, a fire grate is not included.

Figure 2.1 Traditional wood fire (Aprovecho, 2005)

2. Shielded cooking fires—these stoves are often referred to as improved stoves and marketed under a number of names. These devices range from a simple shield of metal

or clay around the combustion space to more complex devices with inlets for directed control of primary and secondary air (Figure. 2.2). Some include electrically powered fans to control air. In some cases, a narrow channel is created around the pot to improve heat transfer from the combustion gases to the pot. There may or may not be a fire grate provided.

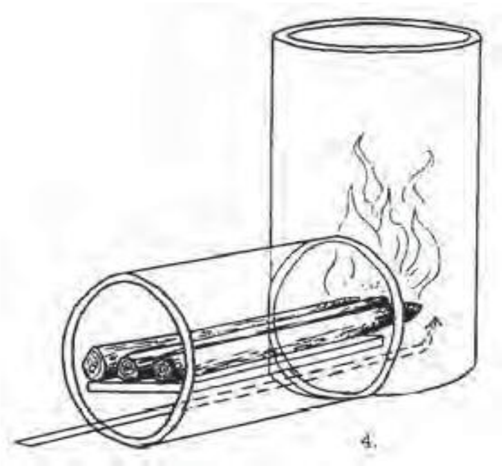


Figure 2.2 An insulated fire Stove (Aprovecho, 2005)

3. Enclosed fires with chimneys—these stoves include the rocket type stove, with insulation around the combustion chamber. The fire is fully enclosed within the combustion chamber. The fuel entrance may be open and permit airflow into the system, (MacCarty, 2013). Alternatively, there may be a tightly sealed fuel door and separate controls for airflow into to the stove. Gases leave the combustion chamber and travel along channels underneath the exposed pot bottoms or a large sealed plate or griddle on which pots are heated or food is cooked directly. The combustion gases then exit to the chimney and are exhausted outside of the kitchen.

Stove designs were developed largely by trial and error (Baldwin, 1987). Wood fuels were relatively cheap during most of the past century, so efficiency was not an important factor. As urban population increased however, wood fuel supplies became relatively more distant from the markets, prices increased and some stove makers began more intensive efforts to improve their models and make them more efficient.

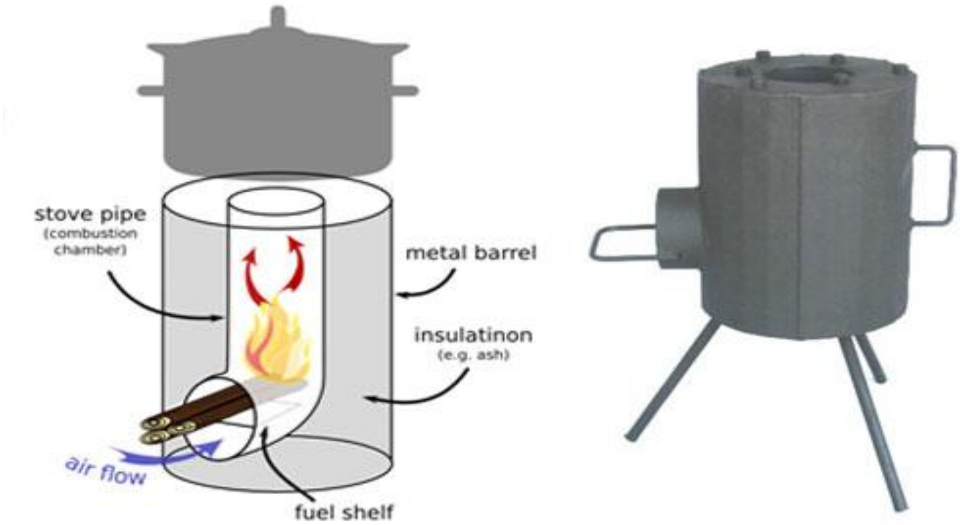


Figure 2.3 Enclosed fire with chimney (Winiarski, 1996)

2.3 Components of Rocket Stove

The rocket stove as first designed by Winiarski (1996) has the following components as shown in figure 2.4:

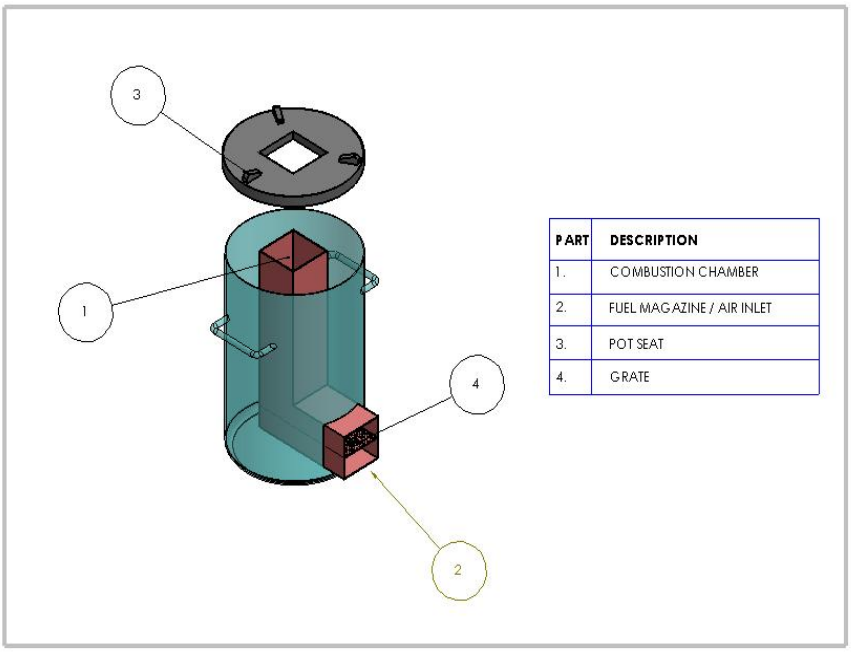


Figure 2.4 The Rocket stove

2.3.1 Combustion chamber

At the end of the fuel magazine, where the fuel burn is located the combustion chamber. This the place where combustion of the fuel takes place, as the fuel burns in the combustion chamber, convection draws new air into the combustion chamber from below, ensuring that any smoke from smouldering wood near the fire is also drawn into the fire and up the chimney. It can be circular or rectangular and can be made from metal, ceramics or clay but it has to be a material that can withstand the temperature and general condition of the combustion chamber. The combustion chamber shape and the material used affects thermal efficiency of the rocket stove.

2.3.3 Chimney

The chimney comes immediately after the combustion chamber. It carries the heat energy generated from the combustion chamber to the heat exchanger. It provides the upward draft needed to maintain combustion, and help transfer the heat to the area where it is needed to ensure efficient use of the heat generated. The chimney is usually insulated to increase the temperature and improve combustion; according to studies, this increase thermal efficiency of the stove. It can be made from the same material as the combustion chamber or from the different material, the most important thing about the chimney is the chimney height and chimney diameter, this affects the stove efficiency. Airflow through the stove is dependent on the chimney effect resulting from the buoyant force of the decreased density air after combustion heat addition.

2.3.2 Fuel Magazine

This is the opening at the side of the rocket stove close to the bottom where the fuel is introduced into the stove and from which it feeds into the combustion chamber. It usually has the same dimension as the combustion chamber for Winiarski constant dimension rocket stove model. It also, serves as the air inlet, where fuel grate holds the fuel and suspend it from the stove floor, so that primary air flows under the fuel into the combustion chamber creating conventional flow. The fuel magazine can be horizontal, with additional fuel added manually, or vertical, with fuel gravity fed.

2.3.3Pot Seat

The pot seat is usually made of a high refractory material so that it can withstand the heat from the chimney. The geometry of the pot seat is very important, as it determine how the pot (heat exchanger) sits on the stove and in turn how much heat reaches the heat exchanger. It determines the pot gap, which is the distance between the bottom of the pot and the stove.

2.3.4 Grate

The grate is a perforated plate that holds the fuel from the stove floor, by so doing the stove inlet is separated into air inlet and fuel magazine, which allows air to flow under the fuel and into the combustion chamber. The grate also helps in reducing conduction heat loss to stove which usually occurs when the fuel lies on the floor.

2.4 Energy Balance in a cooking Stove

Geller as in Burnham-Slipper (2008) carried out extensive tests on stoves and summarized his findings as 84% combustion efficiency, 17% heat transfer efficiency and 43% pot efficiency. This result highlighted the need to address heat transfer as the critical issue in stove design while combustion efficiency is already at a reasonable level. His results have been further broken down as shown in Figure 2.3

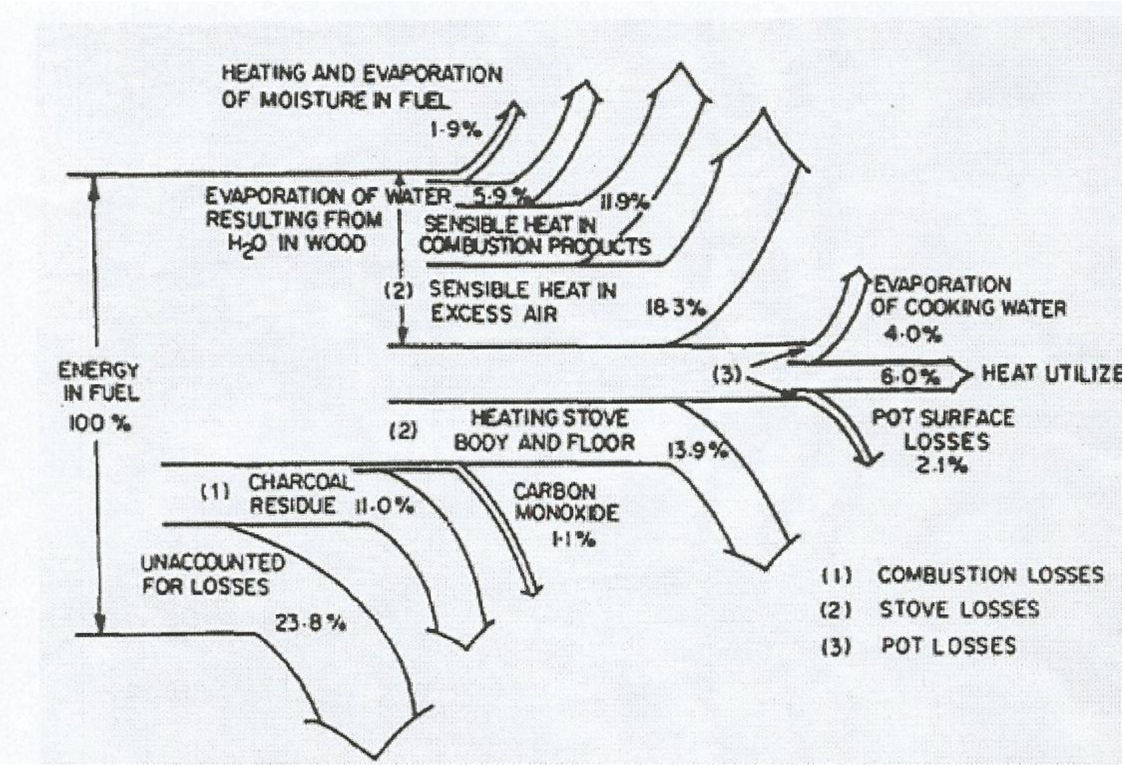


Figure 2.5 Energy Balance for Cooking (Geller, 1982)

Heat transfer is currently underutilised as a means of increasing stove thermal efficiency as shown in Figure 2.3 and opportunities exist that could change this.

One area of improving heat transfer efficiency is by ensuring that a high percentage of heat generated gets to the heat exchanger without considerable losses to the stove body and the environment, one way of doing this is by providing insulation along the combustion gases flow path, thereby ensuring that a high percentage gets to the heat exchanger (Burnham-Slipper, 2008).

2.5 Types of Efficiencies in a Stove

Several parameters have been proposed to evaluate and compare the performance of cooking stoves, each requiring different test procedure. Perhaps the most widely used term is efficiency. There are several definitions of efficiency, relating to different aspects of stove’s operation (Burnham-Slipper, 2008):

2.5.1 Combustion efficiency

This is the ratio of heat energy released by the flame to the chemical energy in the fuel. It depends largely on the type of fuel used, the combustion area and the combustion conditions like amount of air and ambient conditions. It has little effect on thermal efficiency.

2.5.2 Heat Transfer Efficiency

This is the ratio of heat entering the pot (heat exchanger) to the energy in the flame. This is affected by the stove material, air circulation, insulation and the stove geometry. It greatly affects thermal efficiency of the stove. It tells us how much energy we are expecting to reach the heat exchanger.

2.5.3 Pot (Heat exchanger) Efficiency

Pot efficiency is the ratio of the energy remaining in the pot to the energy entering the pot. It tells us how much of the heat reaching the pot is actually used for cooking. It depends on the pot material and how the pot sits on the stove top.

2.5.4 Overall Efficiency

This is the ratio of the energy in the pot to the energy in the fuel. It is the product of all the other definitions of efficiency.

2.6 Review of Related Literatures

For approximately 40 years, many international organisations have been striving to provide people with clean burning efficient cook stoves as an alternative to traditional cooking methods. Over the years, great strides have been made in improving cook stove technology (Zube, 2010). Examples of such improvements include reducing fuel usage of the stove by increasing heat transfer efficiency, reducing air pollution by increasing the combustion efficiency of the fuel and establishing a standard test protocol by which stoves can be evaluated fairly. All these improvements have allowed stove designers to more effectively provide improved cookstoves to people who need them. As improved cookstoves have been distributed throughout the developing world, the quality of air people breathe has improved and environmental damage has been reduced. Despite these considerable improvements in cookstove performance many households in developing countries still rely on inefficient stoves and procedures to cook their food because they cannot afford an improved stove (Zube, 2010).

2.6.1 Past Research on Stove Design and Construction

Joshi *et.al*. (1991), working on biomass stove reported that improved stoves tend to have improved efficiencies. They attributed this improvement in efficiency to insulation around the fire chamber, the use of fire grate, reduction of thermal inertia and small passages for the flue gases to pass by the pot and different other deign strategies. They also reported that improved thermal efficiency was achieved due to increase in heat transfer, but as a result of that combustion efficiency was reduced leading to a higher emission.

Ballard-Tremeer (1996) tested two stoves (Figure 2.4) and found that the classic open fire stove had an efficiency range of 10-15%, while the improved open fire stove has 20-25%. This improvement in efficiency is couple with a 13% reduction in CO emission. The unchanged emission level suggests that the combustion regime has remained relatively unchanged, so that most of the improvement in efficiency has come from the extra insulation provided by the air between the ground and the fire.

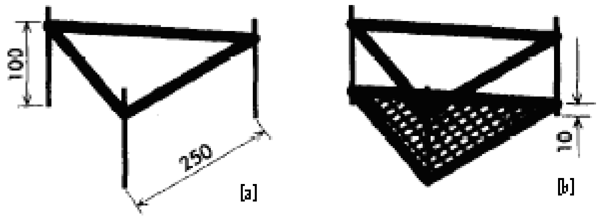


Figure 2.6 Local open fire (a) and improved open fire (b) (Ballard-Tremeer, 1996)

Pemberton-Pigott (2004) developed the VESTO stove, which was designed to burn brush-wood, fuel-wood, agricultural waste and dung cakes and combustion takes place in a tall tampered chamber. Primary air enters at the bottom through intake which induced a vortex and passes up through a bed of fuel which burn from the top down, the secondary air inlet is varied to change fire power. The whole combustion chamber is encased to insulate it, and primary air is taken from the insulated cavity, ensuring that it is preheated. The vortex flow field within the combustion chamber ensure greater mixing of secondary air and volatiles given off by fuel, ensuring complete combustion. It also increases residence time for hot gases thereby increasing heat transfer efficiency. Efficiencies of the VESTO is reported to be in the range of 25-35%.

Huo and Ko (2004) studied how the heat transfer of a flame impinging on a plate is affected by the type of flame, burner-plate distance, equivalence ratio and Reynolds number. Assessing the heat transfer efficiency of a natural flame they concluded that the optimum flame-plate displacement is to be had when the tip of the light-blue premixed flame just kisses the plate: any higher and the core does not have space to react, any further and the hot gases begins to be diluted by excess air.

Ayo (2009), designed, constructed and tested an improved wood stove. The design improvement of the stove focused on the following areas: provision of insulation around the combustion chamber to reduce conduction heat loss across the walls of the chamber, incorporation of smoke rings at the top of the stove, provision of sizable and adjustable air inlet to ensure the availability of sufficient air for the complete combustion of the fuel wood, and the incorporation of chimney to convey flue gases away from the place of use. Performance test results show that the wood stove has a maximum thermal efficiency of 64.4% and power delivery of 2.52kW, but a minimum specific fuel consumption of 0.447.

Bolaji and Olalusi (2009) designed, fabricated and tested an improved coal stove to evaluate the thermal performance of the stove. The performance of the stove was compared with that of traditional coal stove and conventional kerosene stove. The results obtained showed a better performance of the improved coal stove in terms of cooking duration and specific fuel consumption than that of the traditional coal stove and kerosene stove. The results also showed that the improved coal stove with coal burning rate of 0.15 $kghr^{-1}$ can handle fuel more efficiently and economically than traditional coal stove, which has coal burning rate of 0.20 $kghr^{-1}$. The thermal efficiency of improved coal stove was found to be 42.6%, whilst those of kerosene and traditional coal stoves were 40.5 and 28.2%, respectively.

Zube (2010) carried out research on the heat transfer efficiency in biomass stoves, where he focused on thermal efficiency improvement through heat transfer efficiency. He used theoretical approach to study the three modes of heat transfer; conduction, convection and radiation as it applies to cook stoves and used them as a tool to evaluate potential design improvement. Based on these evaluations, certain design modifications were suggested by him as a practical means to boost heat transfer efficiency such as increasing the surface area of the pot exposed to the hot combustion gases clearly improves thermal efficiency and reduces time to boil.

Kulla (2011) designed, developed and tested seven improved stoves. Using both water boiling test and control cooking test, he reported that the average percentage heat utilised were found to range from 20.96% for the least efficient stove to 39.65% for the stove with the highest efficiency. This showed a better improvement over the three traditional stoves commonly in used with the average percentage heat utilised as 11.40% for the three stoves. The percentage fuel saving ranged from 45.18% to 66.14% and the average time saving ranges from 10.05% to 47.43% respectively. He also observed that the nature of wood specie, the quantity of wood, the quantity of water, pot size and type of experiment (cold start, hot start or simmering) all have effects on the outcome of the stove performances.

Schreiner (2011) carried out analysis of the thermal performance and emissions characteristics of improved biomass stoves constructed using earthen materials. Commonly referred to as mud stoves, this type of improved stove incorporates high clay content soil with an organic binder in the construction of its combustion chamber and body. He stated that this stove does not offer significant improvements in fuel economy or air quality relative to traditional open fire cooking due to significant amount of heat been absorbed by the mass of the stove reducing combustion efficiency and heat transfer to the cook pot. Also, an analysis of the thermal and mechanical properties of stove materials was also performed. A material mixture containing a one-to-one ratio by volume of high content clay soil and straw was found to have thermal properties comparable to fired ceramics used in more advanced improved stove designs.

Musa (2014) designed, constructed and tested a wood stove model where he used, sand and saw sawdust as insulator to test the stove performance. He reported a maximum thermal efficiency of 69.5% and power delivery of 2.1990kW with specific fuel consumption of 0.0737, indicating a better performance than the local traditional mud stove.

Sundblad (2014), developed an improved cooking stove for the urban and semi-urban areas in Zambia, aimed at using wood pellets produced from sawdust for cooking. The goal of his research was to develop a stove with the principle of a top-lid updraft gasifier. The final result was a stove for cooking meals in a single pot with the possibility of regulating the primary air supply for better adaptation.

John and Olayinka (2014), researched on the effect of saw sawdust on the insulating effect of Ikere clay as refractory lining, having used various mixture ratio. They reported that if agro waste are mixed with clay in right proportion and proper test carried out, they tend to increase the insulating property of clay by increasing the porosity of the clay generally as the agro waste increases.

2.6.2 Past works on stove Testing and Performance

Geller (1982), carried out extensive test on the stoves in the Ungra area of India over a complete cooking cycle. He used useful energy to calculate the energy balance in the stoves. He defined useful energy to be the energy used to raise the temperature of pot, cooking medium and food and the energy to transform the food to cooked state, and summarized his finding as 84% combustion efficiency, 17% heat transfer efficiency and 43% pot efficiency. There by highlighting the need for further improvement in heat transfer as a means of improving stove efficiency.

Joshi *et al*. (1989) worked on the effect of fuel on stove emission, stated that lower grade fuel not only have a lower calorific value, but also tend to show a lower efficiency: low grade fuels such as cow dung tend to smoulder rather flame (due to low volatile component), with two serious consequences. First, hot combustion gases are less likely to impinge on the bottom of the pot and secondly, there is less radiative heat transfer in the stove

Bryden *et al.* (2000) worked to improve the performance of a plancha or griddle stove, they developed the griddle stove where the pot is not in direct contact with the flames. Instead the exhaust gases from the combustion chamber are used to heat a metal plate which in turn is used to heat a kettle or a pot. These three cooking regimes require quite different temperature distribution over the heated surface with the result that stove optimization cannot be measured as efficiency. Instead they developed a measure of effectiveness based on the uniformity of temperature distribution over the heated surface.

Bhattacharya *et al.* (2002) studied the effect of fuel wood moisture level as well as size on stove emission. They concluded that the size of fuel pieces has no direct effect on stove emission, though increasing moisture content tend to reduce the efficiency of a stove and increase emission of carbon monoxide: energy is consumed in heating and evaporating the water which will otherwise be used in heating the pot and its content. They also investigated the impact of ignition technique on emission, finding that lighting a fire from the top and allowing the combustion zones to work down through the bed of fuels was more efficient. Volatiles are released straight into the hottest part of the flame thereby ensuring thorough combustion, whereas volatiles released from bottom-up burning fire are more liable to escape the hot regions which will encourage them to burn.

America development agency Volunteers in Technical Agency (VITA) developed the Water Boiling Test (WBT) which is widely accepted as the standard efficiency test. The method is simple to implement and requires relatively little measurement or data on material properties. The method yields a set of metrics which can be used to evaluate the performance of the stove: efficiency, time to boil, boil rate, fire power, turn down ratio and specific fuel consumption. In this method latent heat of vaporization is included in the useful energy (Bryden *et al.,* 2005).

2.7 Research Gap

All the researches above have dealt with stove improvement and testing in one form or another, and some quite specifically have pointed to the need to increase the thermal heat transfer in a stove. The need to reduce thermal heat transfer (by reducing heat loss to the stove body) through insulation using wood ash and a mixture of clay-sawdust is an area that is still yet to be fully exploited.

CHAPTER THREE

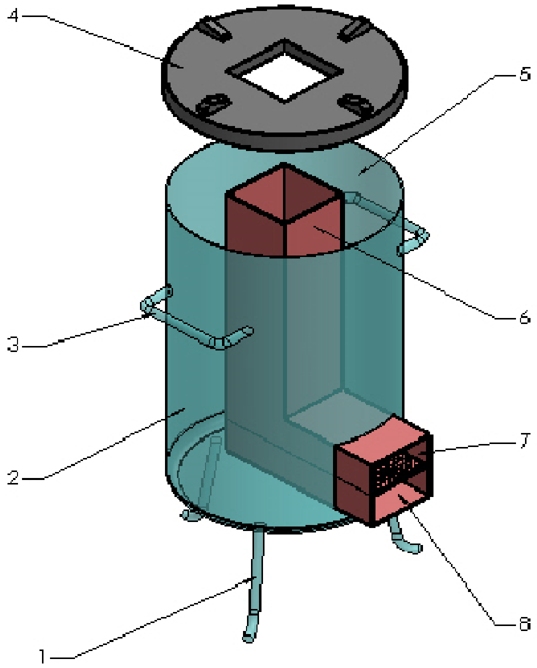
MATERIALS AND METHODS

3.1 Introduction

This chapter describes in details the materials, equipment, and method used in constructing the rocket stove, and the experimental procedure followed in carrying out the various tests.

3.2 The Stove Description

The rocket stove (Figure 3.1) is usually circular in section and generally consists of a square or circular combustion chamber, a top section and a base. The hearth of the combustion chamber is made of mild steel, the outside of which is lined with an insulator. The base of the stove consists of an opening for loading fuel wood into the combustion chamber, and also as opening which serves as combustion air inlets to the chamber. The grate or fuel bed is at the base of the combustion chamber which help to suspend the fuel from the floor of the stove and enable primary air to flow from the bottom of the stove. The top of the stove consists of the pot seat, three refractory rings of different diameters to accommodate different sizes of pot. The pot seat is designed such that the pot sinks to a comfortable position, this increases the amount of hot flue reaching the pot. The chimney is made of mild steel and incorporated at the top of the combustion chamber stove to convey heat to the pot by creating an internal draft, it is also insulated to reduce heat loss by conduction. The diameter of the combustion chamber is such that it is smaller than the pot seat or the external diameter of the smallest pot that can be utilised on the stove. This is to ensure that the maximum amount of heat is transferred to the base of the pot. The distance between the fuel bed and the pot seat is also selected to allow for enough time for the complete combustion of the burning fuel particles before it strikes the base of the pot mounted on the pot seat



PART	DESCRIPTION
1.	TRIPOD STAND
2.	STOVE BODY
3.	HANDLE
4.	STOVE COVER / POT SEAT
5.	LAGGING
6.	COMBUSTION CHAMBER / CHIMNEY
7.	WOOD CHAMBER
8.	AIR VENT

Figure 3.1 The Rocket Stove

3.3 Design Specification

3.3.1 Considerations

Using Winiarski (Bryden *et al*, 2005) method of maintaining a constant cross sectional area under the pot, the height of the gap under the pot was calculated. This height varies as it moves from the centre of the combustion chamber out to the edge of the pot. The choice of the size of the combustion chamber is needed in calculating other parameters (Bryden *et al.*, 2005). Based on that, the size of the combustion chamber is, length L =125mm.

3.3.2 Material Selection for fabrication

The following are the materials used for the fabrication of the rocket stove:

i. Perforated metal sheet was used as the grate so that air can pass through it and under the fuel.

ii. Steel rod was used in constructing the stove handle because of its ability to withstand high temperatures.

iii. Metal sheet (mild steel) used for constructing both the stove combustion chamber and the chimney due to its lightless.

iv. Clay mixed with saw-sawdust was used as insulator around the combustion chamber and chimney to reduce heat loss to the stove body and the environment, the saw-sawdust helps in improving the porosity of the clay and hence its insulating property.

v. Wood ash was used as insulator around the combustion chamber and chimney to reduce heat loss to the stove body and the environment.

3.4 Equipment for Testing

The equipment used in this research is as follows:

i. A differential thermocouple thermometer (KM340), was used for measuring the temperature.

ii. Liquid in glass thermometer (0^0-100^0C), was used for measuring the temperature of water.

iii. A measuring scale used for measuring the mass of wood, clay and water with sensitivity of 0.025kg.

iv. A stop watch (Smith 1/5th sec)

v. A hotplate for thermal testing

3.5 Determination of Thermal Properties of Insulation Materials

3.5.1 Thermal Conductivity

Thermal conductivity λ is defined as ability of material to transmit heat and it is measured in watts per square metre of surface area for a temperature gradient of 1 K per unit thickness of 1 m (Theodore *et al.,* 2011). There are a number of ways of measuring thermal conductivity, each of them suitable for limited range of materials, depending on the thermal properties and the medium temperature. For ambient environments and light materials as in the case of this research, the absolute axial heat flow method is suitable. In this method, the electrical power supplied over a given length L of the sample is measured and recorded. The thermal conductivity of each of the insulating material were calculated from (Theodore *et al.*, 2011)

$$Q = KA\frac{T_2 - T_1}{L} \qquad (3.1)$$

where,

Q = quantity of heat supplied (W)

K = thermal conductivity of material (W/mK)

A = Cross sectional area (m^2)

L = length of material (m)

T = temperature of material (K)

3.5.2 Specific Heat Capacity

Specific heat capacity of a substance is the quantity of heat required to raise the temperature of a unit mass of the substance by one degree. Substances with high specific heat tend to take longer time to show change in temperature and they retain a lot of heat (Theodore *et al.,* 2011). With a quantity of heat Q, passing through a given mass m, of a sample, the specific heat capacity of the sample is given by (Theodore *et al.,* 2011).

$$H = Q.t = m.c_p.\Delta T \qquad (3.2)$$

where,

m is the mass of the substance (kg)

c_p is the specific heat capacity (J/kg.K)

ΔT is temperature change (K)

Q is quantity of heat supplied (W)

t is the time

H is the amount of heat supplied (J)

3.5.3 Thermal Diffusivity

In heat transfer analysis, thermal diffusivity is the thermal conductivity divided by density and specific heat capacity at constant pressure. It measures the ability of a material to conduct thermal energy relative to its ability to store thermal energy. The SI unit is m^2/s. Given density, specific heat and thermal conductivity of a material, thermal diffusivity is calculated by (Schreiner 2011).

$$\alpha = \frac{k}{\rho Cp} \qquad (3.3)$$

where,

K is thermal conductivity (W/(m·K))

ρ is density (kg/m^3)

c_p is specific heat capacity (J/(kg·K))

3.6 Design Equations

3.6.1 Combustion Chamber area (A_c)

The area of the combustion chamber, which will be continued throughout the stove according to Winiarski (1996) constant area is given by (Winiarski, 1996).

$$A_c = l \times l \qquad (3.4)$$

where,*l* is the length of the combustion chamber.

3.6.2 Perimeter of the combustion chamber

For a square combustion chamber as in this case, the perimeter for a known length is given by (Winiarski, 1996).

$$C_c = 4 \times l \tag{3.5}$$

3.6.3 Gap between pot and combustion chamber (*Gap A*)

Gap A (G_A) is the gap between the bottom of the pot and the top edge of the combustion chamber. It is calculated by dividing equation (3.4) by (3.5) giving(Winiarski, 1996).

$$G_A = \frac{A_c}{C_c} \tag{3.6}$$

3.6.4 Pot Circumference (C_p)

This is the distance all the way around the pot. the circumference can be determined from (Winiarski, 1996).

$$C_p = 2\pi r_p \tag{3.7}$$

where r_p is the radius of the pot

3.6.5 Gap at the edge of the Pot (*Gap C*)

This is the gap at the edge of the pot. Gap C written as G_C is calculated by diving equation (3.4) by equation (3.7) giving(Winiarski, 1996).

$$G_c = \frac{A_c}{C_p} \tag{3.8}$$

3.6.6 Gap between pot side and Stove body

This is the distance between the stove’s body and the sides of the pot, given as Gap D which is calculated from (Winiarski, 1996).

$$G_D = G_c \times 0.75 \tag{3.9}$$

Where 0.75 is Winiarski clearance constant

3.6.7 Height of Combustion Chamber

Height of stove entrance = X (Winiarski, 1996)

Height of combustion chamber above stove entrance = 1.5X (3.10)

Total Height of stove body (TH**)** = X + 1.5X + 5cm (3.11)

Total height of combustion chamber = X+1.5X (3.12)

Where 5 cm is the thickness of insulation.

To determine the height of the shelf above the bottom of the combustion chamber use

Shelf height (SH) = 0.3X (3.13)

3.6.8 Thermal Efficiency

The thermal efficiency of a cooking stove is the ratio of the energy reaching the pot to the energy produced by burning wood. It depends largely on how well the heat generated is transferred from the fuel to the pot (Olorunsola, 1999). The thermal efficiency of the stove is given by (Olorunsola, 1999).

Thermal Efficiency (η_T) = $\eta_C \times \eta_{HT}$, (3.14)

where:

η_c is combustion efficiency;

η_{HT} is heat transfer efficiency.

But thermal efficiency is also related to percentage heat utilised (Ayo, 2009).

3.6.9 Percentage Heat Utilised

The percentage heat utilised (PHU) which also known as the thermal efficiency of the stove is expressed as(VITA 1985).

$$PHU = \frac{heat\ energy\ reaching\ water\ in\ the\ pot\ (output)}{heat\ energy\ produced\ by\ the\ burning\ fuel} \qquad (3.15)$$

$$= \frac{(m_w c_w + m_p\ c_p)\,(T_f\ - T_i) + m_v\ LV}{m_f\, c_f - m_c\ c_c} \times 100$$

where:

c_w is specific heat capacity of water

c_p is specific heat capacity of pot

LV is latent heat of evaporation of water

c_fi is calorific value of fuel wood

c_c is calorific value of charcoal

m_w is mass of water

m_p is mass of pot

m_v mass of vapour

m_f is mass of fuel

m_c is mass of charcoal

T_f is the final temperature of the water

T_i is the initial temperature of the water

3.6.10 Burning rate

The burning rate is the ratio of the total mass of wood consumed in grams to the time taken for the test in minutes, expressed as (VITA 1985).

$$BR= \frac{m_w}{T} \quad (3.16)$$

where:

T is time taken

m_w is mass of wood consumed

3.6.11Specific fuel consumption

The specific fuel consumption (*SFC*) is the ratio of the mass of fuel consumed to the mass of food cooked and it is expressed as(VITA 1985).

$$SFC=\frac{m_w}{m_f} \quad (3.17)$$

where,

m_w mass of fuel consumed

m_f mass of food cooked

3.6.12 Duration of phase

This is simply the time taken to perform the test. It is a simple clock difference as given by

$t = t_f - t_i$ (3.18)

t is the total time taken to perform the test

t_f is the finish time

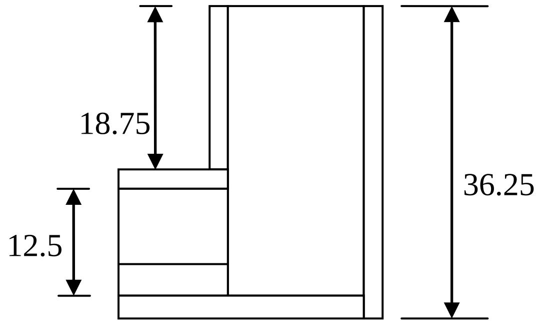
t_i start time

3.7 Design Calculations

Table 3.1 Design calculations

Initial Parameters	Calculations and sketches	Result
L=12.5cm	3.7.1 Calculation of area of combustion chamber, Ac: From equation 3.4 $A_c=L^2$ $=12.5^2cm^2=156.25cm^2$	$156.25cm^2$
L=12.5cm	3.7.2 Calculation of the combustion chamber's perimeter, Cc: Using equation 3.5 $C_c=4*L$ =4*12.5cm=50cm	50cm
$A_c=156.25cm^2$	3.7.3 Calculation of the distance between the pot and the inner edge of the combustion chamber, G_A: From equation 3.6 $G_A = \frac{Area\ of\ combustion\ chamber}{perimeter\ of\ combustion\ chamber}$	

C_c=50cm	$= \frac{A_c}{C_c}$ =(156.25/50)cm=3.1cm	3.1cm
R=15cm	3.7.4 Calculation of pot perimeter, C_p: From equation 3.7 $C_p=2\pi r_p$ =2π*15cm=94.26cm	94.26cm
A_c=156.26cm^2 C_p=94.26cm	3.7.5 Calculation of the distance between the outer edge of the pot and the stove body, G_c: From equation 3.8 $G_c=\frac{Area}{Circumference\ of\ pot}$ = A_c/C_p =(156.25/94.26)cm=1.7cm	1.7cm
G_c=1.7cm	3.7.6 Calculation of the distance between the sides of the pot and the stove body, G_D: From equation 3.9 G_D =G_c*0.75 (0.75 is Winiarski clearance constant) =1.7cm*0.75=1.3cm	1.3cm
X=12.5cm	3.7.8Calculation of the Height of combustion chamber above stove entrance From equation 3.10 =1.5X =1.5(12.5)=18.75cm	18.75cm

X=12.5cm	3.7.9 Calculation of the Total Height of stove, TH: From equation 3.11 TH = X+1.5X+5cm (for thickness of insulation) =12.5 + 1.5(12.5) + 5cm=36.25cm  	36.25cm
X=12.5cm	3.7.10Calculation of the Total height of combustion chamber, Th: From equation 3.12 Th=X + 1.5X + =12.5 + 1.5(12.5)=31.25cm	31.25cm
X=12.5	3.7.11 Calculation of the height of Shelf, SH: From equation 3.13 (SH) = 0.3X=3.75cm	3.75cm

3.8 Methods

The technique followed in the construction of the stoves and the tests carried out are as follows:

3.8.1 Construction

The stove body, the top, the combustion chamber and the chimney of the stove were cut out from the same sheet metal (mild steel) using the guillotine machine in the mechanical workshop, while the stove handle and the stove stand were cut from a metal rod and the pot seat was cut out from a metal pipe using hack saw. The stove body was then rolled and welded into a circular shape as shown in the working drawing in the appendix, while the combustion chamber and the chimney were welded together into an elbow shape and welded to the stove body also as shown in the working drawing in the appendix. The pot seats were welded on the stove top and a square hole in the shape of the chimney was cut out from the stove body to serve as the air inlet, the fuel magazine and flue gases exit point. Following the assembly drawings as shown in the appendix, with the combustion chamber fixed in place, next the pot handle was welded to the stove body completing the construction process of the rocket stove.

3.8.2 Material Testing (Thermal Conductivity and Specific Heat Tests)

(i) **Sample Preparation**

The clay was collected from the Ceramics unit of the Industrial Design Department in the school, sun dried and grinded, then sieved using a sieve size of 75µm. The sieved sample was then mixed with saw sawdust of equal ratio by volume (50:50). Some of the mixture was collected and moulded into rectangular shape to be used for the thermal property test (specific heat, thermal conductivity). While, the wood ash was collected from a local trader, it was ensured that no water was used in quenching the fire, as water tends to reduce the insulating property of ash. Dirt such as charcoal, unburned wood etc. found in the ash were removed by hand picking. The ash was also moulded into shape but the ash was left in the mould so as not to scatter during the test. The following were kept constant while conducting the thermal conductivity test; Quantity of electricity = 2 W, density of ash sample = 605.51 kg/m^3, Sample size = 6 cm by 3 cm, density of clay-sawdust sample = 1112.81 kg/m^3. During the specific heat test only the quantity of the electricity was increased to 50Wand the test lasted for a duration of four (4) minutes, all other parameters were held constant.

(ii)**Procedure for tests**

1. Different samples were prepared and moulded into rectangular shape for easy measurement.
2. The mass of each sample was measured and recorded
3. The samples were placed on a hotplate for a duration of seven (7) minutes and the hotplate regulator adjusted to various power output.
4. At the end of each time the temperature at any two given points were measured for each sample using the differential thermocouple and recorded.

The thermal conductivities and specific heat capacities of the samples were calculated from equations (3.1) and (3.2) respectively.

3.8.3 Cooking test

Stove testing is the systematic measurement of the advantages and limitations of a particular stove model. Its primary aim is to help identify the most effective and desirable stoves for a specific social and economic context. With ongoing stove production, a testing program provides essential quality control and may lead to important design modifications. The standardized stove-test is of three types:

(i) Water boiling test: to measure how much wood is used to boil water under fixed conditions. This is a laboratory test, to be done both at full heat and at a lower “simmering” level to replicate the two most common cooking tasks.

While it does not necessarily correlate to actual stove performance when cooking food, it facilitates the comparison of stoves under controlled conditions with relatively few cultural variables (Bryden 2010).

(ii) Controlled cooking test: to serve as a bridge between the water boiling test and the kitchen performance tests. Here actual cooking is done to determine how much fuel is used for preparing a meal and the time taken to do so.

(iii) Kitchen performance test: this involves how the stove performed in the kitchen generally; like ease of operating it, the friendliness of the stove to its users etc.

Proper monitoring of the stove gives a better idea of the effectiveness of the stove, and reduce the over reliance on thermal efficiency alone to determine which stove was better.

3.8.4 Water boiling test

America development agency Volunteers in Technical Agency (VITA) developed the Water Boiling Test (WBT) which is widely accepted as the standard efficiency test (Bryden *et al.*, 2005). The method is simple to implement and requires relatively little measurement or data on material properties. The method yields a set of metrics which can be used to evaluate the performance of the stove: efficiency, time to boil, boil rate, fire power, turn down ratio and specific fuel consumption (Bryden *et al.*, 2005). The WBT consists of three phases that immediately follow each other. For the first phase “cold-start high power phase”, the test begins with the stove at room temperature and using fuel from a pre-weighed bundle to boil a measured quantity of water in a standard pot. Then replaces the boiled water with a fresh pot of ambient-temperature water to perform the second phase.

The second phase “The hot-start high-power phase” is conducted after the first phase while stove is still hot. Again, the tester uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. Repeating the test with a hot stove helps to identify differences in performance between a stove when it is cold and when it is hot. This is particularly important for stoves with high thermal mass, since these stoves may be kept warm in practice.

The last phase is the "simmer phase" provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. This step simulates the long cooking of legumes or pulses common throughout much of the world (Robert, 2009).

Procedure for Water Boiling Test

All the procedures below were carried out in accordance with the VITA standard of carrying out water boiling test (Bryden *et al.*, 2005)

Phase 1: High power Start (Cold Start)

1. the amount of wood to be used for the test was weighed and recorded.

2. in order to reduce environmental interference the tests were carried out in the boiler room of the mechanical engineering workshop.

3. the mass of an empty dry pot was weighed and recorded and then filled with water to 2/3 its capacity and the new weight was also recorded.

4. the water temperature was measured with the use of a thermometer and thereafter at the commencement of the test the temperature of the water was measured and recorded at intervals of two (2) minutes until the water boils.

5. After the final preparations checks, the stove was lit, in the way it is normally done in the households. For example, use paraffin (kerosene) as the ignition material. A measured amount of paraffin (less than 10 grammes) simply pours over the wood. The test's starting time coincides with the lighting of the paraffin-soaked wood pieces. The amount of paraffin used is allowed to burn out before the test starts proper. The paraffin used may be considered as consumed fuel.

6. The following was recorded regularly:

i. the water temperature in the pot
ii. the weight of any wood added to the fire
iii. any action taken to control the fire (dampers, blowing, etc.)
iv. the fire reaction (smoke, etc)

7. The time taken for the water in the pot to boil fully was recorded.

8. At this time the following was done rapidly:

i. All wood from the stove removed and any charcoal knocked off. The wood together with the unused wood from the previously weighed supply were weighed together.
ii. All the charcoals were weighed separately.
iii. The water temperature was recorded and the weight of the pot with its water content.

The experiments were conducted following the procedures laid out above and the following parameters were kept constant: Pot diameter = 21 cm and mass of pot = 0.35 kg, quantity of wood = 1.00 kg, size of wood = 7.5 cm^2, Quantity of water = 2.05 kg

Phase 2: High Power Start (Hot start)

1. The timer was reset.
2. The pot was refilled with 2L of fresh water and weighed. The temperature of the water was also measured and recorded.
3. The mass of wood to be used was measured and recorded.
4. The fire was started again and the temperature measured at an interval of two (2) minutes until the water was brought to vigorous boiling.
5. At this time the following were done quickly

i. All charcoals were knock off from the wood and the mass of unused wood measured quickly but the charcoal was left in the stove for the simmering stage.

ii. The pot and its content was measured and recorded and replaced back on the stove immediately to avoid too much drop in temperature of the water as the temperature is to be as close as possible to the boiling temperature in order to proceed directly to the simmering “low power” stage.

The following variables were kept constant during the hot phase: Pot diameter = 21 cm and mass of pot = 0.35 kg, quantity of wood = 1.00 kg, size of wood = 7.5 cm^2 quantity of water = 2.05 kg

Phase 3: Low Power (Simmering) Stage

Simmering start almost immediately after the hot start phase and so uses the same experimental set up, the already hot water is allowed to simmer for forty-five (45) minutes but the temperature is not allowed to fall below 6°C of the boiling point, to observe real kitchen performance. This portion of the test is designed to test the ability of the stove to shift into a low power phase following a high-power phase in order to simmer water for 45 minutes using a minimal amount of fuel. The procedure for the test is the same as that for the water boiling test but it is carried out after the completion of the water boiling test.

Procedure Simmering Test

1. For forty five (45) minutes the fire was maintain at a level just sufficient to keep the water simmering at about 3-6 degrees below the boiling point of water.
2. After forty five (45) minutes the following were done

i. The final temperature of the water was measured and recorded

ii. The weight of the charcoal recovered was recorded and all remaining wood.

iii. The pot with its remaining water were weighed and recorded.

iv. The amount of wood consumed, the amount of water remaining, the test duration, the specific fuel consumption was then calculated.

The following parameters were kept constant: Pot diameter = 21 cm and mass of pot = 0.35 kg quantity of wood 1.00 kg, size of wood = 7.5 cm^2, quantity of water 2.3 kg

In order to draw conclusion on this section, there is need to vary other variable and observe the stove performance. This is aimed at further contributing to knowledge on whether the stoves will have constant efficiency when the quantity of water is changed or the cross sectional area of the wood is altered.

The following parameters were used during the experiments on the ash insulated stove and the clay-sawdust insulated stove. Quantity of wood = 1.00 kg, quantity of water and pot = 3.1kg, pot diameter = 21cm, when the quantity of water was increased from 2.05kg to 2.75kg. Also, the following were the parameters used when the sizes of the wood was increased; quantity of water = 1 kg, quantity of wood = 1 kg, cross sectional area of wood 12 cm2 pot size = 21 cm and mass = 0.35 kg. Stove type – ash insulated stove and clay-sawdust insulated stove. The aim of this experiment is to observe the effect of varying the sizes of the wood on the stoves performance, which is mostly regarded as part of the operator's skill (MacCarty, 2013).

3.8.5 Controlled Cooking Test (CCT)

The controlled cooking test (CCT) is designed to assess the performance of the stove by carrying out standard cooking task that is closer to the actual cooking that is done every day (Kulla, 2011). The experimental setup and procedure is similar to the water boiling test as stated above except that this time actual cooking was done to give a more realistic evaluation of the stove. This test shows how the stove works outside the laboratory.

3.8.6 Kitchen performance evaluation test

This covers how the stove performed in the kitchen and things like fuel economy, ease of operation, its range of fuel accommodation, its range of pot accommodation, the ease of maintenance, easy of lighting etc. were observed and the inference used to grade the stove acceptability to both the end users and to the external users (government, NGO and other organization) (Robert, 2009).Kitchen performance test is a measure of the stove's effectiveness. In the end, a stove's effectiveness is measured by its total impact on both the human and non-human worlds, and this clearly affected many factors besides fuel use. Some of them are: ease of operation, will it accommodate a range of fuels, will it accommodate a range of pots, the ease of maintenance, ease of lighting etc. are observed and the inference used to grade the stove acceptability to both the end users and to the external users (government, NGO and other organization) (Robert, 2009). User acceptance, although crucial to the effectiveness of a stove, is not the only important aspect. Consider the converse of a very fuel-economical stove that no one will use: a fuel-wasting stove with horrible emissions that is extremely popular. The stove meets whatever criteria the users look for in accepting a stove, but it fails miserably at obvious aspects of having a positive impact on health and environment. Certainly any NGO, government, or business that is concerned about health effects and fuel demand will not want to be involved with this stove, and from their viewpoint, this stove is not effective. The stove characteristics that are likely to be of concern to an NGO, government, or business are marked under the heading "External Need" (Robert, 2009).

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Material test

Thermal property tests were carried out on the wood ash and clay-sawdust insulation materials, to ascertain their suitability for use as insulation materials in the stove.

4.1.1 Results for material test

Table 4.1 gives the temperature readings from a thermocouple for the ash and clay-sawdust insulators at an interval of one minute for a duration of seven minutes.

Table 4.1 Temperature (°C) passing through each sample

Time (min)	Temperature	Temperature of Ash sample (°C)	Temperature of Clay-sawdust sample (°C)
1	T_1	27	27
	T_2	38	40
2	T_1	29	27
	T_2	85	80
3	T_1	35	30
	T_2	125	120
4	T_1	40	32
	T_2	154	136
5	T_1	55	36
	T_2	163	160
6	T_1	76	40
	T_2	197	185
7	T_1	85	45
	T_2	250	2245

where, T_1 and T_2 are temperatures at two given points

The thermal conductivities of ash and clay-sawdust insulation materials were calculated using equation 3.1 and are given as 0.20W/mK for the ash and 0.16W/mK for the clay-sawdust mixture. Taking the reading after four (4) minutes gives the specific heat capacities of ash and the clay-sawdust as 889 J/kgK and 910 J/kgK, using equation 3.2. Having calculated the values for the thermal conductivities, specific heat capacities and the densities, the thermal diffusivities of the materials is given by equation 3.3 as

$3.67\times10^{-7}/m^2s$ and $1.58\times10^{-7}/m^2s$ for ash and the clay-sawdust insulating materials respectively.

The thermal conductivity of a material is a measure of the effectiveness of the material in conducting heat. Good heat insulators should have low thermal conductivities, in order to reduce the total coefficient of heat transmission. As seen from the result above, the thermal conductivities of both materials are low as it should be, meaning heat transfer across the materials is low and when compared with other insulators, it is seen that it falls within the range acceptable for good insulators (0.02-0.47 W/mK), (Ayugi,*et al.*, 2011).

Also, for good insulator, its specific heat should be as high as possible, a high specific heat means high ability for heat retention for an insulating material. The clay-sawdust insulating material with a specific heat of 910J/kgK, shows a higher heat retention ability than the ash (886J/kgK) but both can compare favourably with some of the best known insulation materials as shown in Table 4.2

Table 4.2 Thermal properties of some insulation materials(Ayugi et al., 2011).

Material	Specific heat capacity (J/kgK)	Thermal diffusivity ($\times10^{-7}/m^2s$)
Glass fiber	960	14.6
Perlite	900	5.27
Insulating cement	882	3.19
Polyurethane	1537	5.58
Charcoal sawdust	800	6.09
kaolin	677	4.27

Thermal diffusivity measures the ability of a material to transmit a thermal disturbance. It indicates how quickly a material's temperature will change. Thermal diffusivity increases with the ability of a body to conduct heat. With a thermal diffusivity of $3.67\times10^{-7}/m^2s$ and $1.58\times10^{-7}/m^2s$ for ash and clay-sawdust respectively, both of them show slow response to thermal disturbance and therefore have the quality of a good insulator (low thermal diffusivity).

All good insulation materials generally have low thermal conductivity, high specific heat capacity and low thermal diffusivity (Kreith, 2000).

4.2Water Boiling Test

4.2.1 Cold Start

The average values for all parameters measured are presented in the Table 4.3 and the water temperature variation against time is presented in Table 4.4 and the calculated performance results is presented in Table 4.5. and Figure 4.1 to 4.4 gives the graphical representations of the calculated parameters.

Table 4.3 Average parameter values for Cold Start WBT

S/No	Parameter	AVERAGE READING FOR THREE STOVES (cold start)		
		Ash stove	Clay-sawdust stove	Stove without insulation
1	Mass of fuel before test	1kg	1kg	1kg
2	Mass of pot + water	2.4kg	2.4kg	2.4kg
3	Temp of cold water	28°C	28°C	28°C
4	Time of start	0	0	0
5	Mass of wood after test	0.8kg	0.8kg	0.4kg
6	Mass charcoal	0.031kg	0.03kg	0.1kg
7	Mass of pot + water after test	2.3kg	2.3kg	2.1kg
8	Temp of water after test	98°C	98°C	98°C
9	Time at the end of test	24min	19.35min	39.50min

Table 4.4 Water Temperature variation for three stoves (°C)

S/No	Time (min)	Water Temperature (°C) in;		
		Ash stove	Clay-sawdust stove	Stove without insulation
1	2	33	35	33
2	4	37	45	40
3	6	42	52	43
4	8	47	58	47
5	10	51	63	50
6	12	57	68	54
7	14	65	75	60
8	16	73	79	63
9	18	79	84	67
10	20	85	88	70
11	22	92	98	72
12	24	98		75
13	26			77
14	28			79
15	30			82
16	32			86
17	34			90
18	36			94
19	38			98

Table 4.5 Calculated Performance results for cold start

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Mass of wood used (kg)	0.20	0.20	0.6
Mass of charcoal recovered (kg)	0.031	0.03	0.1
Heat supplied by wood (kJ)	5356	5356	16068
Heat recovered (kJ)	1009.98	1140.3	3258
Net heat supplied (kJ)	4346.02	4215.7	12810
Mass of pot (kg)	0.35	0.35	0.35
Mass of water (kg)	2.05	2.05	2.05
Mass of steam (kg)	0.1	0.1	0.3
Heat gain by pot (kJ)	26.60	26.60	26.60
Heat gain by water (kJ)	686.50	686.50	686.50
Heat gain by steam (kJ)	226	226	678
Net heat gain (kJ)	939.10	939.10	1391.10
PHU (%)	21.60	22.28	10.86
Firepower (Watt)	2.93	3.10	5.51
Burning rate (g/min)	6.57	6.95	12.35
Specific fuel consumption	0.079	0.075	0.229

Figure 4.1 Percentage heat utilised (%) for cold start

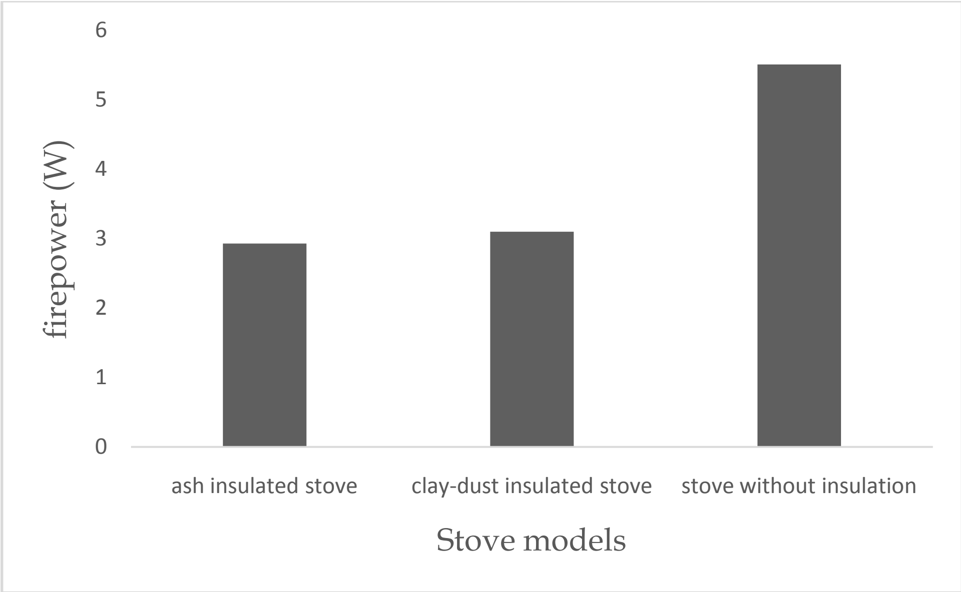


Figure 4.2 Firepower for cold start

Figure 4.3 Burning rate for cold start

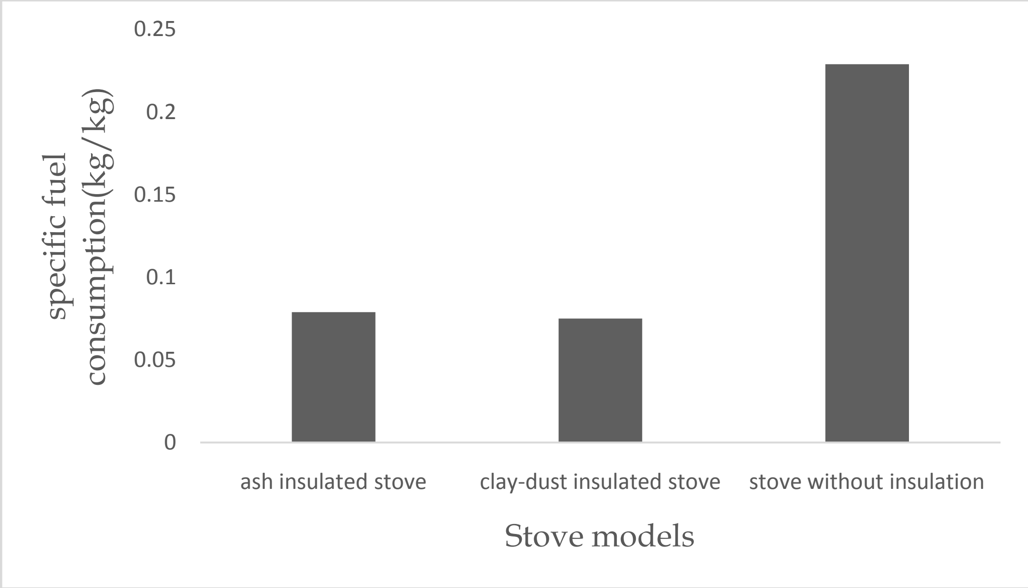


Figure 4.4 Specific fuel consumption for cold start

4.2.2 Hot Start Phase

Average values are represented in the Table 4.6 and 4.7, the calculated performance result is presented in Table 4.8 and the graphical presentation of the calculated parameters are given in Figure 4.5 to 4.8

Table 4.6 Parameter reading for hot start phase (WBT)

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Initial mass of wood (kg)	1.00	1.00	1.00
Final mass of wood (kg)	0.82	0.84	0.65
Mass of charcoal recovered (kg)	0.035	0.034	0.15
Mass of pot (kg)	0.35	0.35	0.35
Initial mass of water (kg)	2.05	2.05	2.05
Final mass of water (kg)	1.85	1.85	1.75
Initial temperature of water (°C)	28	28	28
Final temperature (°C)	98	98	98
Time taken (min)	16.25	16	18.30

Table 4.7 Water temperature variation for hot start

Time (min)	Water Temperature (°C) in;		
	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
0	28	28	28
2	38	38	33
4	48	49	44
6	56	59	53
8	63	67	62
10	72	77	70
12	81	86	79
14	90	91	88
16	98	98	95
18			98

Table 4.8 Calculated Performance results for the hot start phase

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Mass of fuel used (kg)	0.10	0.11	0.55
Mass of charcoal recovered (kg)	0.02	0.025	0.25
Heat supplied by wood (kJ)	2678	2945.8	14729
Heat recovered (kJ)	651.6	814.5	8145
Net heat supplied (kJ)	2026.4	2294.2	6584
Mass of pot (kg)	0.35	0.35	0.35
Mass of water (kg)	2.05	2.05	2.05
Mass steam (kg)	0.1	0.1	0.2
Heat gain by pot (kJ)	26.60	26.60	26.60
Heat gain by water (kJ)	686.50	686.50	686.50
Heat gain by steam (kJ)	226	226	452
Net heat gain (kJ)	939.1	939.1	1165.1
PHU (%)	46.34	44.06	17.70
Firepower (Watt)	2.05	2.16	4.86
Burning rate (g/min)	4.60	4.83	12.00
Specific consumption fuel	0.038	0.039	0.13

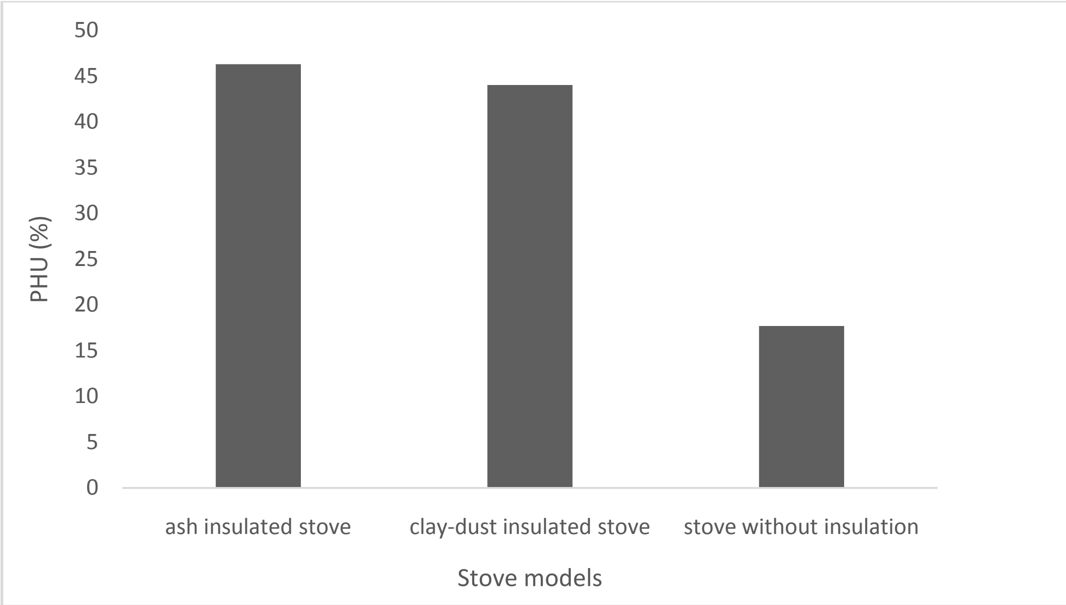


Figure 4.5 Percentage heat utilised for hot start

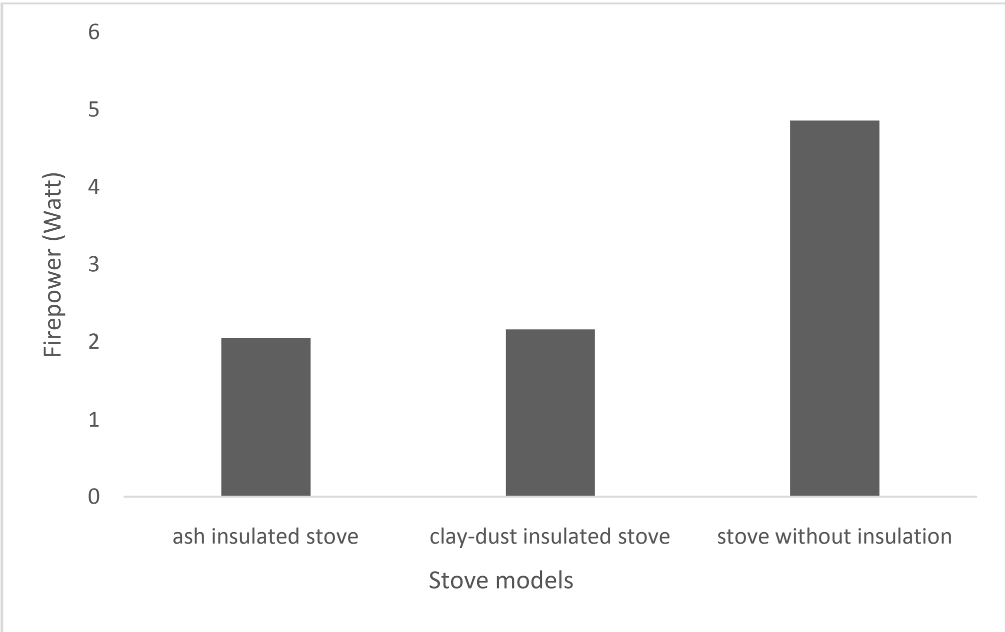


Figure 4.6 Firepower for hot start

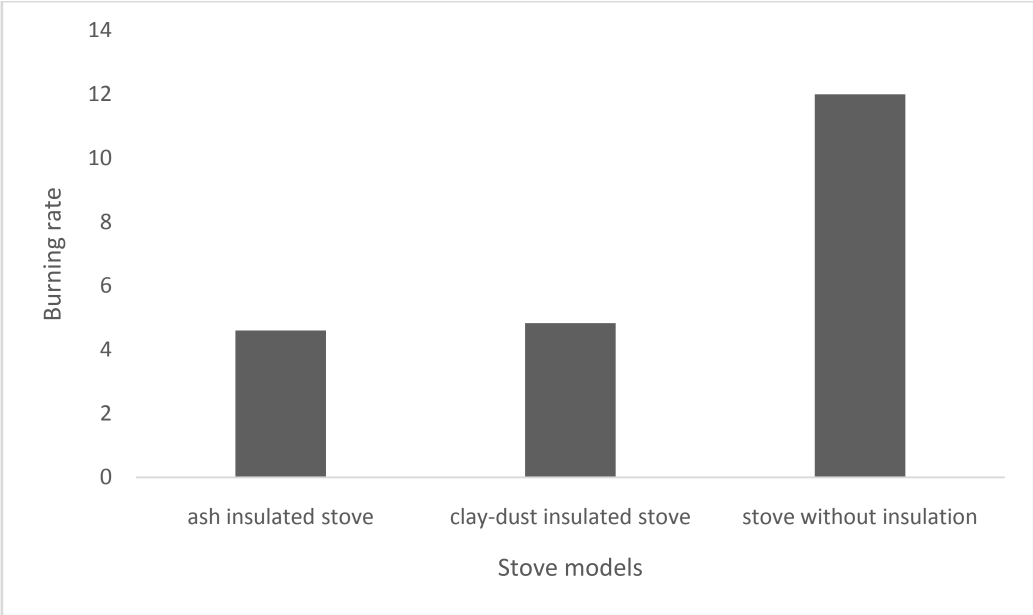


Figure 4.7 Burning rate for hot start

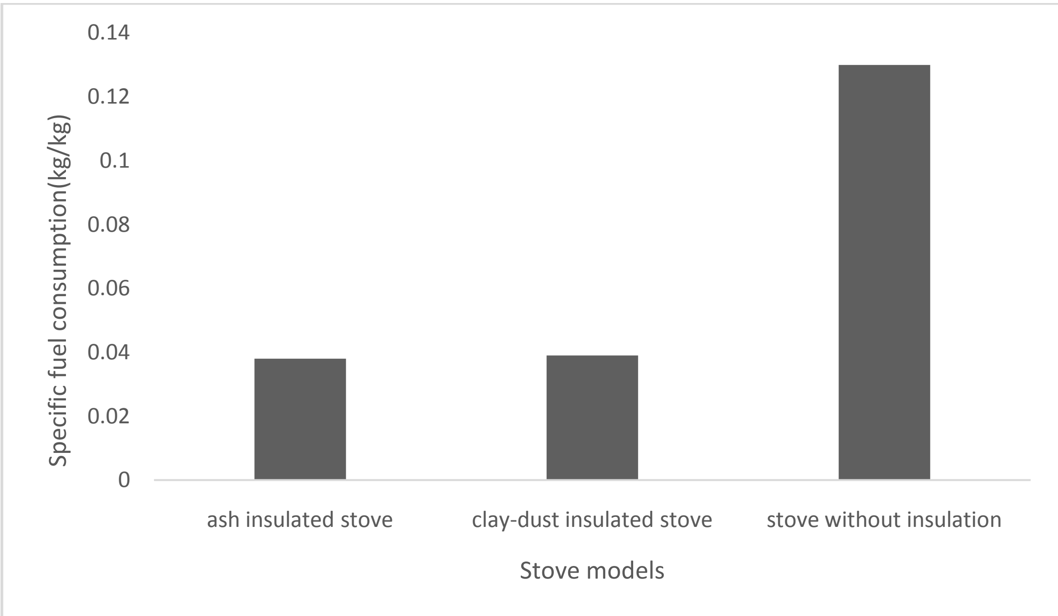


Figure 4.8 Specific fuel consumption for hot start

4.2.3 Simmering phase

The results are presented in Table 4.9 and the temperature variation is presented in Table 4.10. The calculated performance result is presented in Table 4.11, while the graphical representation of the calculated parameters are presented in Figure 4.9 to 4.13

Table 4.9 Average parameter values for simmering phase

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Initial mass of wood (kg)	1.00	1.00	1.00
Final mass of wood	0.60	0.55	0.80
Mass of charcoal recovered (kg)	0.15	0.15	0.23
Mass of pot (kg)	0.35	0.35	0.35
Initial mass of water (kg)	2.05	2.05	2.05
Final mass of water (kg)	1.85	1.85	1.75

Table 4.10 Water temperature variation for the simmering phase

Time (min)	Water temperature (°C) in		
	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
0	89	90	90
2	96	95	96
4	95	95	95
6	94	96	95
8	95	94	96
10	95	94	94
12	94	95	96
14	96	93	93
16	95	96	94
18	95	96	96
20	93	95	93
22	96	96	95
24	95	96	95
26	96	93	94
28	94	95	96
30	93	94	96
32	94	94	93
34	95	95	95
36	95	95	95
38	96	95	96
40	96	96	94
42	95	96	94
44	94	96	95
45	94	95	96

Table 4.11 Calculated results for the simmering phase

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Mass of fuel used (kg)	0.40	0.40	0.65
Mass of charcoal recovered (kg)	0.15	0.17	0.24
Heat supplied by wood (kJ)	10712	10712	17407
Heat recovered (kJ)	4887	5538.6	7819.2
Net heat supplied (kJ)	5825	4873.4	95878
Mass of pot (kg)	0.35	0.35	0.35
Mass of water (kg)	2.05	2.05	2.05
Mass steam (kg)	0.2	0.2	0.3
Heat gain by pot (kJ)	26.60	26.60	26.60
Heat gain by water (kJ)	686.50	686.50	686.50
Heat gain by steam (kJ)	452	452	678
Net heat gain (kJ)	1165.1	1165.1	1391.1
PHU (%)	20.00	23.91	14.50
Firepower (Watt)	2.10	1.76	4.78
Burning rate (g/min)	4.72	3.95	7.80
Specific consumption fuel	0.15	0.096	0.20
Turn down ratio	1.22	1.23	1.02

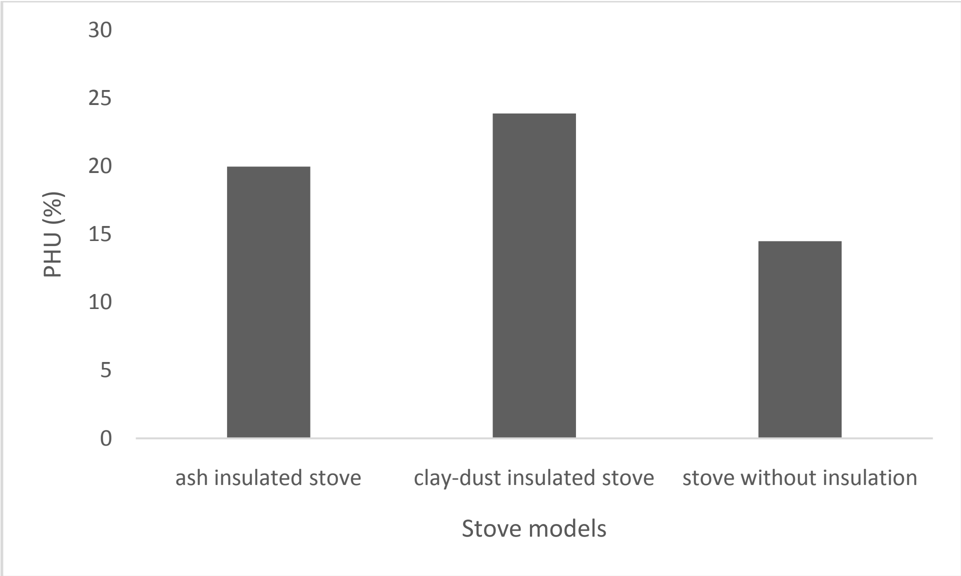


Figure 4.9 PHU for simmering phase

Figure 4.10 Firepower for simmering phase

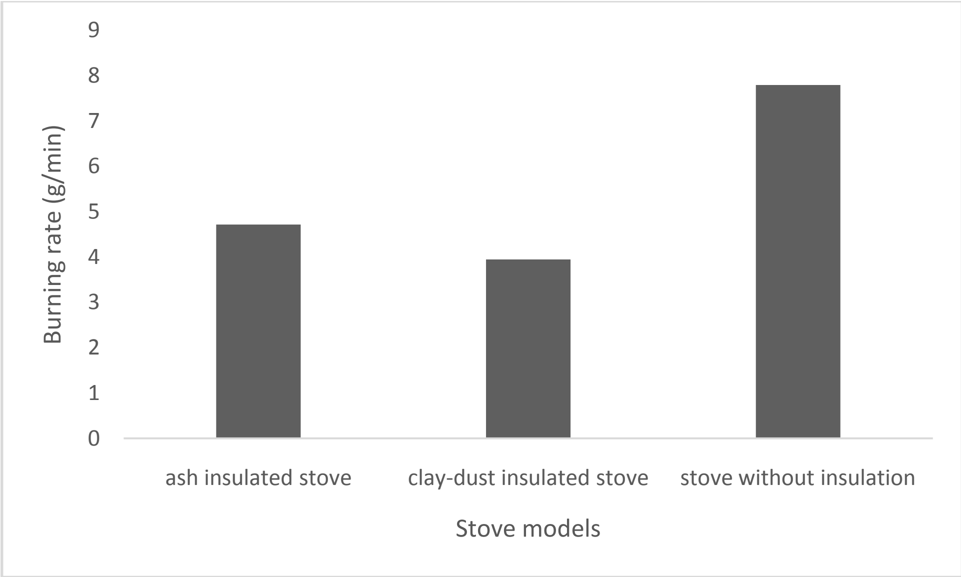


Figure 4.11 Burning rate for simmering phase

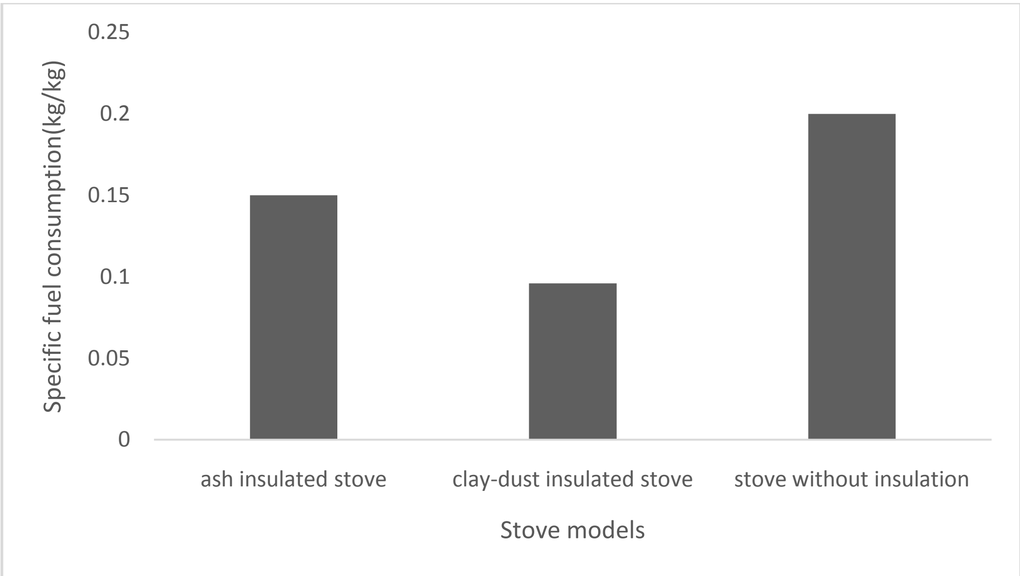


Figure 4.12 Specific fuel consumption for simmering phase

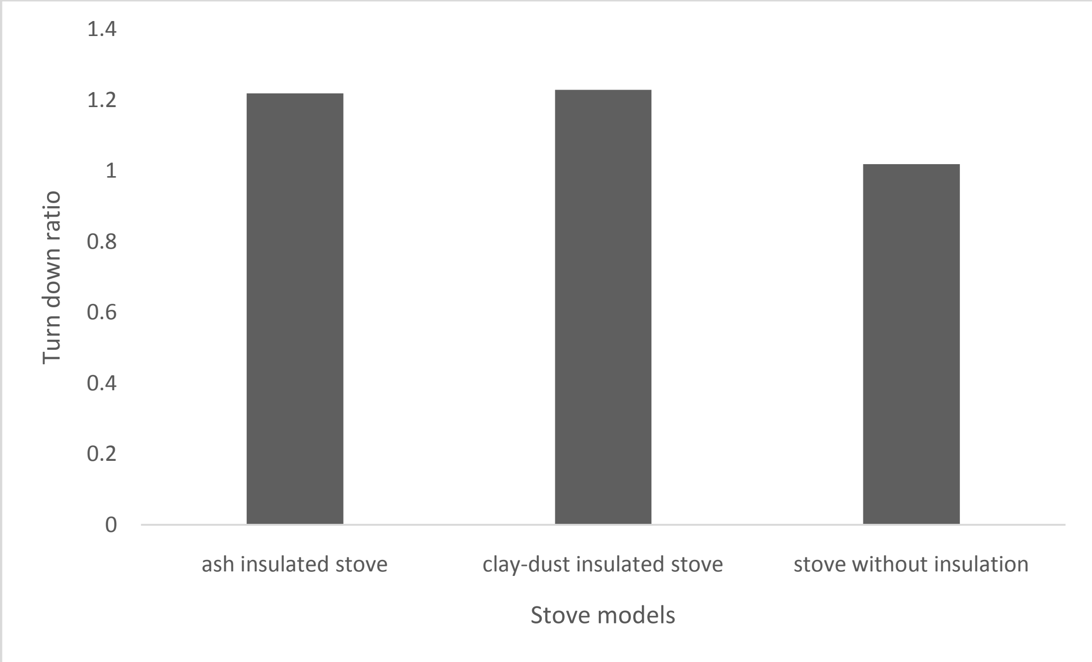


Figure 4.13 Turn down ratio

4.3 Discussion of Results for Water Boiling Test

4.3.1 Percentage Heat Utilised (PHU)

The percentage heat utilised which is the thermal efficiency of the stove is the ratio of the energy reaching the pot to the energy produced by burning wood. Table 4.12 gives a summary of the PHU for the different stoves and for the different phases and Figure 4.14 gives a graphical representation of PHU.

Table 4.12 Summary of PHU for the stove models

Phase	PHU (%)		
	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Cold start	21.60	22.28	10.86
Hot start	46.34	44.06	17.70
Simmering	20.00	23.91	14.50
Average	29.31	30.08	14.35

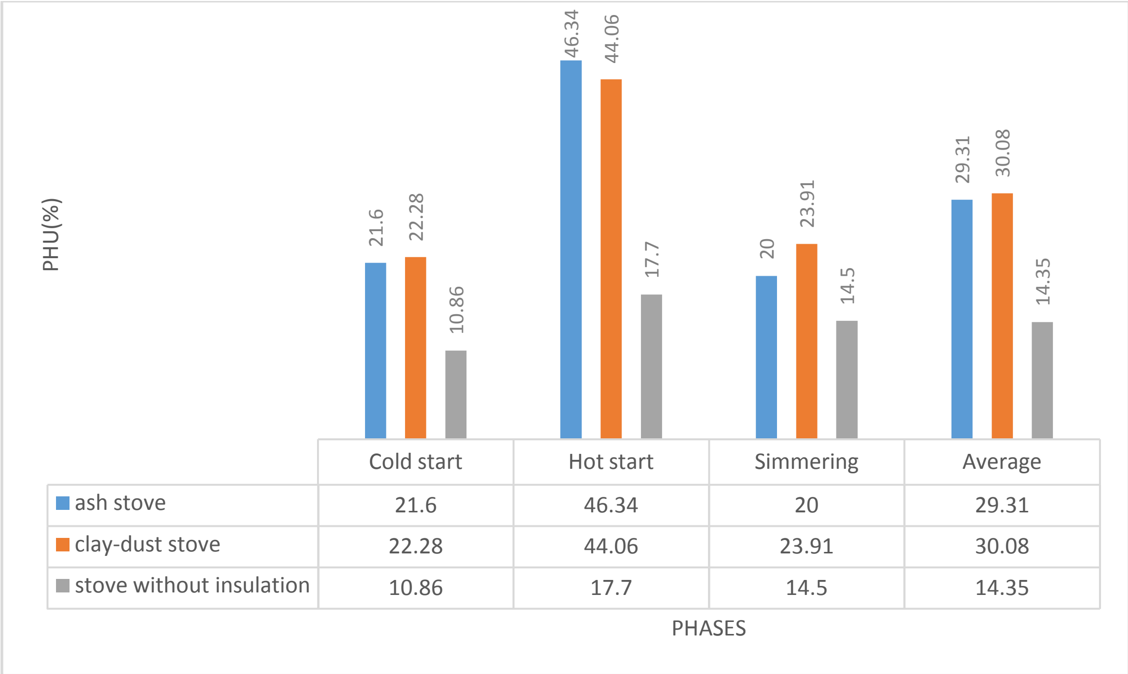


Figure 4.14 Percentage Heat Utilised for the various stoves

From Table 4.12 and Figure 4.14, it is seen that the clay-sawdust insulated stove and the ash insulated stove performed better than the stove without insulation during all the phases of the experiment, showing that insulating the fire does improve thermal efficiency of the rocket stove by reducing the heat conducted to the stove body and the environment. Especially during the hot phase, the insulated stoves double the stove without insulation in terms of thermal efficiency.

4.3.2 Firepower

Firepower gives the wood energy consumed by the stove per unit time. It tells the average power output of the stove (in Watts). Stoves with gradual consumption of fuel are the desirable ones, as they show better utilization of fuel. Table 4.13 gives the firepower for the three stoves and for the three phases.

Table 4.13 Summary of firepower (Watt) for the stoves

Phases	Firepower (Watt)		
	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Cold start	2.93	3.10	5.51
Hot start	2.05	2.16	4.86
Simmering	2.10	1.76	4.78
Average	2.36	2.34	5.05

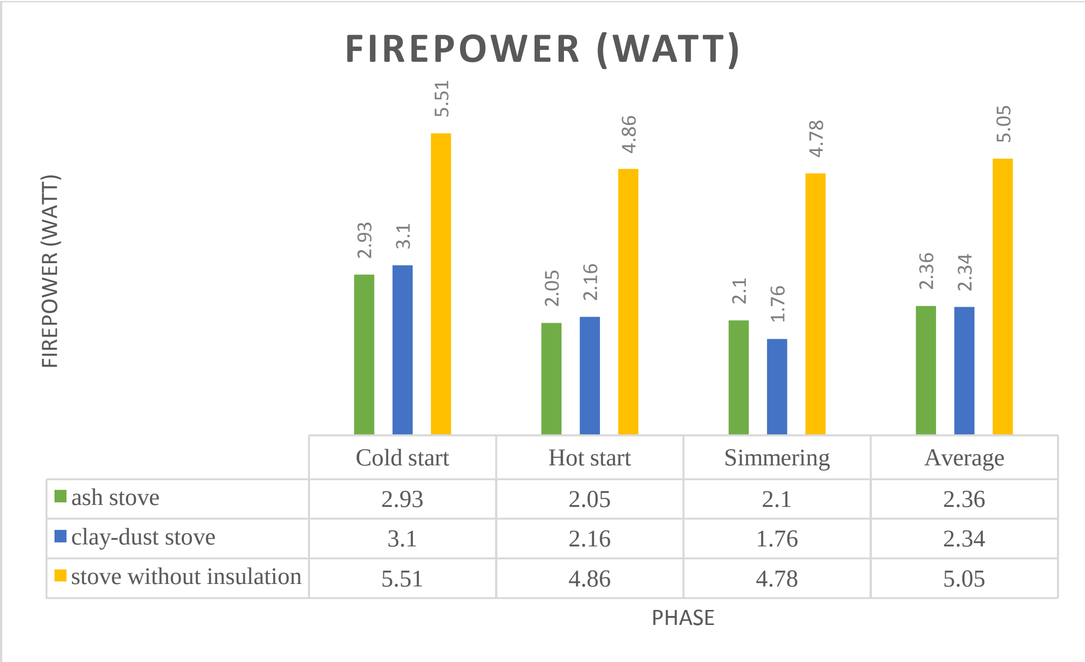


Figure 4.15 Firepower for the different stoves

As shown in Table 4.13, the stoves with insulation around them have lower firepower than the one without insulation round its combustion chamber meaning that less fuel is used per unit time. Both ash and the clay-sawdust mixture showed that they can act as insulation materials in rocket stove, ensuring less fuel is burnt. A graphical representation of Table 4.13 in Figure 4.15 shows clearly, that the stoves with insulation use less amount of fuel for the same purpose as the one without insulation.

4.3.3 Burning rate (g/min)

This is a measure of the rate of wood consumption during the test, thus this is the ratio of the total mass of wood consumed in grammes to the total time taken for the test in minutes. A stove with a good energy utilisation will have low burning rate indicating less wood usage. The burning rate for the three stoves and for the different phases are given in Table 4.14.

Table 4.14 Summary of Burning rate (g/min) for the different stoves

Phase	Burning rate (g/min)		
	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Cold start	6.57	6.95	12.35
Hot start	4.60	4.83	12.00
Simmering	4.72	3.95	7.80
Average	5.30	5.24	10.72

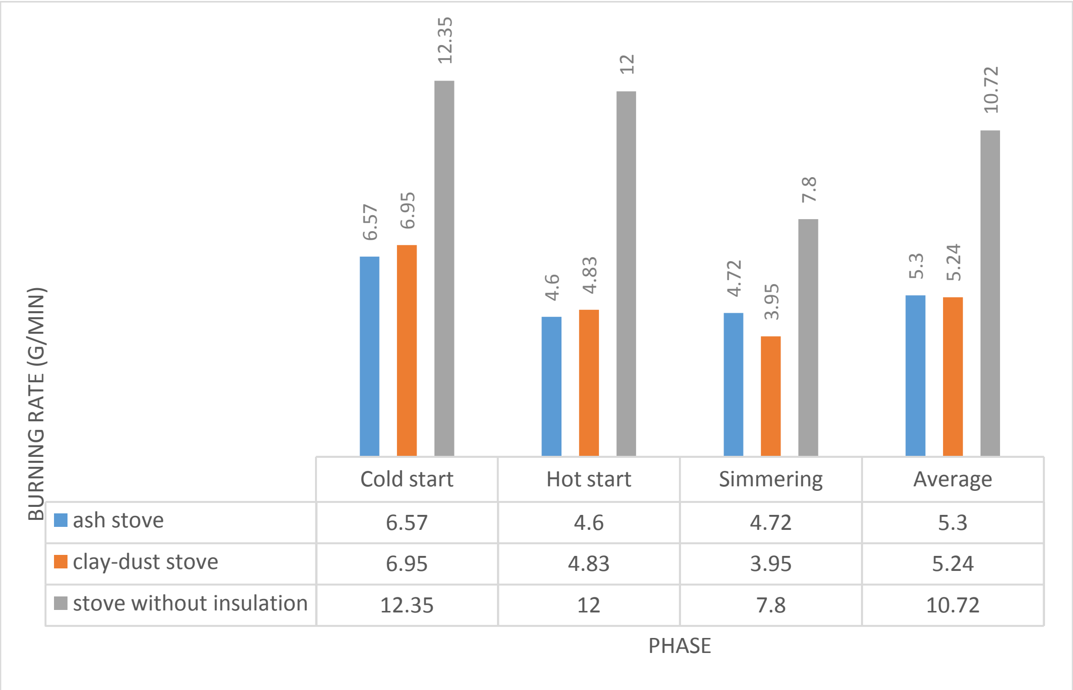


Figure 4.16 Summary of Burning rate

Table 4.14 and Figure 4.16show that the insulated stoves have lower burning rate than the un-insulated one and the clay-sawdust insulated stove shows slight improvement over the ash insulated stove, indicating better performance of the insulated stoves and the clay-sawdust stove over the ash insulated stove. By having lower burning rate, it means that when the stoves are insulated, they tend to use less fuel.

4.3.4 Turn down ratio

Turn down ratio (TDR) indicates the degree to which power output from the stove can be controlled by the user. It is the ability of the stove to be controlled, it also, tells the ease with which the stove can move from high power phase to the low power phase. It is simply the ratio of the firepower during the high power phase to that of the low power phase, this indicates that stoves with low turn down ratio have poor combustion process and are difficult to control (Kulla, 2011). Table 4.15 gives the turn down ratio for the three stoves.

Table 4.15 Turn down ratio for the three stoves

Type of stove	Turn Down Ratio
Ash insulated stove	1.22
Clay-sawdust insulated stove	1.23
Stove without insulation	1.01

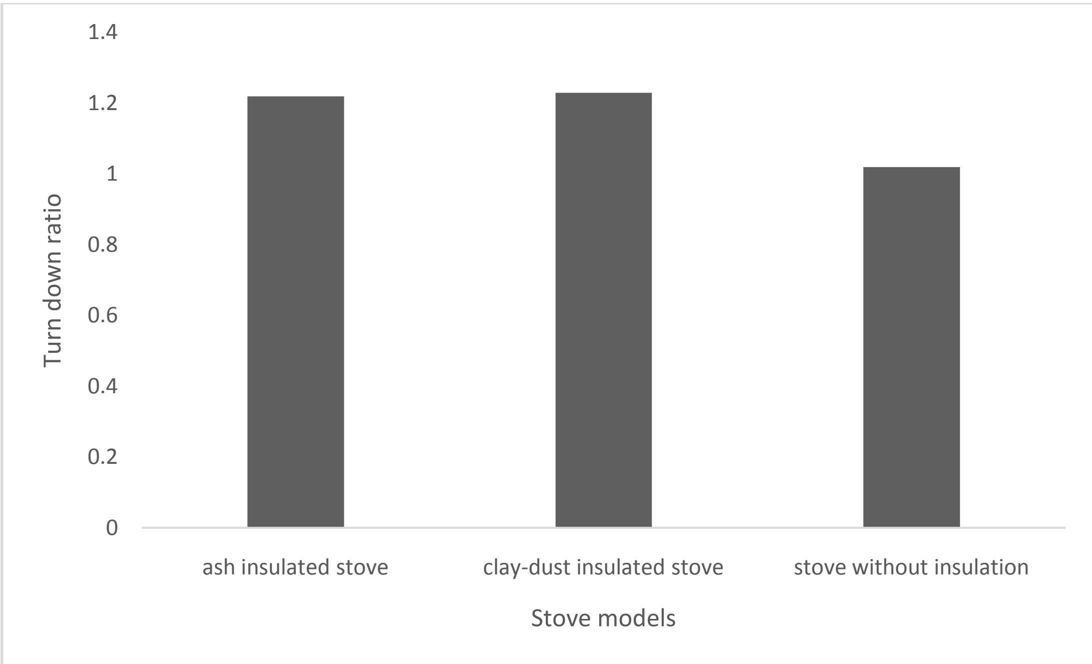


Figure 4.17 Turn down ratio for the different stoves

As shown in Table 4.15 and Figure 4.17, the insulated stoves with a higher turn down ratio have better combustion and are easier to control than the stove without insulation.

4.4 Varying other variables

4.4.1 Different quantity of water

Table 4.16 shows the parameter readings when the quantity of water was increased, the temperature variations against time is presented in Table 4.17. Table 4.18 gives the calculated results for the PHU, burning rate, firepower and SFC when the quantity of the water was increased.

Table 4.16 Parameter readings for varied quantity of water

Parameter	Ash insulated stove	Clay-sawdust insulated stove
Initial mass of wood (kg)	1.00	1.00
Final mass of wood (kg)	0.75	0.8
Mass of charcoal recovered (kg)	0.1	0.09
Mass of pot (kg)	0.35	0.35
Initial mass of water	2.75	2.75
Final mass of water	2.65	2.65
Initial temperature (°C)	28	28
Final temperature (°C)	98	98
Time at the end of test(min)	18	17.50

Table 4.17 Water temperature readings when quantity of water was increased

Time (min)	Water temperature (°C) in;	
	Ash insulated stove	Clay-sawdust insulated stove
0	28	28
2	37	42
4	46	51
6	51	59
8	65	67
10	74	74
12	81	82
14	88	89
16	93	95
18	98	98

Table 4.18 Calculated Performance values for varied quantity of water

Parameter	Ash insulated stove	Clay-sawdust insulated stove
Mass of wood used (kg)	0.25	0.23
Mass of charcoal (kg)	0.1	0.085
Heat supplied by wood (kJ)	6695	6159.4
Heat recovered (kJ)	3258	2769.3
Net heat supplied (kJ)	3437	3390.1
Mass of pot (kg)	0.35	0.35
Mass of water (kg)	2.75	2.75
Mass of steam (kg)	0.1	0.1
Heat gain by pot (kJ)	26.6	26.6
Heat gain by water (kJ)	920.92	920.92
Heat gain by steam (kJ)	226	226
Net heat gain (kJ)	1173.52	1173.52
PHU (%)	34.14	34.62
Fire power (Watt)	3.11	3.08
Burning rate (g/min)	7.0	7.0
Specific fuel consumption	0.045	0.045

Table 4.18 gives the summary of the calculations when the quantity of water was increased while Figure 4.18 to Figure 4.21 give the graphical representation of the experiment. With all other variables constant, the PHU of the stoves reduced (45.34% for 2.05kg of water and 34.14% for 2.75 kg of water) with increase in the quantity of water, burning rate, firepower and specific fuel consumption all increased with increased in water quantity and rightly so, as more fuel was needed to boil the increased quantity of water and it takes longer time to do so (Bryden *et al.*, 2005).

Figure 4.18 PHU when the quantity of water is varied

Figure 4.19 Firepower when the quantity of water is varied

Figure 4.20 Burning rate when the water quantity is varied

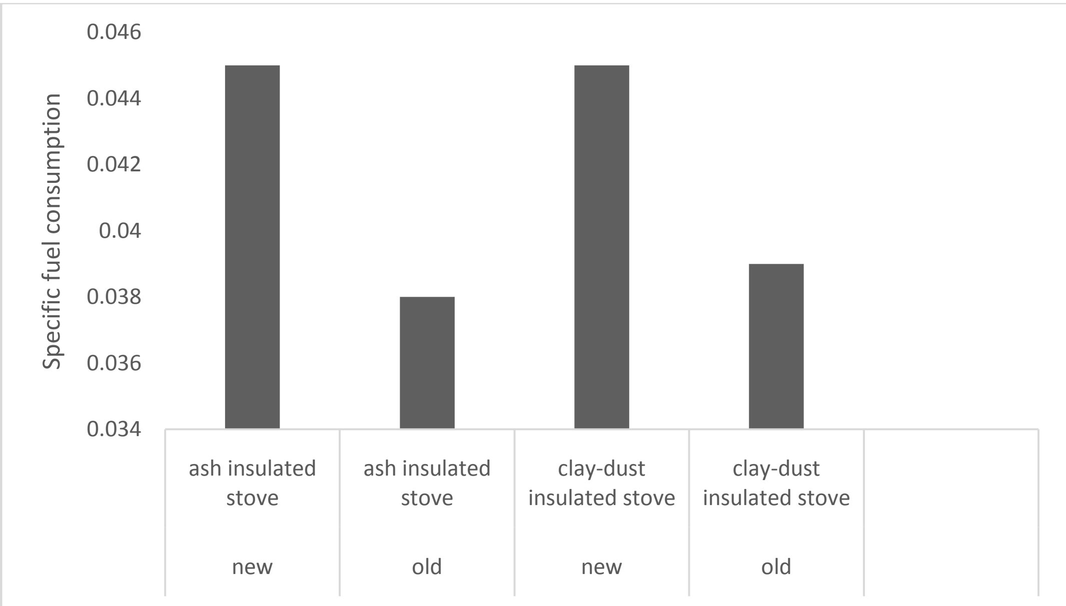


Figure 4.21 Specific fuel consumption when the quantity of water is varied

4.4.3 Varying the sizes of the wood

The readings for the different parameters are given in Table 4.19, the temperature variation is given in Table 4.20.

Table 4.19 Parameter readings when the cross sectional area of the wood was varied.

Parameter	Ash insulated stove	Clay-sawdust insulated stove
Initial mass of wood (kg)	1.00	1.00
Final mass of wood (kg)	0.84	0.85
Mass of charcoal (kg)	0.035	0.035
Mass of pot (kg)	0.35	0.35
Initial mass of water (kg)	2.05	2.05
Final mass of water (kg)	1.95	1.95
Initial temperature of water (°C)	28	28
Final temperature of water (°C)	98	98
Time at the end of test (min)	15.30	15

Table 4.20 Water temperature variation for varied cross sectional area

Time (min)	Water temperature (°C) in;	
	Ash insulated stove	Clay-sawdust insulated stove
0	28	28
2	38	39
4	47	49
6	52	59
8	65	69
10	72	78
12	82	87
14	91	94
16	98	98

Table 4.21 Calculated Performance results when cross sectional area of wood was varied

Parameter	Ash insulated stove	Clay-sawdust insulated stove
Mass of wood used (kg)	0.16	0.15
Mass of charcoal (kg)	0.035	0.035
Heat supplied by wood (kJ)	4284.8	4017
Heat recovered (kJ)	1140.3	1140.3
Net heat (kJ)	3144.5	2976.7
Mass of pot (kg)	0.35	0.35
Mass of water (kg)	2.05	2.05
Mass of steam (kg)	0.1	0.1
Heat gain by pot (kJ)	26.6	26.6
Heat gain by water (kJ)	686.504	686.504
Heat gain by steam (kJ)	226	226
Net heat gain (kJ)	939.104	939.104
PHU (%)	29.87	31.55
Firepower (Watt)	3.33	3.21
Burning rate (g/min)	7.5	7.2
Specific fuel consumption	0.056	0.053

The results in Table 4.21 shows that with increase in cross sectional area, PHU (45.34% for small cross sectional area of wood and 29.87% for large cross sectional area of wood) was reduced for both stoves, meaning that the stove performance reduced. This is due to less amount of air entering the combustion area as the wood increased in cross sectional area. This shows that air entrance into the stove is a very important factor in stove design and usage, as the right amount of air (stoichiometric) is needed for complete combustion of the fuel (Kulla, 2011). Also, with smaller cross sectional area, the wood tends to burn quickly and better and less tending is required. All other measuring parameter (firepower, burning rate and specific fuel consumption) all increased to further confirm that the stove performance is reduced when compared to the case of smaller cross sectional area. This show graphically in Figure 4.22-4.25 below.

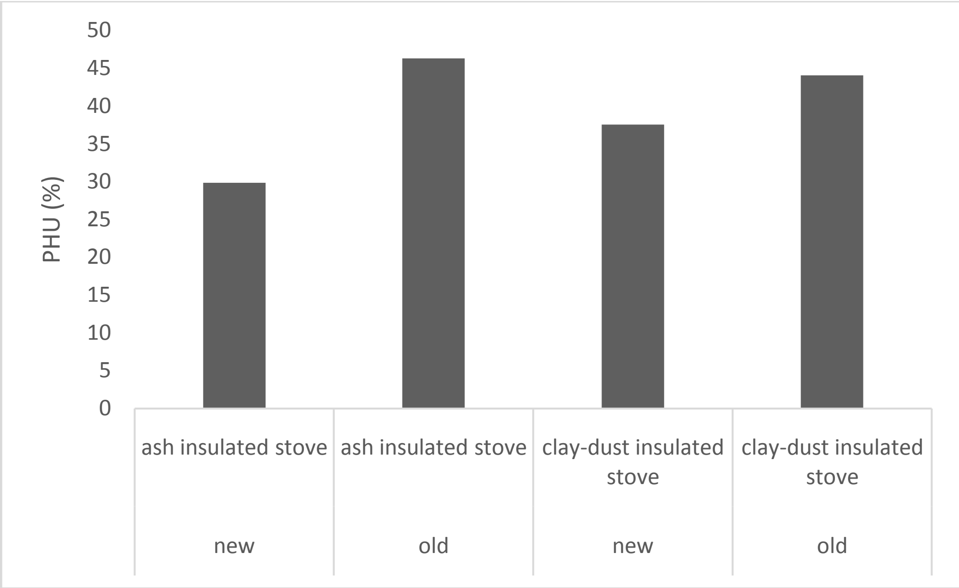


Figure 4.22 Comparison of PHU when cross section al area was varied

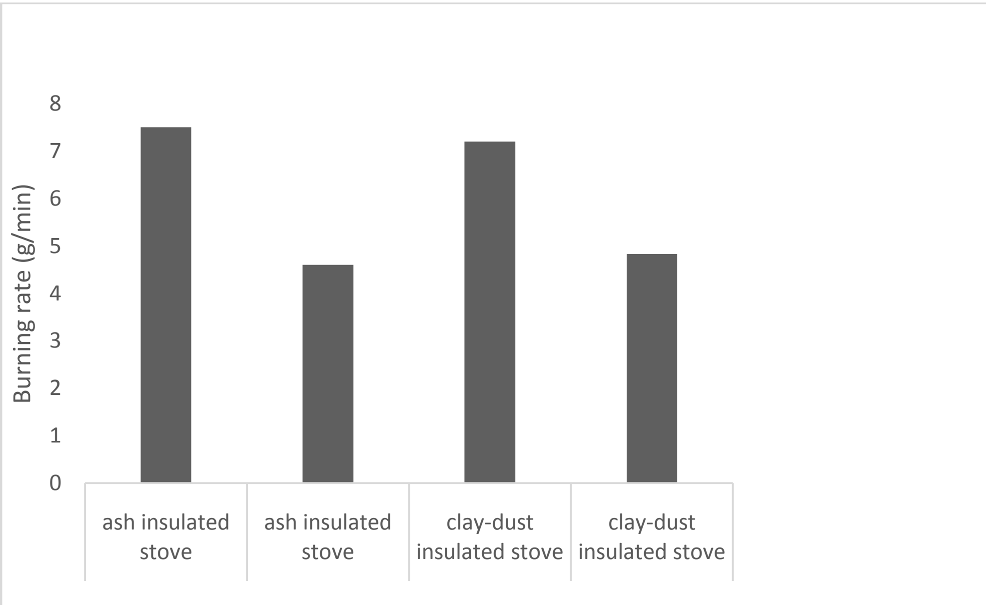


Figure 4.23 Comparison of burning rate when cross sectional area was varied

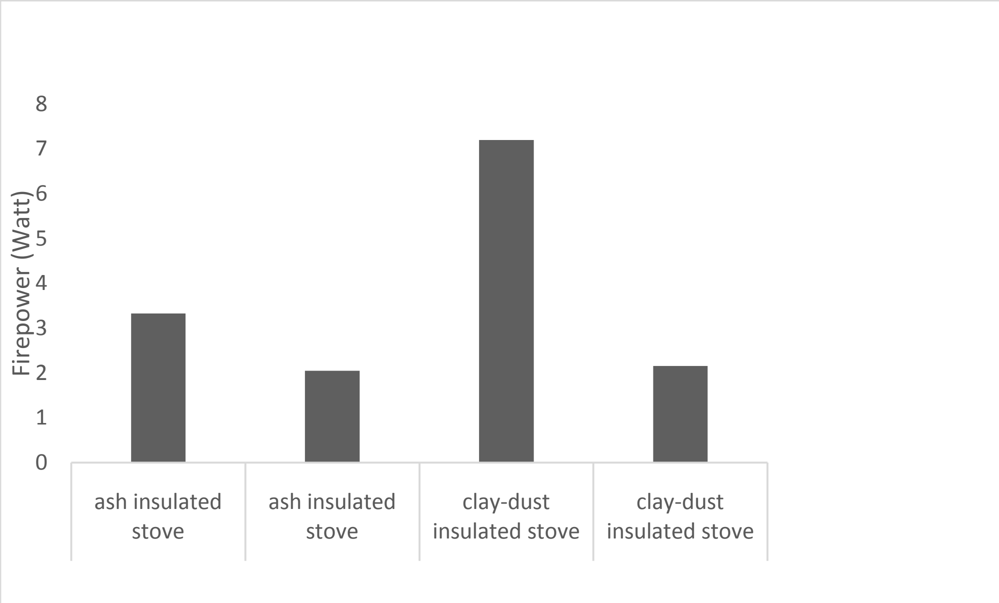


Figure 4.24 Comparison of firepower when cross section area was varied

Figure 4.25 Comparison of specific fuel consumption when the size of the wood was varied

4.5 Control cooking Test

The parameter readings are presented in Table 4.22, while Table 4.23 gives the calculated results for PHU, burning rate and firepower for the controlled cooking test.

Table 4.22Parameter readings for the controlled cooking test

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Initial mass of wood (kg)	1.00	1.00	1.00
Final mass of wood (kg)	0.67	0.66	0.45
Mass of charcoal (kg)	0.23	0.24	0.35
Mass pot (kg)	0.35	0.35	0.35
Mass of water (kg)	0.600	0.600	0.600
Initial mass of rice (kg)	0.200	0.200	0.200
Final mass of rice (kg)	0.72	0.72	0.72
Initial temperature (°C)	28	28	28
Final temperature (°C)	97	97	97
Time (min)	17	17	21

Table 4.23 Calculated Performance results for the controlled cooking test

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Mass of wood used (kg)	0.33	0.34	0.55
Mass of charcoal (kg)	0.23	0.24	0.35
Heat supplied by wood (kJ)	8837.4	9105.2	14729
Heat recovered (kJ)	7493.4	7819.2	11403
Net heat (kJ)	1344	1286	3326
Mass of water (kg)	0.6	0.6	0.6
Mass of pot (kg)	0.35	0.35	0.35
Mass of steam (kg)	0.08	0.08	0.08
Initial mass of rice (kg)	0.2	0.2	0.2
Final mass of rice (kg)	0.72	0.72	0.72
Heat gain by pot (kJ)	26.6	26.6	26.6
Heat gain by water (kJ)	200.93	200.93	200.93
Heat gain by steam (kJ)	180.8	180.8	180.8
Heat gain by rice (kJ)	95.904	95.904	95.904
Net heat (kJ)	504.23	504.23	504.23
PHU (%)	37.5	39.2	15.18
Firepower (Watt)	1.25	1.19	2.50
Burning rate (g/min)	2.82	2.65	5.57

The results obtained in Table 4.23 shows that all the stoves can be used for cooking outside the controlled environment and that the ones with insulation around it performed better than the ones without insulation, with a significant increase in thermal efficiency between the stoves with insulation and the stove without insulation (37.5% for the ash stove, 39.2% for the clay-sawdust stove and 15.18% for the stove without insulation), it therefore goes further to prove that both ash and the clay-sawdust can act as insulation materials in a rocket stove. Figure 4.26-4.28 show the difference between the stoves in terms of PHU, firepower and burning rate graphically.

Figure 4.26 Percentage heat utilization for controlled cooking test

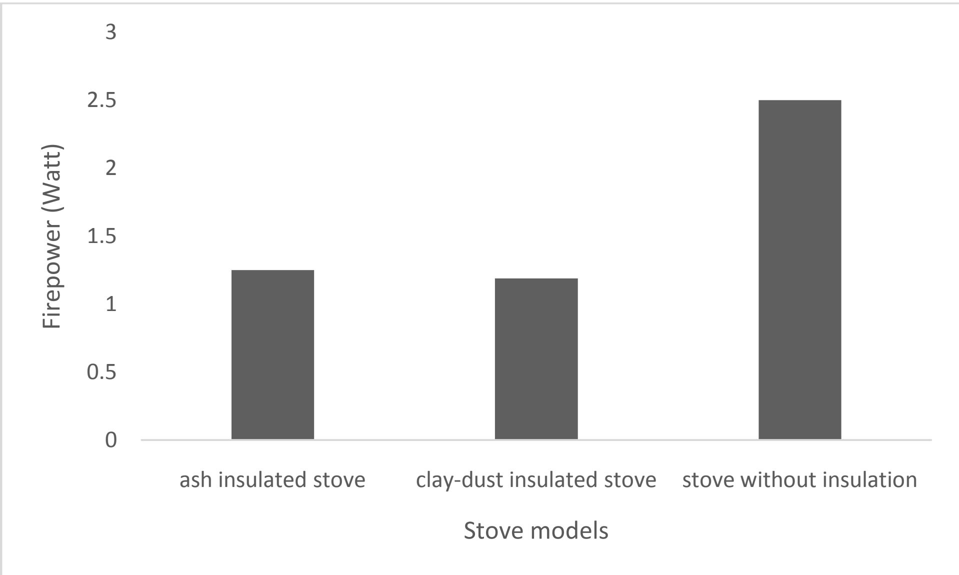


Figure 4.27 Firepower for controlled cooking test

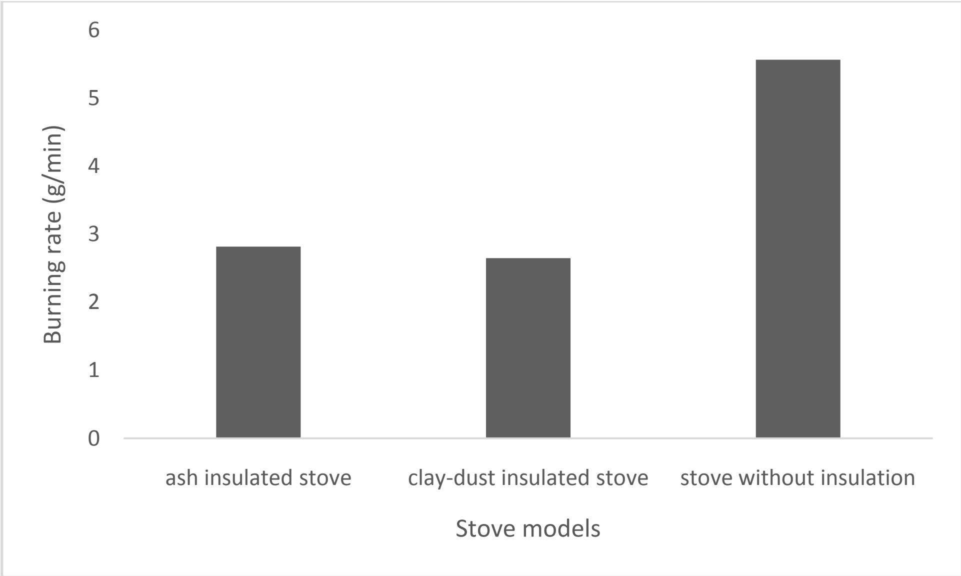


Figure 4.28 Burning rate for controlled cooking test

4.6 Kitchen performance test

4.6.1 User Acceptability

It was noted that fuel economy was greatly enhanced when the stove was insulated, thereby reducing the rate of fuel consumption. Also, more than just wood, other fuels such as charcoal, briquettes can be used in the stove, therefore meeting the wide range of fuel characteristic required with a good stove. Furthermore, conditions such as ease of operating, lighting, ease of control, were all met by the stove. The other characteristics are either simple design constraints (portability, does it have a griddle?) or cannot be sufficiently tested in a laboratory (familiarity, smell, how much training?).

4.6.2 External Need

Factors such as fuel economy, ease of operation, ease of control, ease of lighting, cost, and emissions are of importance to government, and NGO. Only emission test was not done as it is outside the scope of this work. All these conditions were duly satisfied by the stoves as mentioned above.

A quick glance at Table 4.24 shows that the list of characteristics that may influence a user's decision to accept or reject a stove is larger and farther-ranging than the list of characteristics that are generally important to external agencies such as NGOs, governments, and businesses. The implication is that there are more potential pitfalls associated with the user side of the equation, and a design that succeeds in meeting all of the criteria important to an external agency may still fail to attract end user and have a meaningful impact.

Table 4.24 Characteristics influencing stove effectiveness (Robert, 2009)

Factors	User Need	External Need
General characteristics		
Fuel Economy	×	×
Familiarity	×	
Emissions	×	×
Safety	×	×
Durability	×	×
Cost	×	×
Appearance	×	
Usability Factors		
How much training	×	×
Ease of lighting	×	×
Ease of control	×	×
Convenience Factors		
Will it accommodate range of pots?	×	
Will it accommodate a range of fuels?	×	
How hot to use / physical discomfort	×	
Must fuel be processed?	×	×
Noise	×	
Smell	×	

CHAPTER FIVE

SUMMARY, CONCLUSION AND RECOMMENDATIONS

5.1 Summary

Experimental investigation of the effect of insulation materials (ash and clay-sawdust) on the thermal efficiency of the rocket stove was carried out in this research. The aim of this research is to determine experimentally the thermal properties of wood ash and a clay sawdust mixture and test them in a rocket stove using water boiling test to determine their effect on the thermal efficiency of the rocket stove.

The thesis is composed of five chapters, each of them dealing with different aspects of this research. Chapter one is introductory and defines basic terminology used in the thesis, it also describes the various objectives followed in achieving the aim of the thesis, the justification and scope of the research.

Chapter two examined relevant literatures and their contributions to the development of better insulation in stoves and general stove development and it was observed that the use of wood ash and clay-sawdust as insulation materials is an area yet to be fully developed.

Chapter three is subdivided into two parts; materials and methods. Part one gives in detail the different materials and equipment used while carrying out this research and the various reasons for using them. Part two looks at the methods followed in constructing the stove and the approach followed in carrying out the various tests to determine the effect of insulation on the thermal efficiency of the rocket stove, the stove's ability to be used outside the laboratory and the acceptability of the stove by users.

Chapter four concentrate on the results obtained from the various tests and the discussion of the results. Part one describes the various results. While part two discusses the implications of the results on the aim of the thesis.

Conclusions are drawn in chapter five. The aim of the thesis was achieved which was to determine experimentally the thermal properties of wood ash and a clay sawdust mixtures and to test their insulating property in a rocket stove. It is recommended that the effect of these materials on the emissions of the stove be further pursued and also more non toxic materials be experimented upon for use in the rocket stove.

5.2 Conclusion

Both ash and clay-sawdust insulation materials were tested in the rocket stove and the following conclusions were drawn;

1. Both ash and clay-saw sawdust were found to have good thermal properties (low thermal conductivities; 0.2W/mK for ash and 0.16W/mK for clay-sawdust, high specific heat; 889J/kgK for ash and 910J/kgK for clay-sawdust and low thermal diffusivity; $3.67e^{-7}/m^2s$ for ash and $1.58e^{-7}/m^2s$ for clay-sawdust) which is desirable for an insulation material.
2. Thermal efficiency of the rocket stove was improved by 50% when insulated with ash and clay-sawdust insulation materials.
3. The stoves with ash and clay-sawdust as insulators passed the controlled cooking test therefore, can suitably be used outside the laboratory.
4. The stove performed better when, wood of small cross sectional area and just enough water needed for cooking was used.
5. Both user needs and external needs were met by the stove as observed in the kitchen performance test.

5.3 Recommendations

1. The effect of each insulation material on the emission of the stove can be investigated.
2. Other available materials such as sand, charcoal that are non-toxic can be experimented upon to ascertain their suitability as insulation materials in stove construction.
3. Further tests such as operating circle and energy counting can be carried out to evaluate the stove performance on a wide range of use scenarios.

5.4 Contribution to Knowledge

Previous research has shown that improving heat transfer is an area that needs most attention in improving thermal efficiency and the need to achieve this using nontoxic and easily available materials is an area that has not been pursued. This present research has typically shown that there was an improvement in thermal efficiency of the rocket stove when insulated with ash and clay-sawdust as insulation materials by as much as 50%. The thermal properties of ash and clay-sawdust mixture were tested and it was found to be thermal conductivities; 0.2W/mK for ash and 0.16W/mK for clay-sawdust, specific heat; 889J/kgK for ash and 910J/kgK for clay-sawdust and thermal diffusivity; $3.67e^{-7}/m^2s$ for ash and $1.58e^{-7}/m^2s$ for clay-sawdust) making both ash and clay-sawdust suitable insulator in reducing heat loss in the rocket stove. It was also found that the stove performed better when just enough water was used and wood of smaller cross sectional area was used.

REFERENCES

Aprovecho Center. (2005). *Aporvecho's stove research page*. Retrieved from www.aprovecho.org.

Ayo, S. (2009). Design, construction and testing of an Improved Wood Stove. *AU J Technol*, 13(1):12-18.

Ayugi, D., Banda, E., & D'Ujanga, F. (2011). Local Thermal Insulating Materials For Thermal Energy Storage. *Rwanda Journal, Mathematical Sciences, Engineering and Technology*, Volume 23 Series C pg 2-7.

Baldwin, S. (1987). *Biomass stoves: Engineering design, development and dissemination. Ph.D.thesis, Center For Energy and Environmental Studies Princeton University, Princeton.* New Jersey: VITA.

Ballard-Tremeer, G., & Jawurek, H. (1996). Comparison of five rural wood-burning cooking devices: Efficiency and emission. *Biomass and Bioenergy*, 11(5): 419-430.

Barnes, D. (1994). *What makes people cook with improved biomass stoves? : a comparative international review of stove programmes.* Washington D.C: World Bank.

Bhattacharya, S., Albina, D., & Khaing, A. (2002). Effect of selected paramters on performance and emission on biomass-fired cookstove. *Biomass and Bioenergy*, 23(5):387-395.

Bolaji, O., & Olalusi, O. (2009). Development of an Improved Coal Stove for Cooking in Developing Countries. *AU Journal of Tehcnology*, 12(3):182-187.

Bond, T., Doherty, S., Fahey, D., Forster, M., Berntsen, T., DeAngelo, B., & Zender, G. (2013). Bounding the role of black carbon in the climate system: A scientific. *Journal of Geophysical Research-Atmospheres.*, 118(11):5380-5552.DOI: 10.1002/jgrd.50171.

Bruce, N. (2000). Indoor Air Pollution in Developing Countries: a major environmental and public health challenge. *World Health Organisation*, (pp. 1078-1092).

Bryden, M. (2010). *Aprovecho Research Center.* Retrieved from http://bioenergylists.org/stovesdoc/Pcia/Design Principles for Wood Burning Cookstoves.pdf.

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R., & Goyer, k. (2000). A study of the Effectiveness of plancha Stove: Preliminary results. *International Conference on Biomass-Based fuel and Cooking systems.*

Bryden, M., Still, D., Scott, P., Hoffa, G., Ogle, D., Bailis, R., & Goyer, K. (2005). *Design Principles for Wood Burning Cook Stoves, Aprovecho Research Center/Shell Foundation/Partnership for Clean Indoor Air.* USEPA EPA-402-K-05_004.

Burnham-Slipper, H. (2008). *Breeding a Better Stove: the use of Computtational Fluid dynamics and Genetics Alogrithms to Optimize a wood Burning stove for Eritrea.* Nottingham: PhD Thesis, University of Nottingham.

Desai, M., Mehta, S., & Smith, K. (2004). Indoor smoke from solid fuels:Assessing the environmental burden of disease. *Environmental Burden of Disease*, 4:16-19.

Ebiega, E. O. (2012). *Design, Construction and Testing of a Rocket Stove.* Zaria: An Undergraduate Project, Mechanical ENgineering, Ahmadu Bello University.

Foundation, U. N. (2008). *Blueprint for Action: The West African Economic Monetary Union, Biomass Energy Regional Program The Hub for Rural Development in West and Central Africa.*

Geller, H. (1982). Cooking in the Ungra area: Fuel efficiency, energy losses and opporunities for reducing fuel consumption. *Biomass*, 2(2):83-101.

Huo, S., & Ko, Y. (2004). *Effects of heating height on flame appearance, temperature field and efficiency of an impinging laminar jet flame used in domestic gas stove. Energy conversion and management.* 45:1583-1595.

John, F. A., & Olayinka, O. A. (2014). The Effect of Sawdust on the Insulating Effect of Ikere Clay as Refractory Lining. *AU J.T.*, 17(3): 143-147.

Joshi, V., Venkatamaran, C., & Ahuja, D. (1989). Emissions from burning biomass fuels in metal cookstoves. *Environemental Management*, 13(6):763-772.

Joshi, V., Venkatamaran, C., & Ahuja, D. (1991). Thermal performance and emissions characteristic of biomass-burning heavy stoves with flue. *Pacific and Asian Journal of Energy*, 1:1-19.

Karekezi, S. (1992). The role of a stoves information network in addressing the indoor air pollution - an African perspective. *Indoor Air Pollution from Biomass Fuel, Working Papers from a WHO Consultation*, (pp. pp. 89-104). Geneva, Switzerland.

Kreith, F. (2000). *CRC Handbook of Thermal Engineering.* Colorado: CRC Press LLC.

Kulla, D. M. (2011). *Technology Improvement for Safety and Economy in Wood Burning Devices in Ngeria.* Progress report Ph.D Seminar paper, Department of Mechanical Engineering, ABU Zaria.

Legros, G., Havet, I., Bruce, N., & Bonjour, S. (2009). *The Energy Access Situation in Developing Countries.* World Health Organization and UNDP.

Lim, S., Vos, T., Flaxman, A., Danaei, G., Shibuya, K., Adair-Rohani, H., & Memish, Z. (2012). *A Comparative Risk Assessment of Burden of Disease and Injury AttribuTable to 67 Risk Factors and Risk Factor Clusters in 21 regions, 1990-2010: A Systematic Analysis for the Global Burden of Disease Study 2010.* Lancet 380:2224–60.

MacCarty, N. A. (2013). *A zonal model to aid in the design of household biomass cookstoves.* Ames, Iowa: An MSc thesis in Mechanical Engineering, Iowa State University.

Madubansi, M., & Shackleton, C. (2007). Changes in fuelwood use and selection following electrification in the Bushbuckridge lowveld, South Africa. *Journal of Environmental Management*, 83-101.

Musa, H. (2014). *Design, construction and testing of a Modeled woodstove using Local Heat Insulators.* An Undergraduate Project, Deparment of Mechanical Engineering, ABU Zaria Unpublished.

Olorunsola, A. (1999). The development and performance evaluation of a briquette burning stove. *Nigerian J. Renewable Energy*, 7(1 & 2): 91-5.

Pemberton-Pigott, C. (2004). *the variable energy stove.* Retrieved from www.newdawnengineering.com: 2015.10.18

Rehfuess, E. (2006). Fuel for life - household energy and health. *World Health Organisation.* Geneva.

Robert, P. T. (2009). *The uses of laboratory testing of biomass cookstoves and the shortcomings of the dominant U.S. protocol.* Ames, Iowa: MSc Thesis, Iowa State University.

Schreiner, N. H. (2011). *Performance Characteristics And Design Recommendations For Biomass-Burning Stoves Using Earthen Construction Materials.* Michigan: An MSc Report: Michigan Technological University.

Scott, P. (2006). *Rocket Stove for Sub-Saharan Africa. Bioling Point.* 50:7-8.

Sovacool, B. (2012). *The political economy of energy poverty: A review of key challenges. Energy for Sustainable Development.* 16:272-282.

Sundblad, F. (2014). *An improved cooking stove for the urban and semi-urban areas in Zambia.* An MSc Thesis in Insawdustrial Design Engineering, Chalmers University Of Technology Gothenburg, Sweden.

Theodore, B., Adrienne, L., Incropera, f., & Dewitt, D. (2011). *Fundamentals of Heat and Mass Transfer.* Jefferson City: JOHN WILEY & SONS.

Volunteers in Technical Assistance (VITA). (1985). *Testing the efficiency of wood-burning cook stoves.* Arlington.

Winiarski. L.(1997). *Rocket Stove Design Principle.* http/www.aprovechoresearchinstitue.com.

Winiasrki, L. (1996). *The Wood burning Stove.* Aprovecho.

World Health Orgainsation (WHO). (2004). Addressing the links between indoor air pollution, household energy, and health. WHO/HDE/HID/02.10.

Yawas, D. (2003). Performance evaluation of an improved three-burner wood fired stove. *Nigerian Society Engineers Technical Transactions*, 38(3): 65-76.

Zube, D. J. (2010). *Heat Transfer Efficiencies of Biomass Cookstove. An MSc Thesis.* Colorado: Colorado State university, Fort Collins Colorado.

Appendix A: Specific heat for selected foods (Kulla, 2011)

Food	Moisture content (wet basis)	Specific heat (a) (kJ/kg°C)
Rice	10.5-13.5	1.76-1.84
Flour	12-13.5	1.80-1.88
Meat	39-90	2.01-3.89
Milk	87.5	3.85
potatoes	75	3.51

(a) Average specific heat between 0° and 100°C

Appendix B: wood species and their characteristics (Kulla, 2011)

Name	*Eucalyptus Cioriodra*	*Delonix Regia*	*Gmelina Aborea*	*Magnigera Indica*	*Cassia Siamea*
Family name	mrytaceae	casealpinoidae	verbnaccae	verbnaccae	Leguminosae Caesalpionoidea
Local name	Dogon Yaro (turare)	Dogon Turawa (barkachi)	Malena (madauchi)	Mangoro	Labadiya
Calorific value of wood (MJ)	29.38	24.34	21.3	28.06	26.78
Calorific value of charcoal (MJ)	33	38.4	33.8	30.66	32.58

Appendix C: Plate 1 and 2

Plate1 Weighing a sample using Electronic weighing scale

Plate 2 A sample on Hotplate

Appendix D:Different views of the rocket stove

Plate 3 Front view of the rocket stove

Plate 4 Top view of the Rocket stove

Appendix E: Sample Calculations of results

1. Calculation of thermal conductivity for wood ash and clay-sawdust insulation material, from equation 3.1

$Q = KA\frac{T_2 - T_1}{L}$

Where Q = 2 W

For wood ash,

$T_2 = 245\ ^0C$

$T_1 = 80^0C$

$A = 6 * 3 = 18\ cm^2$

L = 3 cm

for clay-sawdust,

$T_2 = 253\ ^0C$

$T_1 = 45\ ^0C$

$A = 18\ cm^2$

L = 3 cm

For wood ash

$2 = K * 0.0018 * \frac{245-80}{0.03}$

K = 0.2W/mK

Similarly, for clay-sawdust

K = 0.16W/mK

2. Specific heat for woods ash and clay-sawdust insulation materials, from equation 3.2

$H = m.c_{p.}\Delta T$

Where Q = 50W, m = 0.035kg, t = 4 min, ΔT = 387 K (wood ash), ΔT = 377 K (clay-sawdust)

$\therefore$ for wood ash the specific heat is given as

$50 * 4 * 60 = 0.035 * c_p * 387$

$c_{p.}$ = 886 J/kgK

also, for clay-sawdust the specific heat is

$c_{p.}$ = 910 J/kgK

3. The thermal diffusivity for wood ash and clay-sawdust insulation materials, from equation 3.3,

$$\alpha = \frac{k}{\rho Cp}$$

Where for wood ash

$K = 0.2 W/mK$, $\rho = 605.5$, $c_p = 886$ J/kgK

$\therefore \alpha = \frac{0.2}{605.5*886} = 3.7\ e^{-7}\ /m^2s$

Similarly, for clay-sawdust, $K = 0.16$ W/mK, $\rho = 1112.8$ kg/m^3, $c_p = 910$ J/kgK

$\alpha = \frac{0.16}{1112.8*910} = 1.58\ e^{-7}\ /m^2s$

4. Sample calculation of performance results for cold start phase for the three stoves,

Parameter	Ash insulated stove	Clay-sawdust insulated stove	Stove without insulation
Mass of wood used (kg)	0.2	0.2	0.6
Mass of charcoal recovered (kg)	0.031	0.03	0.1
Calorific value of wood C (kJ)	26780 e^3	26780 e^3	26780 e^3
Calorific value of charcoal Cc (kJ)	32580 e^3	32580 e^3	32580 e^3
Heat supplied by wood H_w (kJ)	H_w = m* C = = 0.2 * 26780 e^3 H_w = 5336	H_w = m*C = 0.2*26780 e^3 H_w = 5336	H_w = m*C = 0.6*26780 e^3 H_w = 16068
Heat recovered from charcoal H_c (kJ)	H_c = m* Cc = 0.031* 32580 e^3 Hc = 1009.98	H_c = m* Cc =0.03*32580 e^3 H_c = 1140.3	H_c = m* Cc =0.1*32580 e^3 H_c = 3250
Net heat supplied (kJ)	4346.02	4215.7	12810
Mass of pot (kg)	0.35	0.35	0.35
Mass of steam (kg)	0.1	0.1	0.3
Mass of water (kg)	2.05	2.05	2.05
Latent heat of vaporization of steam Lv (kJ/kg)	2260	2260	2260
Temperature change T	80 ^{0}C	80 ^{0}C	80 ^{0}C
Heat gain by pot Hp (kJ)	Hp = m*c*T = 0.35* 0.215*353 Hp = 26.60	Hp = m*c*T = 0.35* 0.215*353 Hp = 26.60	Hp = m*c*T = 0.35* 0.215*353 Hp = 26.60
Heat gain by water (kJ)	Hw = m*Cw*T = 2.05*4.186*80 Hw = 686.50	Hw = m*Cw*T = 2.05*4.186*80 Hw = 686.50	Hw = m*Cw*T = 2.05*4.186*80 Hw = 686.50
Heat gain by steam Hs (kJ)	Hs = Lv*m_s = 0.1*2660 Hs = 266	Hs = Lv*m_s = 0.1*2660 Hs = 266	Hs = Lv*m_s = 0.3*2660 Hs = 678
Net heat gain (kJ) = Hp+Hw+Hs	939.10	939.10	1391.10
PHU (%)= $\frac{net\ heat\ supplied}{net\ heat\ gain}$	21.6	22.28	10.86
Firepower= $\frac{net\ heat\ supplied}{60*time\ taken}$	= $\frac{4346.02}{60*24}$ = 2.93	= $\frac{4215.7}{60*22}$ = 3.10	= $\frac{12810}{60*39}$ = 5.51

Burning rate (g/min) = $\frac{mass\ of\ wood\ consumed}{time\ taken}$	= $\frac{200}{30.4}$ = 6.57	=$\frac{200}{28.2}$ = 6.95	= $\frac{600}{48.3}$= 12.35
Specific fuel consumption = $\frac{mass\ of\ fuel\ consumed}{mass\ of\ water}$	= $\frac{0.2}{2.05}$ = 0.097	= $\frac{0.195}{2.05}$ = 0.95	= $\frac{0.6}{2.05}$ = 0.292

Similarly, performance results for the hot phase, simmering phase and the control cooking can all be calculated following the above pattern.