UNIVERSITY OF NAIROBI

FACULTY OF SCIENCE AND TECHNOLOGY

DEPARTMENT OF CHEMISTRY

A STUDY ON EFFICIENCY AND EMISSIONS FROM IMPROVED COOK STOVES IN KENYA

BY:

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A THESIS SUBMITTED FOR EXAMINATION IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR AWARD OF THE DEGREE OF MASTER OF SCIENCE DEGREE IN ANALYTICAL CHEMISTRY OF THE UNIVERSITY OF NAIROBI

2022

DECLARATION

DECLARATION BY STUDENT

I declare that this project is my original work to the best of my knowledge and has not been submitted elsewhere for examination, award of a degree or publication. Where other people's work or my own work has been used, this has properly been acknowledged and referenced in accordance with the University of Nairobi requirements.

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Supervisors' Approval

I hereby confirm that his project has been written and submitted with my approval as supervisor and therefore approve it for submission to the University.

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DEDICATION

I dedicate this work to my children (Gabby and Ethan), my parents (Mr and Mrs, Isaiah Mutua) and my classmates for the support and experiences they have offered me, both socially and academically, which have enabled successful completion of an eventful and memorable postgraduate study.

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Firstly, my greatest appreciation goes out to my supervisors Prof. Jacob P. Kithinji and Prof. John Onyari for their expertise, guidance and supervision together with providing resources without which this research wouldn't have reached its successful completion.

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I appreciate my family, my children (Gabby and Ethan) and friends for constantly encouraging me and urging me on all the time.

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ABSTRACT

This study investigated the thermal efficiency and emissions performance characteristics of various local and imported cook stoves. The low penetration and adoption of some of the efficient energy stoves has been attributed to lack of technical data to guide formulation and development of standards focusing on design and construction of the promising energy stoves, potential and current best-fit fuels and technology for testing and validating the energy stoves before adoption by institutions and households (Raman, 2014). It is on this basis that this project evaluated the efficiency and emissions from imported and local cook stoves used in Kenya by testing their thermal efficiencies and carbon monoxide and particulate matter emissions. Water boiling test (WBT) was conducted for firewood and charcoal cook stoves to determine their thermal efficiencies and Carbon Monoxide (CO) and Particulate Matter ($PM_{2.5}$). Out of the 76 sample cook stoves tested, the imported stoves were found to have better thermal efficiencies compared to locally assembled cook stoves. On the other hand, the local stoves were found to have lower Carbon Monoxide (CO) and lower Particulate Matter ($PM_{2.5}$) emissions compared to the imported cook stoves.

The imported firewood cook stoves had thermal efficiencies ranging between 27-37% while the local cook stoves had thermal efficiencies ranging between 17-31%. Local cook stoves had Carbon Monoxide (CO) emissions ranging from 4-25ppm. This was lower than that of imported cook stoves that had emissions ranging from 13-47ppm.
The imported firewood cook stoves had particulate matter ($PM_{2.5}$) emissions ranging from 942-2985µg/m^3 while the local cook stoves had emissions ranging from 221-1330µg/m^3. For charcoal cook stoves the local stoves had thermal efficiencies ranging between 26-47% while the imported cook stoves had thermal efficiencies ranging from 30-46%. The local cook stoves had carbon monoxide (CO) emissions ranging from 35-96ppm while the imported cook stoves had the same emissions ranging from 49-67ppm.

The Three-Stone cook fires had low thermal efficiencies at 14% and high carbon monoxide emissions at 50ppm and particulate matter emissions was an average of 6265μg/m^3. The thermal efficiencies for liquid fuels ranged between 33-49% while the carbon monoxide emissions ranged between 1-14ppm. The particulate matter emissions ranged between 39-95 μg/m^3. From the results it was observed that the liquid fuels burned with less emissions compared to solid fuels. They had thermal efficiencies higher than solid fuels.

Keywords: Thermal Efficiency, Biomass, Cook Stoves, Water Boiling Test, Carbon Monoxide, Particulate Matter and Emissions.

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LIST OF ABBREVIATIONS

CCT: Controlled Cooking Test

CO: Carbon monoxide

CO_2: Carbon dioxide

G/liter: Grams per Litre

G/min: Grams per Minute

ICS: Improved Cook stove

Jiko: a container made of clay or metal and used for burning small piece of wood, firewood or wood. It is used for giving heat and cooking.

Jua Kali: Means 'hot sun' and is the local Kenyan name given to groups of people who work with metal and wood for a living.

KJ/litre: Kilojoules per Litre

KPT: Kitchen Performance Test

KShs: Kenya Shillings

Mg/m^3: Milligrams per meter cubed

Min: Minutes

OSHA: Occupational Safety and Health Administration

PIC’s: Products of incomplete combustion

PM: Particulate matter

PPM: Parts per million

WHO: World Health Organization

CHAPTER 1 : INTRODUCTION

Socio-economic and environmental development of countries depend solely on affordability, reliability and accessibility of modern energy and energy services. In Kenya, only 69.7% of the population is connected to the national electricity grid, (World Bank, 2019). A population of over 75% relies on biomass (traditional) for cooking, house warming and other energy services (Ministry of Energy, 2019). Moreover, the appliances commonly used by over 80% are known to be quite inefficient in energy conversion and conservation due to limited technical information which could be useful for the formulation of standards, (Karekezi *et al*, 2004). This leads to serious wastage of fuels used, aggravated deforestation as well as significantly high cases of indoor air pollution that in turn causes respiratory diseases. This scenario enhances poverty among communities, contributes to global warming due to excessive use of biomass resources and general stagnation of nations. In Kenya, achievement of Vision 2030 can be a mirage unless this trend in energy provision and consumption is reversed.

1.1 HISTORY OF COOK STOVES IN KENYA

Cook stoves began appearing in early years of 1980s. Their design was aided by groups such as CARE-Kenya and UNICEF. There was mixed response from the users. Their designers were majorly of the US and Europe origins and had forgotten about marketing the stoves. Field testing was too brief and results were often inaccurate (Daniel Kammen, 2006).

More fundamental problems were experienced with the earlier prototypes. Designers acted as if it would have been just a simple exercise to make improvements on the efficiency of some of the stoves. After several trials, it was found that wider investigations on engineering design and stove physics were required. This analysis showed that greater heat loss from fire (approximately 50-70%) occurred as a result of conduction and radiation through the metal walls. Most designers of the early stoves put measures in place to deliver a lot more fire directly to the cooking pot. (Daniel Kammen, 2006).

The design of one of the early improved jikos was realized when an aid group-Kenya Renewable Energy Development Program sponsored a research group to Thailand to study the Thai bucket (shown in figure 1.1 below), an improved jiko. The design of the jiko that resulted had metal walls that sloped inwards. The insulating liner was made of mica (vermiculite) and ceramic material. The inner surface walls of the stove were cemented from top to bottom. This caused a lot of heat to be retained inside the vessel. Exposure to the trapped hot gases resulted to metal fatigue which eventually caused structural segments to crack. This first generation improved jiko was received positively by the purchasers.

Source:importfood.com

Figure 1.1: Thai Bucket Cook Stoves

Several international and governmental charity groups continued working with a consortium of craftspeople, Jua Kali (literally means 'hot sun' and is the local Kenyan name given to a group or groups of people who work with metal and wood for a living) to correct the problem.

In the mid-1980's better stove designs eventually came out. During this time several academics started publishing analyses of optimal insulating properties of the ceramic liner materials and optimal combustion temperatures. In Kenya, women have contributed to the improved designs. For instance, they suggested the recasting the metal bucket design into the shape of an hourglass. This helped in preventing the new stove from tipping over, when food was stirred in a vigorous manner in the Thai-influenced implement. The resulting and additional training of the women organizations and aid groups caused additional acceptance for more efficient stoves. Businesses, churches and schools helped create interest to other buyers.

1.2 BENEFITS OF THE JIKO

The ceramic Jiko has so far had a significant impact on household savings. Women have been the biggest beneficiaries in that they control a share of household income and at the same time they are the key decision makers in the purchase of fuels. Several people have invested the savings resulting from reduced fuel purchases in school fees for their children as well as small businesses.

Currently about half of all households found in urban areas in Kenya own and own the ceramic Jiko. The purchasers of these jikos on the other hand are both from the poor and the well up backgrounds. The stove programs have focused on rural areas and this has led to a challenge owing to the concentration of demand in these urban. This was however justified owing to the fact that most of users in the rural set ups are where most of the population lives and most these are poor. But the KShs 450 to KShs 5,000 price for the stoves has proved quite high for many and this has led to them resulting to collecting firewood and cooking over open fires. For town and city households, who sought ways to cut their unavoidable fuel costs have opted for more efficient stoves. (Daniel Kammen, 2006).

Ceramic Jiko successful implementation and adoption in Mombasa and Nairobi was noticed by many of the women groups that had been formed in rural areas. An alliance, Maendeleo ya Wanawake (meaning "Women's Development") was developed as a result of the need to work together between charity and government aid organizations in Nairobi and women groups. From these efforts, a more affordable and simplified version of the ceramic Jiko came up. The Maendeleo stove has the insulating element similar to the one in ceramic Jiko but without the outer metal casing. The liner is set in the middle of the open fireplace. It is then reinforced with stones and mad. A pot placed on top of the stove heats as quickly as one placed on a Kenya ceramic Jiko. Indoor smoke is reduced considerably due to more efficient combustion. Further, a Maendeleo stove is usually placed near a wall of the house or kitchen so that smoke can exit more easily. (Kammen, 2006).

1.3 FUELS USED IN COOKING

Over 3 billion people use solid fuels like coal and biomass including charcoal, animal dung, wood and agricultural residues as the key energy source in their households. These fuels are usually burned in fires that are open and stoves without enough ventilation are burned in open fires and rudimentary stoves with inadequate ventilation. This exposes family members, particularly children and women to indoor smoke that is toxic. Households with low incomes in developing nations such as Kenya mainly depend on solid fuel for their energy need while those of higher income countries use processed fuels and/or electricity like natural gas and liquefied petroleum gas (LPG). (WHO, 2018).

Fuels like biogas, LPG and ethanol are usually more efficient, safer, appealing and cleaner. However, they come at higher cost than the traditional fuels.

Many solid fuel based cook stoves found in the market reduce particulate matter and carbon monoxide emissions. In this study the indoor pollutants studied were carbon monoxide and particulate matter ($PM_{2.5}$). (Susan C. Anenberg *et al*, 2013).

1.4 PARTICULATE MATTER ($PM_{2.5}$)

Particulate matter is the sum of all liquid and solid pollutant particles suspended in air. They vary in composition and size. This is a pollutant that affects a lot more people than any other pollutant. It is mainly composed of mineral dust, water, black carbon, sulfate, ammonia, nitrates and sodium chloride. It is also composed of liquid and solid mixture of particles of inorganic and organic matter suspended in the atmosphere. Particles with a 10-micron diameter or less (≤) are the most life threatening. These particles penetrate deeper into the lungs. Exposure to these small particles could lead to cardiovascular and respiratory diseases. Lung cancer could also occur as a result of this exposure (Morakinyo OM *et al*, 2016).

1.5 CARBON MONOXIDE (CO)

Carbon Monoxide is an odorless, colorless gas. It results from the incomplete burning of fuels. It also results from cigarette smoke and when there is incomplete combustion of biomass fuels. CO pollution levels also result from industrial processes. Automobile is the key source of CO pollution in urban areas. In a domestic home set up, inefficient cook stoves are a source of carbon monoxide and in turn a source of pollution, health complications and in some cases death.

In this study various cook stoves emissions of carbon dioxide were determined and compared.

1.6 WHO GUIDELINES ON AIR QUALITY

A World Health Organization (WHO) guideline is defined as any information developed by WHO that contains recommendations for public health policy or clinical practice. Recommendations are statements that are designed to aid end-users make informed decisions on when, how and whether to undertake specific actions such as clinical interventions, diagnostic tests or public health measures, with the aim of achieving the best possible collective or individual health outcomes. (WHO, 2011).

Problems associated with indoor air pollution are key risk factors for human health in high, middle and low income nations. Indoor air is key because most family members tend to be indoors most of the time of the day.

The WHO guidelines give a unified basis for the protection of public health from adverse effects of indoor air pollution exposure. The guidelines are also meant to bring down or eliminate the hazardous or likely hazardous pollutants.

1.7 CARBON CREDIT

A carbon credit is a term used to refer to any tradable certificate or permit that represents the right to emit one tonne of carbon dioxide or the mass of another greenhouse gas with a carbon equivalent (tCO_2e), (Collins English Dictionary,11th Edition).

The main aim of carbon credit is promoting market mechanisms to push industrial and commercial processes towards reducing Green House Gases (GHGs). A Green House Gas is a gas in the earth's atmosphere that contributes to the greenhouse effect by trapping heat (absorbing infrared radiation) from the sun. Chlorofluorocarbons and Carbon dioxide are some of the greenhouse gases. This is done through Kyoto Protocol. Kyoto Protocol is an international treaty that aims at reducing global warming by reducing the Green House Gases concentration in the atmosphere.

The evaluation and documentation of the efficacy of improved imported and local cook stoves for poverty reduction and improved livelihood of Kenyan communities is one of the outputs of Testing and Development of standards for cook stoves industry in Kenya.

1.8 MAIN OBJECTIVE

The overall objective of the study is to establish a database on efficiency and emission levels from improved institutional stoves and a wide range of household stoves, both improved and unimproved.

1.8.1 SPECIFIC OBJECTIVES

i. Conduct water boiling tests on selected improved and unimproved stoves
ii. Determine the CO emission levels from selected improved and unimproved stoves currently in the Kenyan market.
iii. Determine the levels of particulate matter emissions from selected improved and unimproved stoves in.
iv. Establish the efficiency selected improved and unimproved stoves.
v. Document database on emissions and efficiency tests of selected stoves.

1.9 JUSTIFICATION AND SIGNIFICANCE

The low market penetration and adoption of some of the efficient energy cook stoves has been attributed to lack of technical data to guide formulation and development of standards focusing on design and construction of the promising energy stoves, potential and current best-fit fuels and technology for testing and validating the energy stoves before adoption by institutions and households (Raman, 2014). It is on this basis that this project evaluated the efficacy of improved imported and local cook stoves used in Kenya by testing their thermal efficiencies and Carbon Monoxide and Particulate Matter emissions.

The successful implementation of the project will benefit project implementers, local communities, investors and policy makers. Business communities will benefit from trading with of stoves with proven thermal, carbon monoxide and Particulate Matter emission efficiencies. Communities in rural areas will benefit from access to modern bioenergy. Women and the girl child will benefit from less time spent collecting traditional biomass and minimize exposure to indoor air pollution.

The fuels used were procured locally; Firewood; charcoal; kerosene; ethanol and gelled ethanol.

CHAPTER 2 : LITERATURE REVIEW

2.1 COOK STOVES

2.1.1 THREE STONE COOKING FIRES

This is a traditional method of cooking that requires three stones of the same height and size on which a cooking vessel is balanced over a fire. This is a very basic stove heated by burning biomass or fossil fuels. Figure 2.1 below shows the three stone cooking fire:

Source:modi.mech.columbia.edu

Figure 2.1: A Three Stone Cooking Fire

Three-Stone Fires arose from the need to have foods being cooked indirectly on open fires through mediums such as cooking pots and pans. It is the most ancient and the most affordable stove to produce, it requires three stones, balanced over a fire and similar height and on which a cooking pot is placed. Some of the advantages of Three-Stone Fires include:

1. It is the cheapest stove compared to other found in the market
2. Domestic lighting is one of the key uses of three stone fires that the improved cook stoves cannot perform.
3. A three stone fire producing lots of smoke in an environment could have the added benefit of preventing insect bites.
4. There is a flexibility to use a variety of fuels in different seasons. (Foley, *et al*, 1984)

This method of cooking, however has several challenges and problems such as those listed below:

1. The smoke is released directly to the house and this causes numerous health related problems. According to WHO, "Every year, indoor air pollution is responsible for the death of 1.6 million people – translating to one death every 20 seconds." (WHO, 2010).
2. As heat escapes into the air, fuel is wasted. This subsequently translates to requiring more labor by the user to collect wood fuel. This also results in faster deforestation rate.
3. Continued use of open fire may lead to suffering a risk of scalds and burns by the user especially if the stove use is indoors, (Naeher L, *et.al*, 2007). In addition, blowing the fire for oxygen supply could lead to a discharge of burning embers that could lead to eye injuries.

These negative impacts can be minimized with the use of improved cook stoves.

2.1.2 IMPROVED COOK STOVES

An improved cooking stove is a stove which requires less fuel to prepare the same food amount than a traditional one. It also produces less smoke compared to a traditional stove (Boy Erick, *et al*, 2000). Improved cook stoves significantly reduce the smoke, either by having excess of air or having a better combustion or both.

Since the commencement of the modern technology, the key target has been to come up with a cheaper, more efficient stove than the commonly used three stone cooking fire.

2.1.3 CLASSIFICATION OF IMPROVED COOK STOVES

Several improved cook stove designs have been developed over time. Different models fall under different categories of classification. The classification is majorly according to fuel type, according to the function of the stove and according to the construction material of the cook stove.

1. **Fuel Type**

Most Improved Cook stove (ICS) designs use specific fuel and will only operate optimally when burning a particular fuel type for which they are designed. For instance a cook stove designed to use rice husks as fuel, will not perform if fed with firewood. Similarly, a cook stove designed to exclusively use charcoal may burn firewood but will do so sub optimally. Major types of cook stoves falling in this category include firewood, briquette biomass fuel, charcoal, dual firewood-charcoal, granular/loose agricultural residue, sticks form agricultural residue and cow dung cake fuel improved cook stoves. (Mercado I.R. *et al*, 2014).

2. **Portability**

On the basis of portability, an improved cook stove can either be portable or fixed. Improved cook stoves made of metallic or ceramic materials are light in weight and this allows the end users flexibility in where to work with the cook stoves. These cook stoves are classified as portable. On the other hand, cook stoves that are made of stones or clay or bricks or a combination of these materials are heavy in weight and are hence fixed. Cook stoves under this category can be sub-divided further depending on the number of pot holes e.g. single, double, triple etc. (Mercado I.R. *et al*, 2014).

3. **Function**

Under this category, the cook stoves are either multifunctional or mono-functional. A mono-function improved cook stove is designed to perform a single special function which could either be roasting, meat roasting, cooking or fish smoking. A multi-function cook stove on the other hand will perform more than one function for example water heating in addition to cooking. (Mercado I.R. *et al*, 2014).

4. **Construction materials**

Improved cook stoves can be made of a single material or a combination of materials for different parts. Classification based on materials is key in guiding cook stove promoters or sellers to select appropriate design or designs for a specific target group based on factors such as locally existing production skills like metal fabrication or pottery skills, estimated cost of end product and available materials. (Mercado I.R. *et al*, 2014).

5. **International Workshop Agreement (IWA) tiers of performance**

This is new framework for rating cook stoves performance and was developed by International Standards Organizations' (ISO) in 2012. The framework provides a system of rating cook stoves by classifying them in relation to a set of specified ranges based on fuel efficiency, particulate matter ($PM_{2.5}$) and carbon monoxide emissions. (DKS ISO 17225-3:2014)

Lots of work has been done in recent years to design and promote stoves that are either fuel efficient or address the health issues brought about by traditional cooking fires (Roden *et al*, 2014). These are known by various names: improved stoves, improved cook stoves, wood conserving stoves and smokeless stoves.

Depending on the local materials available, community needs and environmental conditions several designs of improved cook stoves have been developed.

These improved stove designs, when they work optimally, don't fill the houses with smoke that is harmful (the efficient burning of the biomass reduced smoke, and a venting or chimney removes that smoke), and use less fuel, (ESD, 2000).

The Ministry of Energy and Petroleum (MoEP) in partnership with other Government agencies, international and local Non-Governmental Organizations (NGOs) and Civil Societies and private investors have participated in development and promotion of many energy end use appliances. These appliances are efficient and with carbon monoxide and particulate matter emissions that comply with international specifications. The appliances targeted include institutional and household improved imported and local cook stoves which utilize un-carbonized biomass, charcoal, kerosene and currently bioethanol from biomass resources. Figure 2.2 below shows some of the improved imported and local cook stoves in the Kenyan market. The cook stoves are figure 2.2A Maendeleo cook stove. Maendeleo is a Swahili word meaning development or progress. The idea behind the name was that the cook stove was progressive. Figure 2.2B shows Upesi cook stove. Upesi is a Swahili word that means efficient. The idea behind the name was to give the impression of how efficient the cook stove was. The figure 2.2C, Kuni Mbili cook stove. Kuni Mbili in Swahili means two sticks of firewood. The idea was that the cook stove was fuel efficient in that it used very little firewood. Figure 2.2D shows the Rocket cook stove.

<table>
<tr><th>A. Maendeleo Stove</th><th>B. Upesi stove</th></tr>
<tr><td>

stoves.bioenergylists.org</td><td>

research.net</td></tr>
<tr><th>C. Kuni Mbili Stove</th><th>D. Rocket Stove</th></tr>
<tr><td>

enterprise.scode.co.ke</td><td>

Theepicenter.com</td></tr>
</table>

Figure 2.2: Different Designs of Improved Cook Stoves

2.2 HEALTH EFFECTS OF PARTICULATE MATTER

There exists a correlation between particulate matter ($PM_{2.5}$) high concentration exposure and increased morbidity, mortality or both over time and daily. Similarly, mortality decreases when the concentrations of fine particulates in an environment are reduced. Population growth and quality of life can thus be estimated in terms of improved particulate air pollution. There is no limit that has been set below which no damage is noticed. The WHO (2005) guidelines on particulate matter concentrations are as follows:

$PM_{2.5}$

10µg/m^3 annual mean

25µg/m^3 annual mean

PM_{10}

20µg/m^3 annual mean

50µg/m^3 annual mean

Additionally, the Air Quality Guidelines give tentative targets for $PM_{2.5}$ and PM_{10} concentrations whose aim is to promote a change from high to low concentrations. If these targets were to be achieved, notable risks reduction for chronic and acute health effect can be expected. The ultimate objective should be a progress towards the guideline values, (WHO, 2005).

WHO Air Quality Guidelines estimates that a yearly PM_{10} reduction from levels of 70µg/m^3 could reduce pollution related deaths by about 15%.

Exposure to indoor pollutants resulting from burning of solid fuels in traditional stoves or open fires acts to increase the risk of lower respiratory infections and related deaths among children and women that spend most of the time in environments where cook stoves are used.

The allowable indoor, according to World Health Organization WHO, 2018 exposure concentrations over time for carbon monoxide (CO) are shown in table 2.1 below:

Table 2.1: Allowable Indoor Carbon Monoxide (CO) Exposure Concentrations

CO Concentration (ppm)	Maximum Exposure Time
90 - 100	15 Minutes
50 - 80	30 Minutes
25 - 35	1 Hour
9 -10	8 Hours

The Occupational Safety and Health Administration (OSHA) allowable CO_2 exposure average is 5000ppm over 8-hour period. OSHA ensures that employees work in healthful conditions by enforcing and setting standards. They also provide education, training and outreach to the public.

Work and studies on determining effects of indoor air pollution on health has remained behind compared to work done on outdoor pollution majorly because development of policy in the field of air pollution has put more focus on outdoor air pollution. This can be noted from the much focus and emphasis that has been put in photochemical smog and coal smoke, standards applicability to outdoor air pollutants concentrations and the fact that policy and science communities focus has been in public health for the wealthy countries and disregarded the diseases burden resulting from indoor pollution from burning of biomass fuels experienced in developing countries.

2.3 THEORY OF PARTICULATE MATTER MEASUREMENT

Several instruments are used in measuring various particulate matter characteristics. Particle size and the particle concentration are the most important parameters in these measurements. A particle's behavior in ambient air can be determined by a particle size analyzer. These measurements are used standardize emission limits and assure air quality standards. Instruments used to determine particle size distribution use the particles' behavior i.e. optical mobility and electrical, aerodynamics and diffusion, (P. Kulkarni *et al,* 2016).

The commonly used methods for particulate matter measurements are concentration methods and optical methods. Concentration methods include gravimetric methods while optical methods include light absorption, light extinction and light scattering methods.

A. Gravimetric Methods

In these methods the particles weight concentration is measured by determining the weight of the filters both before and after sampling. The filters collect particulate matters in all fractions (coarse modes, nucleation and accumulation) unless if there is an impactor or cyclone to get rid of the larger particles (Giechaskiel *et al,* 2015).

B. Optical Methods

In these methods of detection, particles are radiated by a beam of light. This beam is then irradiated in various scattering directions. Simultaneously, some of the irradiated light is converted into other forms energy (absorption), (Giechaskiel *et al,* 2015).

Optical instruments that are used for particle concentrations measurements are based on extinction, scattering and absorption of light principles.

2.3.1 Light Scattering

A dispersion photometer which is an instrument of scattering of particles is used to determine the light intensity scattered in one or multiple angles, (Giechaskiel *et al*, 2015). The light that is scattered is measured by introducing a photometer detector. The light that is scattered from a combination of all the particles in the optical detection volume is measured by these photometers (Hinds, 2010). Most of the instruments do use visible light (~600nm) and measure at angles of 90°, 45° or less than 30°. Some of these photometers include Respirable Aerosol Monitor (RAM) and its newer version called DataRam 4. It stores data continuously (Costa *et al*, 2012). It shows a correlation with another instrument, that measures particle concentration and size. The instrument is UCB-PATS (University of California Berkeley-Particle and Temperature Sensors). Chowdhury, *et al* used the photometer and according to them, it uses smoke detection technology. This technology combines chambers of ionization and photoelectric sensors. This combination makes it possible to measure the particles with precision. A light emitting diode (LED) is used in the light dispersion chamber, with a wavelength of 880nm. The intensity of the light scattered at 45° is measured using a photodiode. The ionization sensor is more sensitive to PM_1 while the photoelectric sensor is more sensitive to particles with less than 2.5µm aerodynamic diameter.

2.3.2 Light Absorption

Instruments used in the light absorption principle determine the concentration of black carbon. Black carbon is composed of the aerosol. Black carbon absorbs light strongly. This does make it a radiative agent and contributes negatively to climate changes. Some of the equipment using this technique include Spot Meter, Aethalometer, Photoacoustic Soot Sensor (PASS) and Laser Induced Incandescence (LII). (Giechaskiel *et al*, 2015).

2.3.3 Light Extinction

To enable light extinction in aerosols to be measured a Cavity Ring Down, (CRD) system was developed by Peterson, *et al* and Mellon, *et al*. Opacity Meter is also used in the measurement of light extinction. In Cavity Ring Down the aerosols are produced by drying and atomization. These dry particles are then sorted in different sizes using a Differential Mobility Analyzer (DMA). The CRD cell exit is where the selected particles are counted. (Giechaskiel *et al,* 2015).

2.4 CARBON MONOXIDE

2.4.1 Health Effects of Carbon Monoxide

Carbon Monoxide enters the blood stream through inhalation. It binds chemically to hemoglobin. Hemoglobin carries oxygen to the body cells, but when CO binds to it, it is unable to bind with oxygen. This results to a reduced amount of oxygen delivered to body tissues. The percentage of hemoglobin inactivated by CO depends on the concentration of CO, the length of exposure and the amount of air breathed. The initial symptoms of CO poisoning are similar to those of flu. They include coughing, paleness, dizziness, irregular breathing, fatigue, nausea and headache.

Carbon monoxide exposure reduces exercise ability in healthy young persons. People with cardiovascular diseases are also affected. The latest OSHA allowable limit of exposure for carbon monoxide is 5000 ppm over an 8-hour time-weighted average (TWA).

2.4.2 Theory of Carbon Monoxide Measurement

The Carbon Monoxide sensor is fitted with three electrodes that are dipped in an electrolyte that is non-metallic. The liquid electrolytes are usually dissolved salts or acids. These electrodes are the working, the counter and reference electrodes. The working electrode is made of platinum and is the most important. Platinum catalyzes the oxidation of carbon monoxide to carbon dioxide. This oxidation is aided by a hydrophobic gas-permeable membrane. The CO gas goes through this membrane and is oxidized electrochemically. The reaction for this oxidation is as shown below:

$$\mathbf{CO + H_2O \rightarrow CO_2 + 2H^+ + 2e^-}$$

Equation 1: Oxidation of Carbon Monoxide

The electrons resulting from the reaction flow through the external circuit from the working electrode, producing an output signal of the sensor. A stable electrochemical potential in the electrolyte is provided by the reference electrode. The thermodynamic potential is kept constant by protecting the reference electrode from CO gas exposure. Additionally, current flow through the reference electrode is not allowed because this would lead to altering the thermodynamic potential. The counter electrode (CE) functions as the second half cell and completes the electrochemical cell. It also enables electrons to leave or enter the electrolyte.

The signal current is converted to a voltage by a potentiostat. It also acts to control the working electrode potential. A diagram of the potentiostat and the sensor is shown below (figure 2.1). The amplifier (U2) converts the current from the working electrode (WE) current (signal) to a voltage. The working electrode voltage is maintained at the bias potential (Vbias) by the circuit. The potential at the reference electrode (RE) is compared to the stable input voltage, Vbias. The counter electrode (CE) voltage is generated by the op-amp U1 and is enough to give a current equal and opposite to that of the working electrode. Simultaneously, a constant voltage is maintained between the working and the reference electrodes. A chemically selective filter is also fitted in the CO sensor and any gas that may cause interference before they reach the working electrode. This enables the sensor to have minimal response to gases that may interfere. (https://www.coleparmer.com).

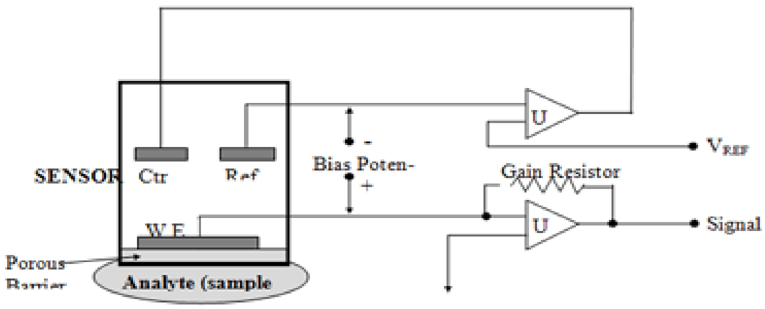


Figure 2.3: Schematic of Electrochemical Sensor and Circuit

2.5 FUELS USED IN COOKING

About 3 billion people in the developing world use biomass fuels for their household energy sources. This accounts for about 10% of all human energy use and 78% of renewable energy supply. Biomass fuels include charcoal, firewood and dung (Granderson *et al*. 2009; Jetter and Kariher 2009). There is an increased shift from biomass to fuels like LPG, Kerosene and electricity. This fact notwithstanding, it is predicted that the number of the population using biomass will still increase over the next four decades (Barnes *et al*. 1994; International Energy Agency 2006; Legros *et al*. 2009). Biomass use for cooking purposes results in high levels of indoor pollution. These emissions have a direct impact on aspects of development, including human health, climate change, natural resource use and household economy.

Several studies show the relationship between biomass burning and human health. There exists a link between biomass indoor pollution and the deaths of more than 1.6 million people yearly. These emissions also cause pulmonary diseases, which represents about 2% of the global burden of disease (Smith-Sivertsen *et al*. 2009; Northcross *et al*. 2010). Additionally, recent studies have linked biomass cook stoves to global warming. Biomass cook stoves emit other products of incomplete combustion, such as methane, nitrous oxide, nonmethane hydrocarbons and oxides of nitrogen, organic carbon particulate matter, organic matter, and black carbon (McCarty *et al*. 2008). Black carbon (BC) is the second contributor to high global temperatures after CO_2.

2.5.1 Liquefied Petroleum Gas (LPG)

Liquefied Petroleum Gas (LPG) is a blend of short chain hydrocarbon compounds. It majorly consists of butane (C_4H_{10}) or propane (C_3H_8) or a mixture of both. At room temperature, both gases are odourless and colourless. LPG in domestic cooking cylinders contains more butane than propane. This is because the fuel value per kilogram of butane is higher than propane. The specific calorific value of LPG is around 45 MJ/kg or 12.68 kWh/kg depending on the LPG composition. Comparatively, wood has an energy content in the range of 14-18 MJ/kg or 3.89 - 5 kWh/kg (depending of the moisture content and type of wood) and charcoal in the range of 27 - 33 MJ/kg or 7.5 - 8.34 kWh/kg (depending on the type of charcoal). If used as a cooking energy fuel, LPG could help check the over reliance on the use of biomass and wood in developing countries. (www.energypedia.info).

2.5.2 Ethanol

Ethanol (C_2H_5OH) is a clear liquid that is mainly distilled from starch. The starch is first converted into sugar, or sugar-containing biomass feedstock. Bio-ethanol feedstock can be categorized into three major groups: starch crops (potatoes, cassava, sweet potatoes, wheat and rice), sugar crops (sugar beet, sorghum and sugarcane) and Ligno-cellulosic. There however a challenge of balancing between using these food crops for ethanol production and consuming them as food. It also requires setting up huge farm lands in order to get enough raw materials.

Ethanol burns with a slow, steady flame. It should be stored in closed containers due to its combustible nature and also due to the high possibility of evaporation. Ethanol is one of the cleanest burning fuel compared to charcoal and firewood. Burning cleanly means it burns with less carbon monoxide and particulate matter emissions. It is slowly but steadily gaining acceptance in Kenyan urban households. The calorific value of gel fuel by manufacturers is 22.8 MJ/kg.

Although ethanol and ethanol based gel fuels can offer a clean and efficient fuel source for households, it might be difficult to set-up a reliable supply for ethanol and gel fuel and to encourage rural households, which rely upon cheap or free gathered fuelwood for cooking to switch to using ethanol as cooking fuel.

2.5.3 Kerosene

Kerosene use for cooking is common developing countries, particularly in urban households. This is because biomass is bulky and is not readily available in urban areas. Also there are restrictions on the use of firewood and charcoal in most urban residential areas. On the other hand LPG and electricity and are unreliable or expensive. Kerosene is usually transported in bulk, with rural areas purchasing kerosene by litre or bottle. There are a limited number of studies that give details of the quantity of kerosene used for cooking or lighting. Portable kerosene stoves are commonly used for cooking with kerosene. The Primus stoves invented in 1892 or the wick-stove is the most commonly used. Figure 5.3 A below shows the Primus Stove while figure 5.3 B shows a wick stove.

A. Primus Stove (image source:alamy.com**)** **B. Wick Stove** (image source: www.sky.garden)

Figure 2.4: A. Primus Stove and B. Wick Stove

Advantages of cooking with kerosene include:

i. Cooks fast when used in ideal (pressurized) stoves.

ii. Fuel storage is easy.

iii. It can be purchased in small affordable quantities especially for low income families.

iv. It is an alternative source of cooking energy for urban electricity users.

v. It is an alternative where access to free biomass for cooking is a challenge.

Kerosene also comes with several disadvantages and these include:

i. It is a non-renewable resource.

ii. Kerosene can produce high levels of pollutants when used in cheap wick stoves. This contributes to indoor air pollution.

iii. Kerosene has an unpleasant smell compared to LPG and biomass.

iv. Due to its high flammability, poor handling of kerosene can cause serious accidents.

The WHO discourages the use of kerosene in households because of poisoning, the high risk of burns and deaths. Cheap wick stoves can have high levels of smoke emissions, which can cause health problems to the users and those exposed. The emissions include different compounds, which can be categorized into carbon monoxide, particulate matter, polycyclic aromatic hydrocarbons, formaldehyde, nitrogen oxides and sulfur. Kerosene is at times looked at as the clean alternative to biomass cooking fuels. There is however a lack of enough studies that examine health effects of PM-composition and exposure concentrations to verify this assumption. There is an increase need to shift from biomass to with less smoke emissions and more efficient liquid fuels and LPG. The latter are however expensive and out of reach for many households.

2.5.4 Water Boiling Test (WBT)

Water Boiling Test (WBT) is a simplified simulation of the cooking process. The main aim of WBT is to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced during the cooking process.

2.5.5 Benefits and Limitations of Water Boiling Test

The Water Boiling Test (WBT) for efficiency can be performed anywhere in the world with simple and affordable equipment. Its key benefits are:

- Provide laboratory or initial assessments of stove performance in a controlled set up
- It is easy to compare the performance of different cook stove designs
- It makes it possible to evaluate cook stoves changes at different stages of development
- The WBT makes it possible to select the most promising products for field trials
- It ensures that different cook stove designs meet the intended performance based on tests.

Controlled tests are key to comparing various technical aspects of cook stove designs and evaluations of performance before they can reach the end user. While laboratory based tests allow differentiation between stoves, field-based tests give better indication of performance during actual use.

The Water Boiling Test was developed to assess stove performance in a controlled manner. Although the WBT is a useful tool, it’s important to consider its limitations. It is a simulation of the cooking process and it is conducted in controlled conditions by trained technicians. Laboratory test results might differ from those obtained when cooking real foods, even if efficiency and emissions were measured in the same way for both tests. In order to confirm desired impacts (whether it is smoke or particulate matter reduction, fuel conservation, or other impacts), stoves should be tested under real conditions of use.

CHAPTER 3 : METHODOLOGY

3.1 INTRODUCTION

The Water Boiling Tests, emissions tests (carbon monoxide, carbon dioxide and smoke ($PM_{2.5}$)) for each stove were carried out at the University of Nairobi, Department of Chemistry Laboratories.

3.2 Water Boiling Tests

These tests were carried out according to Water Boiling Test (WBT) version 4.2.2 Methodology. Calculation for variable such as thermal efficiency (%), time taken to boil water in minutes, amount of fuel consumed in grams, specific fuel consumption (g/liter) and burning rate (g/min) was done. A sample excel sheet for WBT is given in Appendix 1. The materials and apparatus used are listed below:

3.3 MATERIALS AND APPARATUS

1. EL – USB Carbon Monoxide Data logger. It was used for Carbon Monoxide monitoring. The Carbon Monoxide was monitored in real time.
2. Thermocouple Thermometer. It was used for the determination of temperature at various stages of the test.
3. Wood Moisture Meter. It was used for determining the moisture of firewood used during the test.
4. Particulate Data logger from the Berkley Air Monitoring Group ($PM_{2.5}$). It was used to determine the concentration of $PM_{2.5}$ during the test.
5. Electronic Kitchen Scale Model EK3752 (Max weight - 5Kg/11lb). It was used to weigh the firewood, charcoal and water during the test.

6. Firewood. It was the main fuel used during the test.
7. Axe and a Sharp Panga that were used to reduce the size of firewood for efficient combustion.
8. 25 Litres of Clean Water. The water was the main component of the test and was boiled during the test.
9. Medium sized Standard Aluminum Pots. They were used to hold the water during the water boiling test.
10. Heat Resistant Pad. It was used for protecting the weighing scale against excessive heat.
11. Shovel. It was used to remove the hot charcoal or firewood after the tests.
12. Dust Pan. It was used to clean and remove ash and unburnt firewood and charcoal from the cook stove.
13. Heat Resistant Gloves. They were used to hold the hot cooking pot and protect the hands from excessive heat.
14. Metal Tray that was used for holding the firewood and charcoal during weighing.
15. A Matchbox. It was used for lighting the cook stove.
16. A Digital Camera that was used in taking and storing of photographs during the test.
17. A digital Timer. It was used to determine various parameters of time during the test.
18. Laptop Computer. It was used to store the data results realized from the test. It stored the data in a WBT spreadsheet.

3.3.1 Emission Tests

The emission tests were carried out in a typical kitchen environment where real time concentrations of carbon dioxide (CO_2), carbon monoxide (CO) and particulate matter ($PM_{2.5}$) measurements were monitored.

3.3.2 Kitchen Dimensions

The kitchen dimensions were as follows: -

Height-8.3ft -width-9.5ft -length -11.3ft

Windows: - w1-height-2.2ft; -width-2.8ft; w2-height-2.8ft -width-2.1ft

Doors: - d1-height-6.6ft -width-2.92ft; d2-height-6.6ft-width-4.8ft

The figure below shows kitchen set up during the tests:

Figure 3.1 below shows the Carbon Monoxide (CO), Carbon Dioxide and Particulate Matter (PM_2) monitors mounted on the wall. They were protected and held in a fixed position by an improvised wire mesh that allowed free flow of air. Figure 3.2 below shows the mounted thermometer sensor placed in the cooking pot and the data display window mounted on the wall of the kitchen. Figure 3.3 above shows the lit cook stove placed near a window and next to monitoring sensors according to the guidelines. Figure 3.4 shows the entire Water Boiling Point testing set up as the testing is progressing. The monitoring sensors are discussed in details in section 3.5.

Figure 3.1: CO, CO_2 and PM_2 Monitoring Sensors

Figure 3.2: Cooking Pot, Cook Stove and Thermometer

Figure 3.3: Cook Stove Set Up

Figure 3.4: Water Boiling Test Set Up

3.4 SAMPLE IDENTIFICATION AND COLLECTION

The cook stoves for the tests were identified as those found in the Kenyan market. They comprised of those imported into the market, those locally designed and manufactured and the prototypes that were at the development or design stages. They were further categorized as charcoal, firewood, multipurpose and traditional cook stoves. Table 3.1 below shows the distribution of the cook stoves under these categories:

Table 3.1: Distribution of Sampled Cook Stoves

	Charcoal	**Firewood**	**Multipurpose**	**Liquid**	**Traditional**	**Totals**
Local Cook stoves	15	21	12	2	5	**55**
Imported Cook Stoves	9	8	0	4	0	**21**
Total	24	29	12	6	5	**76**

The cook stoves were labeled before testing. The labeling was done according to the fuel type and whether they were local or imported. The coding and labelling was done and the cook stoves abbreviated as follows:

1. **CL** for locally manufactured charcoal cook stoves
2. **MPF** for multipurpose firewood cook stoves
3. **MPC** for Multipurpose charcoal cook stoves
4. **FL** for local firewood cook stoves
5. **CI** for imported charcoal cook stoves
6. **FI** for imported firewood cook stoves.
7. **L** for liquid fuel cook stoves.

All the cook stoves codes and label designations were recorded in Appendix 2. Each cook stove was assigned a unique code number that differentiated each of them. The total number of tested cook stoves was 76.

3.5 COOK STOVE EMISSIONS EVALUATION INSTRUMENTS

3.5.1 Carbon monoxide (CO) monitoring

Carbon Monoxide levels in the Households were determined using EL-USB-CO Carbon Monoxide (CO) Data Logger with a USB Interface. It was mounted on the wall enclosed in a wire mesh that would allow for free flow of air. The logger records ambient carbon monoxide levels in parts per million (PPM) and has the following specifications:

- 0 to 1000 PPM CO Measurement Range
- Storage capacity of up to 32,510 Measurements
- SB Interface for Set-up and Data Download
- Expected sensor life was 4 years
- Internal Lithium Battery

Figure 3.5 below shows EL-USB-CO data logger:

Figure 3.5: EL-USB-CO Data Logger

3.5.2 Carbon dioxide (CO_2) and Temperature Monitoring

The Levels of Carbon Dioxide were monitored using the Telaire 7001 Carbon Dioxide Monitor (shown in figure 3.6 below). It was mounted on the wall together with other sensors and the real time CO_2 levels determined. The monitor had the following features and specifications:

- Monitor Temperature and Carbon Dioxide Readings
- Provides a 0 to 4 Volt Output
- 0 to 10,000 ppm Carbon Dioxide Measurement on Display
- 0-2,499 ppm Carbon Dioxide Measurement Output
- Available as a Kit with Data Logger

Figure 3.6: Telaire 7001 Carbon Dioxide Monitor

CO_2 data was analyzed by taking the maximum and minimum values of each household. Real time temperature analysis was conducted using the Telaire 7001 Monitor and its designated Hoboware. Maximum, minimum averages and standard deviations for each household were recorded. For temperature monitoring the Telaire 7001 Monitor has the following specifications:

- Operating range: (0°C to 50°C), 0 to 95% RH, non-condensing.
- Display resolution: ±1 ppm.

- Repeatability: ±20 ppm.
- Accuracy: ±50 ppm or 5% of reading.

3.5.3 Particulate Matter $PM_{2.5}$

The particulate matter ($PM_{2.5}$) particles were monitored with UCB Particle and Temperature Sensor (UCB-PATs).

Figure 3.7: UCB-PATS Data Logger

UCB data logger, shown in figure 3.7 above has a detection limit of between 30- 25,000 $\mu g/m^3$, a logging interval of between 1-240 minutes and a storage capacity of 32768 records.

3.5.4 Moisture Meter

The moisture meter shown in figure 3.8 below was used to determine the moisture content of the firewood and charcoal before they were used. It has the following features:

- Reading depth: 5/16"
- Low end reading range: 5 to 12%
- Moderate range: 5 to 17%
- Saturated range: Above 17%

Figure 3.8: Moisture Meter

3.5.5 Weighing Balance

The weighing balance, shown in figure 3.9 below was used to measure the weight of firewood, charcoal and water during the water boiling test. Table 3.5 shows the weighing balance features and specifications. The weighing balance was protected from excessive heat by a heat resistant pad.

Figure 3.9: Weighing Balance

Table 3.5: Weighing Balance Specifications

Capacity	30 kg
Accuracy	0.005kg
Display	Big easy readable red LED display
Power	6V, 300mA rechargeable battery
Operating Temperature	-10 °C to +50 °C
Optional	RS - 232 Connection; MS checkered top plate

3.5.6 Carbon Monoxide and Carbon Dioxide Monitoring

Ambient $PM_{2.5}$, CO_2 and CO emission concentrations were measured 1 meter away and 1.5 meters above the stove. Real-time measurements of CO and CO_2 were taken using a TSI IAQ-CALC 7545 (TSI Inc., The TSI IAQ-CALCs were calibrated immediately before deployment with NIST traceable zero and span gases, and again following deployment to check for any potential changes in response.

The reported values were average for each of the three phases: cold start, hot start and simmering phases (Appendix 1).

3.5.7 Particulate Matter

The particulate matter ($PM_{2.5}$), are particles that are suspended in the air and have an aerodynamic diameter not exceeding 2.5 micrometers. These particles were monitored using a UCB Particle and Temperature Sensor (UCB-PATs). This data logger has a detection limit of between 30- 25,000 μg/m^3, a logging interval of between 1-240 minutes and a storage capacity of 32768 records. The results are shown in Appendix 1.

The values reported were average concentrations for each of the three phase: Cold start, hot start and simmering phases.

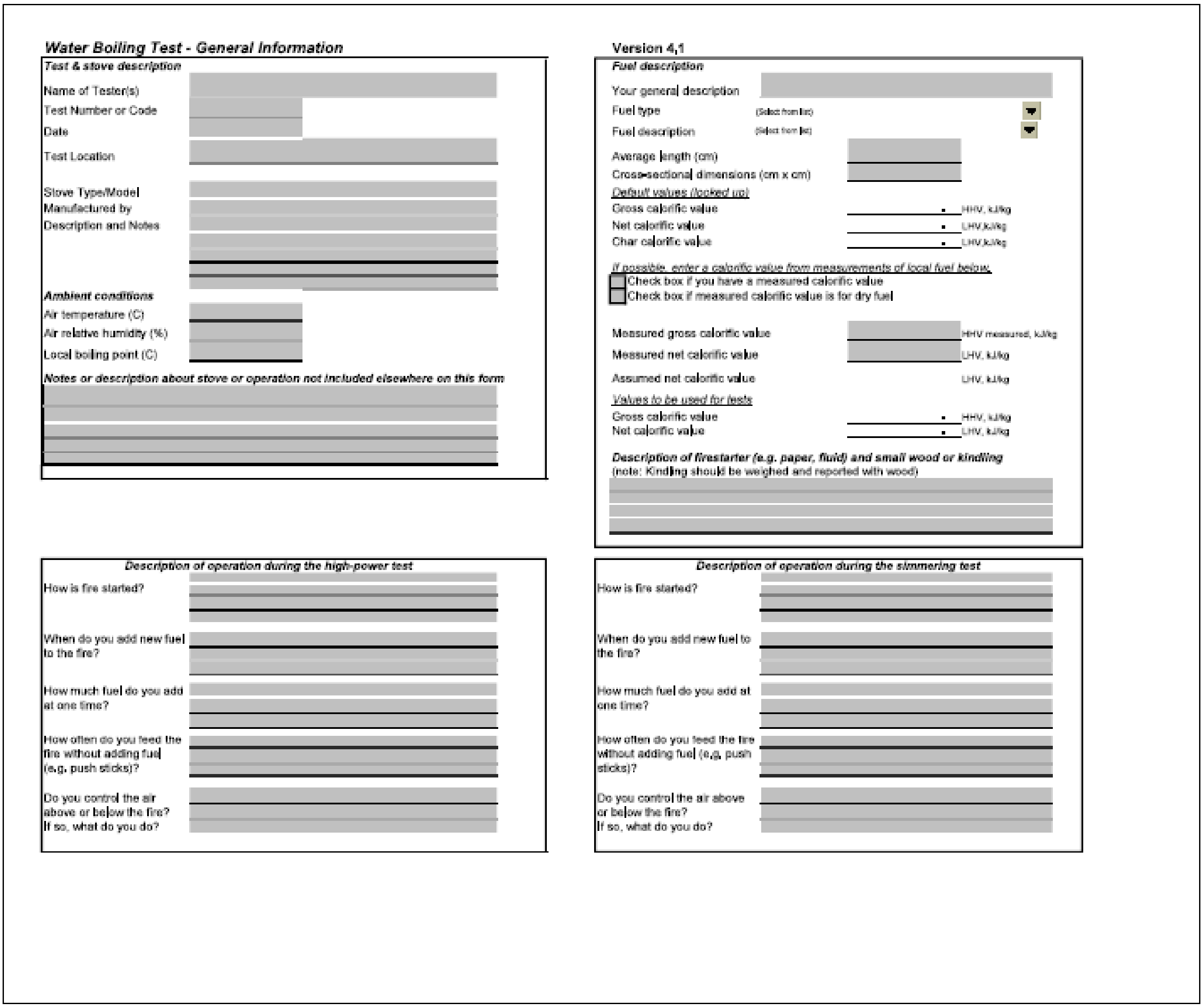
3.5.8 Fuels used in the tests

The fuels used were procured locally; Firewood was mainly eucalyptus from vendors; charcoal from charcoal vendors within the Nairobi environs; kerosene was procured from the petrol stations; ethanol procured from East Africa Spectra and gelled ethanol from supermarkets.

3.5.9 WATER BOILING TEST (WBT) (Version 4.1.2)

Water Boiling Test (WBT) simulates the normal cooking process and is intended to help stove designers have an understanding of how energy transfer from the fuel to the cooking pot takes place. It is designed to be a simple method by which stoves that are made for different cooking uses and manufactured in different locations can be compared using a replicable, standardized test.

The water boiling test (WBTs) key strength is its replicability and simplicity. Additionally, it gives an initial stove performance understanding. This helps in the design process. It has also been shown that fuel use for different cooking tasks can be predicted by knowing the thermal efficiency at low and high power, as in the case of this version of WBT. The template for the data input spreadsheet is shown in figure 3.10 below. The template shows the general information of the test, describing the conditions under which the tests were carried. It also shows the description of the operations carried out during each phase of the tests.



Water Boiling Test - General Information

Test & stove description
Name of Tester(s)
Test Number or Code
Date
Test Location
Stove Type/Model
Manufactured by
Description and Notes

Ambient conditions
Air temperature (C)
Air relative humidity (%)
Local boiling point (C)

Notes or description about stove or operation not included elsewhere on this form

Version 4,1

Fuel description
Your general description
Fuel type (Select from list)
Fuel description (Select from list)
Average length (cm)
Cross-sectional dimensions (cm x cm)
Default values (locked up)
Gross calorific value HHV, kJ/kg
Net calorific value LHV, kJ/kg
Char calorific value LHV, kJ/kg

If possible, enter a calorific value from measurements of local fuel below.
Check box if you have a measured calorific value
Check box if measured calorific value is for dry fuel

Measured gross calorific value HHV measured, kJ/kg
Measured net calorific value LHV, kJ/kg
Assumed net calorific value LHV, kJ/kg
Values to be used for tests
Gross calorific value HHV, kJ/kg
Net calorific value LHV, kJ/kg

Description of firestarter (e.g. paper, fluid) and small wood or kindling
(note: Kindling should be weighed and reported with wood)

Description of operation during the high-power test
How is fire started?
When do you add new fuel to the fire?
How much fuel do you add at one time?
How often do you feed the fire without adding fuel (e.g. push sticks)?
Do you control the air above or below the fire? If so, what do you do?

Description of operation during the simmering test
How is fire started?
When do you add new fuel to the fire?
How much fuel do you add at one time?
How often do you feed the fire without adding fuel (e.g. push sticks)?
Do you control the air above or below the fire? If so, what do you do?

Figure 3.10: WBT Data Input Template

The test has three concurrent phases. In the **first phase**, the **cold-start high-power test**, the testing starts at room temperature. It uses a bundle of firewood with a known weight or alternative fuel of interest to boil a pre-weighed amount of water in a cooking pot. Shortly after, the boiled water is replaced with another pot of cold water for the second phase of the test.

The **second phase** or the **hot-start high-power test**, is carried out immediately after the first test whilst the stove is still hot. Once more, a pre-weighed fuel is used to boil a known amount of water in a pot. Carrying out the test again with a hot stove helps the tester to determine the difference in performance when a stove is hot and when it is cold.

The **third phase** is carried out immediately after the second. In this phase, the aim is to determine the amount of fuel that is required to simmer a known quantity of water at slightly below boiling for about 45 minutes. This phase mimics the long time taken to cook pulses or legumes common in many countries. These tests combine help determine some aspects of the stoves' performance at low and high power outputs.

3.6 TESTS PROCEDURE

The following preliminary steps were carried out before actual tests on the stoves began;

1. Sufficient water and wood fuel (firewood) were first collected with all of the firewood being obtained from the same source. Kindling used to start the fire were prepared and included in the pre-weighed bundles.
2. Two practice tests on each stove were performed so as to familiarize with the specific characteristic of each stove and the testing procedure. This helped in the handling of the stoves during the actual tests. The local boiling point of water was determined using these tests.
3. A standard pot size to be used during the tests was chosen. A medium sized one was selected. Enough time and space to carry out the tests without disturbance was settled upon. The testing was carried out inside a room that had enough ventilation to get rid of the harmful emissions done indoors. The room was also protected from wind.
4. Actual testing procedures then began with the following initial steps:
5. The initial page of the Data Calculation Form was duly filled. This did include information about the stove under assessment, test conditions and fuel used. Each series of test was sequentially serialized for future reference.
6. The two Data Loggers (particulate and CO) were configured using a laptop computer. This involved setting warning levels as well as time intervals the loggers should use to record the readings.
7. Each of the following parameters were then measured and recorded on each of the series of tests on the Data Calculation Forms:

a. Air Temperature.
b. Wood Average Dimensions (height x length x width). Wood of similar size and optimal size for the stoves were used to reduce variations in test conditions.
c. Wood moisture content. This was measured using the Wood Moisture Meter provided. Three pieces of wood were sampled and used for this determination.
d. Dry weight of the standard pot selected for use without lid (Lids are not to be used on any phase of the WBT).
e. Weight of charcoal container.
f. A Digital Thermometer and a sensor were used to determine the local water boiling point.

8. Two bundles of wood fuel were prepared and weighed; one bundle for each of the two phases of the tests.

Once the above initial steps were conducted and all the measured parameters recorded, the tests proceeded as follows:

3.6.1 Phase 1: High Power

The timer was prepared and only started when the fire had started.

The pot was filled with 2.5kgs of clean water at room temperature. The water amount was measured by placing the empty pot on a weighing scale. Water then was poured into the pot until the combined weights of the water and the pot was 2.5 kg more than the weight of the empty pot.

Using a wooden fixture, the thermometer was placed on the pot to enable the water temperature be determined from the middle, 5 cm above the bottom of the pot. The initial temperature of the water was recorded.

Fire was then started on the stove at room temperature in a way similar to common kitchen practices. When the fire was consistent, the timer was switched on and the starting time noted down. The fire was controlled using ways commonly used locally to make the water boil without wasting fuel.

Once the water reached a known local boiling temperature, the following was quickly done:

1. The time that the water took to reach the local boiling temperature was noted and recorded.
2. The wood which was in the stove was then removed and extinguished. The charcoal that was loose was struck from wood and put in the container for weighing charcoal.
3. The wood that was unburnt was removed and together with wood from the pre-weighed bundle weighed and recorded. The pot was then weighed together with water and result recorded.
4. The charcoal that remained from the stove was removed and put together with the charcoal that was knocked off the wood. They were weighed together and result recorded.

This, did complete the high power phase. The next phase began immediately while the stove was hot.

3.6.2 Phase 2: High Power (Hot Start)

The timer reset and was started only when the fire was consistent.

Once again the pot was filled with 2.5kgs of cold water that was fresh. The pot was weighed together with the water and initial temperature determined. Both of these measurements were recorded.

The fire was once more lit using wood and kindling from the second pre-weighed bundle earmarked for the test in this phase. The start time was noted. The fire controlled in a similar way to previous phase. The time that it took the pot to reach local boiling point was noted and recorded.

The following was done quickly after the boiling temperature was reached:

1. The unburned wood from the stove was removed. The loose charcoal was knocked off but maintained within the area of combustion (charcoal weighing at this stage was not required).
2. The removed wood from the stove and the wood that was not used from the previously weighed bundle were weighed. The pot with the water in was then weighed and immediately placed on the stove. These results were recorded.

The wood that was removed from the fire was replaced and relit immediately to proceed to the next phase.

3.6.3 Phase 3: Low Power (Simmering)

The timer was reset and the thermometer replaced on the pot. The fire was then adjusted to maintain the water as close to 3°C below the established boiling temperature. The test could not be valid if the pot temperature went 6°C below the established local boiling temperature.

The fire was maintained for 30 minutes after which the following was rapidly done:

1. The finish time was recorded.

2. All the wood was removed and charcoal knocked off and placed in the charcoal container. The wood that remained was then weighed together with the unused wood from the pre-weighed bundle.
3. The final water temperature was recorded. The pot was then weighed together with the water that remained. The result was noted and recorded.
4. All the charcoal that remained from the stove was removed and weighed together with charcoal knocked from the sticks. The weights of the pan and that of the charcoal was recorded.

This completed the Water Boiling Test. The results were inputted into the Data Calculation Software. The required output was obtained. The particulate matter and CO emissions data was downloaded from the data loggers and the results stored in a laptop computer.

CHAPTER 4 : RESULTS AND DISCUSSION

4.1 COOK STOVES

The cook stoves investigated were categorized as wood fuel (firewood, charcoal) and liquid fuel stoves. However, they are further categorized as Multipurpose (wood and charcoal) cook stoves, imported charcoal cook stoves, imported firewood cook stoves and traditional cook stoves. The results of all tested cook stoves are shown in table 3.1 and the codes in Appendix 2.

4.2 WBT AND EMISSION RESULTS

The summary of parameters measured during Water Boiling Test and emissions data results for all the stoves investigated were as listed below. The fuels used in the test included solid fuels (firewood and charcoal) and liquid fuels used were ethanol, gelled ethanol and kerosene.

Solid fuels (Firewood and charcoal)

a. Thermal efficiency,

b. Time taken to boil water,

c. Burning rate,

d. Specific fuel consumption,

e. Fuel Consumption,

f. Carbon monoxide

g. Particulate matter ($PM_{2.5}$)

h. Carbon dioxide.

A summary of thermal efficiencies of all the stoves (Charcoal –red, firewood-green and liquid =yellow) data are summarized as shown Figure 4.1 below:

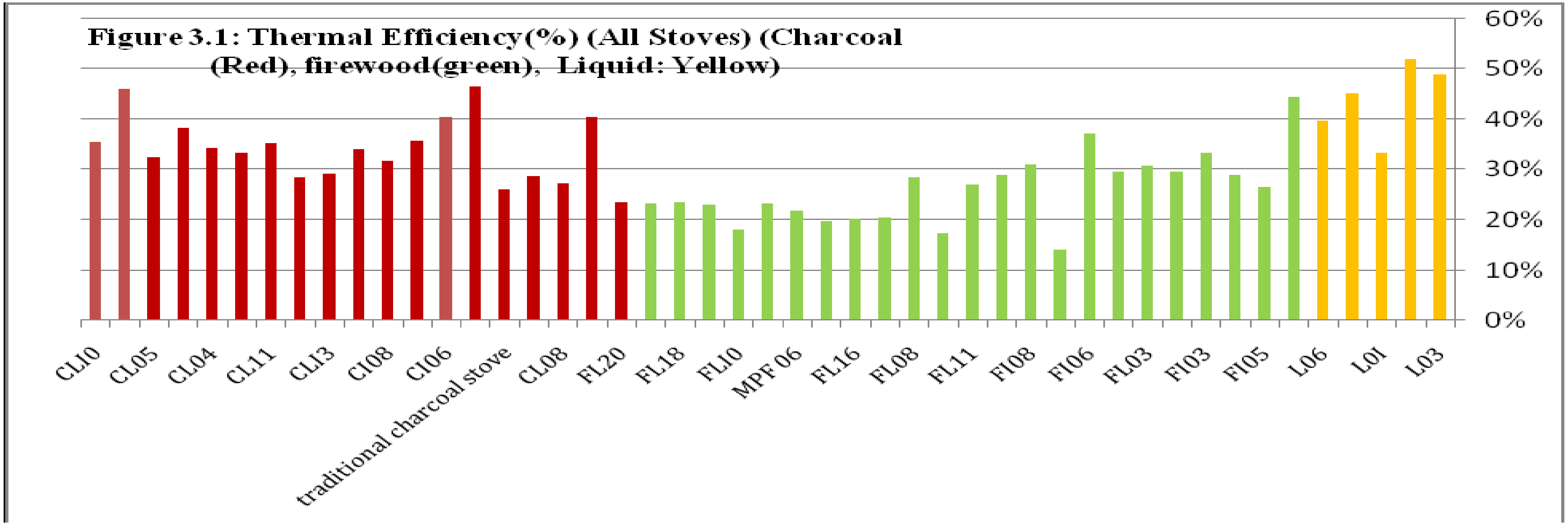


Figure 4.1: A summary of thermal efficiencies of all the stoves

4.3 FIREWOOD STOVES

4.3.1 Thermal Efficiencies

The distribution of thermal efficiencies for firewood stoves are summarized in Table 4.1. The thermal efficiencies for the firewood stoves ranged between 13 - 37% (Local stoves ranged between 17-31% while the imported stoves showed improved efficiencies compared to the local stoves ranging between 27-37%).

A stoves' efficiency is determined by several factors: the type of design of stove which will include the burning surface area, quality of insulation materials and those of the liners, the size of the door as well as the overall weight of the stove among others. The major distinction between the local and imported stoves is the liners. The bulk of the local stoves are made out of clay - liners which are heavy and are not necessarily insulating materials used in their construction. As a result of this, the stoves therefore tend to have a large thermal mass which acts as heat sink. On the other hand, the imported stoves are built of relatively lightweight insulating materials and some fitted with metallic inserts. The metal parts are expensive and add to the cost of the stove. Some stove manufacturers are therefore faced with the challenge of improving the efficiency of the stoves in order to attract carbon credit from companies which sets thermal efficiency of firewood stoves at a minimum efficiency of 25±5. A compromise is required between the material's thermal mass and the durability. Fillers made of organic material like vermiculite, sawdust or charcoal can improve their insulating characteristics when mixed with clay. The organic material burns away at the time of firing of the liners. This leaves air spaces that act like insulators in the liner made of clay. In addition to making the liner lighter, the filler also makes it weaker. In this regard a compromise exists.

Table 4.1: Distribution of Cook Stoves' Thermal Efficiency (%)

Thermal efficiency (%)	Firewood Cook Stoves (%)		
	(17-27)%	(28-31)%	(32-37)%
Local Cook Stoves	86	14	0
Imported Cook Stoves	13	63	25

4.3.2 Carbon Monoxide.

The ambient CO levels for the all the firewood stoves are shown in table 4.2. The Ambient CO concentration levels ranged between 4-47 ppm (Local stoves having a range between 4-25 ppm while the imported stoves showed ranged between 13-47 ppm. The CO being a product of incomplete combustion therefore, the higher levels of CO levels emitted by the stove gives a measure of incomplete combustion taking place inside the stove. CO emissions from liquids were found to average at 0ppm. This was due to the fuels burning more efficiently.

Figure 4.2: Distribution of stoves' ambient CO emissions by firewood stove type

	Firewood Cook Stoves (%)		
CO(ppm)	4-10	11-20	21-48
Local	50	29	21
Imported (N8)	0	25	75

Comparisons of ambient carbon monoxide (CO) concentration levels between imported and local cook stoves are presented in figure 4.2. The differences in CO levels could be due to differences in design of the stove. Carbon monoxide being a product of incomplete combustion the result could be explained by the fact that the combustion chamber has limited supply of air and therefore, more CO forms due incomplete combustion processes as a result of inadequate supply of oxygen to completely burn CO to CO_2. The imported stove designs have tendency to produce more CO than the locally manufactured stoves due to the limited supply of air into the combustion chamber.

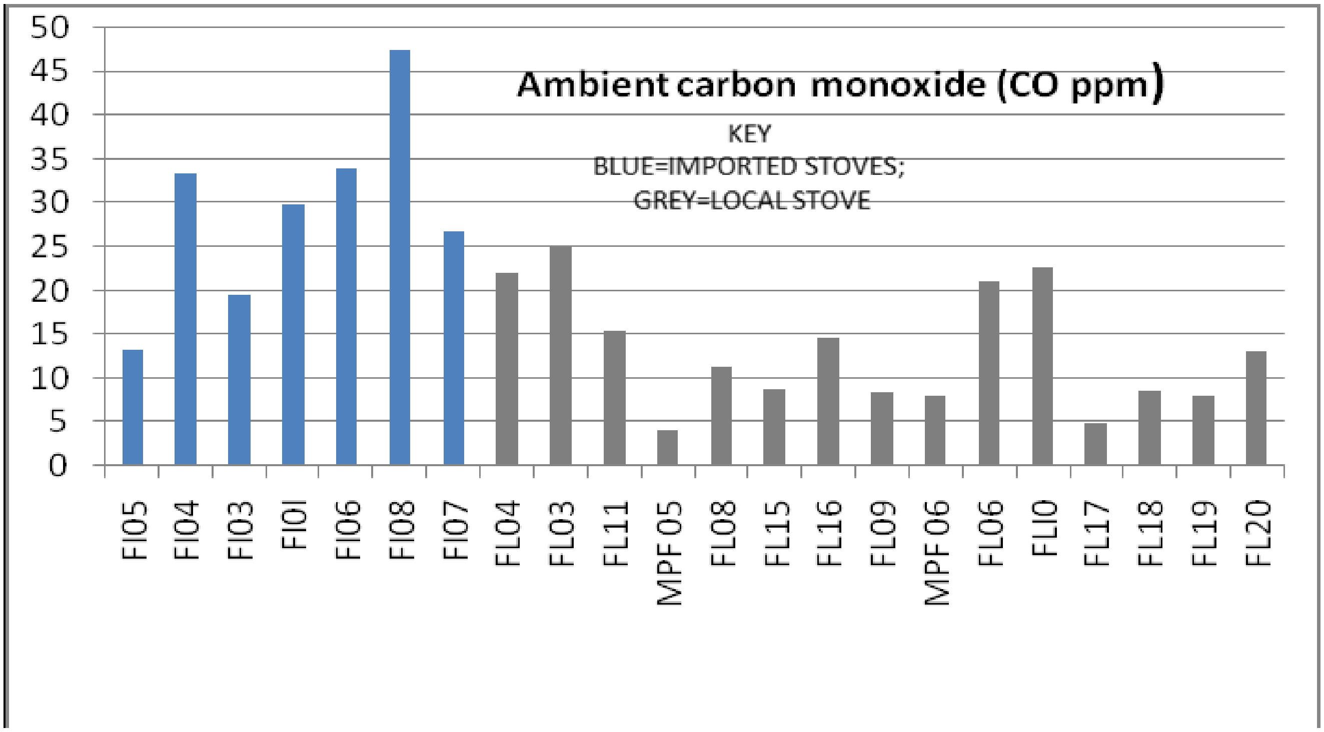


Figure 4.3: CO average ambient concentrations of stoves during the WBT.

The WHO indoor standards for exposure are given in the table 4.2 below shows that most of the stoves emitted CO beyond the recommended guidelines of 1 hour set at 30.6 ppm. Given that cooking proceeds one hour it means the stove users need to be sensitized about the danger of CO exposure. Moreover, the users should be advised to use the stoves in well ventilated environment.

Table 4.2: WHO Indoor Air: Carbon Monoxide and Particulate Matter Guidelines

Carbon Monoxide (CO)		Particulate Matter (PM)		
Averaging time	Concentration (mg/m^3)/(ppm)	Range	Averaging time	Concentration ($\mu g/m^3$)
15 minutes	100(87.3)	$PM_{2.5}$	Annual	10
1 hour	35(30.6)		24-hour mean	25
8 hours	10(8.7)	PM_{10}	Annual	20
24 hours	7(6.1)		24-hour mean	50

4.3.3 Particulate Matter

The ambient particulate matter levels all the firewood stoves ranged between 221-2985 $\mu g/m^3$ (Local stoves having a range between 221-1330$\mu g/m^3$ppm while the imported stoves showed a range between 942-2985$\mu g/m^3$). The particulate matter results from incomplete combustion and therefore, the levels of particulate emitted by the stove gives a measure of extent of combustion taking place in the stove.

The WHO indoor standards for exposure are given in the table 4.2 above shows that most of the stoves emit particulate matter beyond the recommended guidelines for 24-hour set at concentration of 25$\mu g/m^3$. Given that cooking periods exceeded one hour it means the stove users need to be sensitized about the danger of particulate exposure. There is need to advise the stove users to use the stoves in well ventilated environments.

Approximately 3 billion people heat their homes and cook by use of fuels such as dung, coal, charcoal, crop wastes and wood in open fires and cook stoves that are leaky. Most of these people are from poor backgrounds and mainly found in middle and low income nations.

These inefficient technologies have the disadvantage of producing household air pollution levels that are high. They may result in different health-threatening pollutants. These may include small soot particles that find their way deeper in the lungs if inhaled. Where there are poor ventilation settings, indoor smoke may be as much as 100 times above allowable levels for small particles. Women and children are mostly affected by these pollutants because they spend most of the time near the fire places.

4.3.4 Time Taken to Boil Water.

Table 4.4 below shows time taken to boil water in minutes (Min) for the firewood cook stoves. It can be observed that Time Taken to Boil Water ranged from 17-39 minutes with local stoves ranging between 17-37 minutes and imported stoves ranging from 17-39 minutes. However, majority of stoves both imported and local registered times to boil ranging between 19-37 minutes.

Table 4.3: Distribution of Time Taken to Boil Water for Firewood Cook Stoves

Description	Firewood Cook Stoves (%)		
Time Taken to Boil Water (Min)	17-18	19-37	37-39
Local Cook Stoves	14	86	0
Imported Cook Stoves	23	63	13

4.3.5 Burning Rate

Burning rate indicated how much fuel was burnt per minute in the stove. Table 4.4 below shows the distribution of firewood cook stoves' burning rates. The burning rates ranged from 10-30 g/min with local stoves ranging from 10-30g/min and imported stoves ranging from 10-16 g/min.

The difference between the local and imported stoves can be explained by the fact that most imported stoves showed better burning efficiencies compared with local firewood stoves hence the lower burning rates.

Table 4.4: Distribution of Firewood Cook Stoves' Burning Rates

	Firewood Cook Stoves (%)		
Burning Rate (g/min)	10-11	12-16	17-30
Local Cook Stoves	14	71	14
Imported Cook Stoves	38	63	0

4.3.6 Specific Fuel Consumption

Specific fuel consumption is a measure of the quantity of fuel that is required to simmer or boil a litre of water. Table 4.5 below shows the distribution of specific fuel consumption for both the local and imported firewood stoves. Local stoves had values ranging from 87-147g/l while imported stoves had values ranging from 87-127g/l. This difference can also be explained by the improved burning efficiency of imported stoves compared with local stoves.

Table 4.5: Distribution of Firewood Cook Stoves' Specific Fuel Consumption

	Firewood Cook Stoves (%)		
Specific Fuel Consumption(g/l)	87-91	92-127	128-147
Local Cook Stoves	7	51	43
Imported Cook Stoves	25	75	0

4.3.7 Fuel Consumption

Fuel consumption is a measure of the quantity of dry wood fuel consumed during the water boiling test. Table 4.6 below shows the distribution of the fuel consumption for both local and imported firewood cook stoves. The values for fuel consumption ranged between 396-969g. Majority of local cook stoves were in the range of 533-969g (64%) while majority of imported cook stoves fell in the range of 412-532g (75%).

Table 4.6: Distribution of Firewood Cook Stoves' Fuel Consumption

	Firewood Cook Stoves (%)		
Fuel Consumption(g/l)	396-411	412-532	533-969
Local Cook Stoves	7	29	64
Imported Cook Stoves	13	75	13

4.4 CHARCOAL COOK STOVES

4.4.1 Thermal Efficiencies

The thermal efficiencies for the charcoal stoves are shown in table 4.7 below. The efficiencies ranged between 26 and 47%. Local stoves' efficiencies ranged between 26-47%. 42% of the stoves had efficiency below 30% while 50% of them had efficiencies between 30-40% and 8.3% had efficiencies above 40%. As for the imported stoves most of the stoves 83% were found to have efficiencies between 30-40% and while 17% had efficiencies ranging between 32-46%. As was said about the firewood stove, a stove's efficiency is determined by several factors: the type of design of stove, quality of insulation materials and those of the liners, the size of the door as well as the overall weight of the stove among others. The major distinction between the local and imported stoves is the liners. The bulk of the local stoves are made out of clay - liners which are heavy and are not necessarily insulating materials used in their construction.

As a result of this, the stoves therefore tend to have a large thermal mass which acts as heat sink. On the other hand, the imported stoves are built of relatively lightweight insulating materials and some fitted with metallic inserts. The metal parts are expensive and add to the cost of the stove. Some stove manufacturers are therefore faced with the challenge of improving the efficiency of the stoves in order to attract carbon credit from companies which sets thermal efficiency of firewood stoves at a minimum of 35±5. Furthermore, the stoves tested during this study are made by artisan and each stove could vary or lack uniformity. This is because there is no standardization during the process of production. The performance of the stove may not be guaranteed on all the products due to lack of uniformity - highlighting the importance of businesses to incorporate quality control.

Table 4.7: Thermal Efficiencies for Charcoal Cook Stoves

	Firewood Cook Stoves (%)		
Thermal Efficiency (%)	26-32	33-45	46-47
Local Cook Stoves	50	42	8
Imported Cook Stoves	17	67	17

4.4.2 Carbon Monoxide.

The ambient CO levels for the charcoal cook stoves are given in table 4.8 below. The CO levels ranged between 35-96 ppm (Local cook stoves having a range between 35-96 ppm while the imported stoves showed a range between 49-67 ppm. The CO results from incomplete combustion therefore the higher levels of CO levels emitted by the stove give a measure of extent of combustion taking place inside the cook stove.

According to the WHO, 2010 guidelines in table 3.3 charcoal cook stoves exceeds the 1-hour limit of 30.6 ppm and some exceeds the 15 min guidelines set at 87.3 ppm.

The CO results ought to be considered with caution. There is a likelihood that they represent to a very small extent the performance of the stoves for a certain setting, laboratory conditions and task. These results should not be used to ascertain any health effects of the stove.

Several stove programs have mainly focused on fuel use minimization and not ultimately put into consideration the effects of exposure to emissions. Results obtained and shown in this study have improved stoves that show both decrease and increase in emissions exposure compared to traditional methods that they target to replace. This emphasizes the importance of educating the stove users on the dangers of CO.

Table 4.8: Distribution of Charcoal Cook Stoves' Carbon Monoxide Emissions

	Charcoal Cook Stoves (%)		
CO (ppm)	26-32	33-45	46-47
Local Cook Stoves	50	42	8
Imported Cook Stoves	17	67	17

4.4.3 Time Taken to Boil Water

Table 4.9 below shows the distribution of water boiling times in minutes for both local and imported charcoal cook stoves. The boiling time for local stoves ranges between 18-35 minutes with majority of local cook stoves falling in the range of 18-28 minutes (58%). For the imported cook stoves, boiling time ranges between 18-51 minutes with majority of imported cook stoves falling in the range of 35-51 minutes (83%). This observation could be explained by the fact that since more energy is required to boil the water, the local cook stoves used more fuel to bring water to boil at a shorter time than the imported cook stoves. This implies that where the speed of cooking is a more variable than the amount of fuel used, then cooking on local cook stoves becomes a more important characteristic of the stove and vice versa when the amount of fuel (or the cost of the fuel) is an important feature.

Table 4.9: Distribution of Time Taken to Boil Water for Charcoal Cook Stoves

Time taken to Boil Water (min)	18-28	29-35	36-51
Local Cook Stoves (%)	58	42	0
Imported Cook Stoves (%)	17	0	83

4.4.4 Burning Rate

The distribution of the burning rate in grams (g) for both local and imported cook stoves is presented in table 4.10. The burning rate for local stoves ranged between 3-17g/min with majority of local stoves falling in the 6-17g/min range (92%) while that of imported cook stoves ranging between 3-5g/min (100%). This means more charcoal fuel is consumed in local cook stoves compared with imported cook stoves to do the same work.

Table 4.10: Distribution of Burning Rate for Charcoal Cook Stoves

Burning Rate(g/min)	3-5	6-17
Local Cook Stoves	8	92
Imported Cook Stoves	100	0

4.4.5 Specific Fuel Consumption

Table 4.11 shows the distribution of specific fuel consumption in grams per liter for charcoal local and imported stoves. Local stoves fell in the range of 34-108g/l with majority being in the range of 56-108g/l (50%). Imported stoves had specific fuel consumption values ranging from 34-55g/l with majority of them falling in the range of 47-55g/l (83%). This again indicates that local stoves consumed more fuel as compared with imported stoves to boil 1 liter of water. This could be explained by insulation materials used with the local stoves made of massive heat sinking materials. This resulted in the release of little heat into the pot leading to more fuel consumption.

Table 4.11: Distribution of Specific Fuel Combustion in g/l by Cook Stove Type

	Charcoal Cook Stove (%)		
Specific Fuel Consumption (g/l)	34-46	47-55	56-108
Local Cook Stoves	17	33	50
Imported Cook Stoves	17	83	0

4.4.6 Fuel Consumption

Table 4.12 below indicates the distribution of fuel consumption in grams for the local and imported charcoal cook stoves. Local stoves had fuel consumption values ranging between 136-514g with majority of cook stoves falling in the range of 211-514g (50%). Imported models had fuel consumption values ranging between 136-210g with majority of stoves falling in the range of 172-210g (83%). This indicates that local charcoal cook stoves consume more charcoal fuel compared with imported cook stove models.

Table 4.12: Distribution of Fuel Consumption by Charcoal Cook Stove

	Charcoal Cook Stoves (%)		
Fuel Consumption (g)	136-171	172-210	211-514
Local Cook Stoves	17	33	50
Imported Cook Stoves	17	83	0

4.5 TRADITIONAL STOVES

4.5.1 Traditional Charcoal Stove

The burning characteristics and emissions from traditional charcoal stoves are given in table 4.13 below. The charcoal stove has characteristics of high CO emission and low particulate emissions. There is need to inform, educate and sensitize the users the dangers of Carbon Monoxide exposure and the need of using the stoves in a well ventilated environments.

Table 4.13: Burning Characteristics of Traditional Charcoal Cook Stoves

Parameter	Units	Charcoal Cook Stoves
Time Taken to Boil Water	Min	29
Burning Rate	g/min	9
Thermal Efficiency	%	26
Specific Fuel Consumption	g/liter	108
Fuel Consumption	gram	340
Carbon Monoxide (CO)	ppm	76
Particulate Matter	$\mu g/m^3$	1218

4.5.2 Traditional 3-Stone Fire Cook Stove

The burning characteristics and emissions from traditional 3-stone fire stove are given in table 4.14 below. The 3-stone place has characteristics of low Time Taken to Boil Water, relatively low CO emissions and high particulate matter emissions compared to charcoal stove. The Time Taken to Boil Water is one key factor that the makes the user prefer the three stone fire compared to other stoves. However, there is need to inform the users of the dangers of particulate matter exposure and the need for using the stoves in a well-ventilated environments.

Table 4.14: Burning characteristics of Traditional 3-Stone Firewood Cook Stoves

Parameter	Units	Charcoal Cook Stoves
Time Taken to Boil Water	Min	15
Burning Rate	g/min	40
Thermal Efficiency	%	14
Specific Fuel Consumption	g/liter	511
Fuel Consumption	Gram	1981
Carbon Monoxide (CO)	ppm	50
Particulate Matter	$\mu g/m^3$	6265

4.5.3 Institutional Cook Stoves

The burning characteristics of institutional firewood stoves for three phases of tests are shown in table 4.15 below. Phase 1 is the cold start phase, phase 2 is the hot start phase while phase 3 is the simmering phase. The institutional stove used in this work was equipped with a chimney. The ambient concentrations for CO and particulate are lowest during simmering - phase 3. This is expected since very little fuel is added to the stove during this phase. The residual heat from the insulating bricks is used sufficiently during the simmering phase.

Table 4.15: Burning Characteristics of Institutional Firewood Cook Stoves

Parameter	Phase 1	Phase 2	Phase 3
Time Taken to Boil Water (min)	67	35	45
Thermal Efficiency (%)	65	72	43
Specific Fuel Consumption (g/l)	158	126	58
Burning Rate (g)	44	69	23
Carbon Monoxide (CO) (ppm)	20	29	13
Particulate Matter (µg/m^3)	793	1210	553

4.6 LIQUID FUELS

The distribution of parameters measured during WBT is given in table 4.16 below. The Liquid fuels (kerosene, ethanol and gelled ethanol) stoves achieved much higher thermal efficiencies (33 - 52%). This is as a result of the liquid fuels having higher calorific value per unit volume compared to calorific values of solid fuels. Therefore, liquid fuel stoves have generally higher efficiency than those burning solid biomass in this case firewood and charcoal. Additionally, the liquid fuels burn cleaner (they have low CO emissions with very little $PM_{2.5}$ emissions) than stoves burning solid fuels with low emissions of CO (1-14 ppm) and relatively lower particulate (39-93 µg/m^3). Pressurized kerosene is attractive due to shorter time it takes to boil water.

Table 4.16: Distribution of Parameters by Liquids Cook Stoves

Parameter	Units	L03	L04:Pressurized Kerosene	L0I	L05: Kerosene	L06	L02
Time Taken to Boil Water	Min	29	9	50	15	26	22
Burning rate	g/min	3	4	4	3	8	7
Thermal efficiency	%	49	52	33	45	40	45
Specific fuel consumption	g/liter	42	38	91	40	60	65
Fuel Consumption	grams	95	66	116	74	221	195
Carbon Dioxide (CO_2)	ppm	496	583	564	659	552	585
Carbon Monoxide (CO)	ppm	4	11	6	14	1	12
Particulate Matter ($PM_{2.5}$)	$\mu g/m^3$	50	93	54	95	39	44

CHAPTER 5 : CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The Water Boiling Test (WBT) results showed that the imported firewood cook stoves had a higher thermal efficiency than those of local stoves. The imported cook stoves had thermal efficiencies ranging between 27-37% while the local cook stoves had thermal efficiencies ranging between 17-31%. This was because local cook stoves had insulating materials that had a huge thermal mass compared to those of imported cook stoves.

Local cook stoves had Carbon Monoxide (CO) emissions ranging from 4-25ppm. This was lower than that of imported cook stoves that had emissions ranging from 13-47ppm. This was attributed to the design of the imported cook stoves that allowed limited supply of air in the burning chamber.

The imported cook stoves had particulate matter ($PM_{2.5}$) emissions ranging from 942-2985µg/m^3 while the local cook stoves had emissions ranging from 221-1330µg/m^3. This was due to incomplete combustion resulting from limited supply of air getting into the combustion chamber.

For charcoal cook stoves the local cook stoves had thermal efficiencies ranging between 26-47% while the imported cook stoves had efficiencies ranging from 30-46%. This was attributed to the fact that the imported stoves had inner liners that did not absorb and retain heat. On the other hand, the local stoves were made of liner materials like clay that had high thermal mass.

The local cook stoves had carbon monoxide (CO) emissions ranging from 35-96ppm while the imported cook stoves had the same emissions ranging from 49-67ppm. This was due to incomplete combustion taking place in the combustion chambers of the imported cook stoves.

The Three-Stone cook fires had low thermal efficiencies at 14% and high carbon monoxide emissions at 50ppm and particulate matter emissions was an average of 6265µg/m^3. The cooking fire however it took less Time Taken to Boil Water compared to the firewood and charcoal cook stoves.

The Institutional Stove had a high thermal efficiency of an average 62% for the three phases and low carbon monoxide (CO) emissions of 25ppm and particulate matter ($PM_{2.5}$) emissions of 950µg/m^3. The low CO emissions were because the stove was equipped with a chimney.

In summary, the results the imported firewood stoves had better thermal efficiencies than the local stoves. This is because stoves have focused on reducing fuel use and have to a less extent put into consideration the stoves impact on exposure to emissions. The results in this study show cases of improved stoves that decrease and increase emissions exposure compared to traditional cooking methods they look forward to replacing.

More charcoal was consumed in local charcoal stoves compared to that consumed in imported charcoal stoves.

It was also noted that liquid fuels had higher thermal efficiencies the solid fuels (charcoal and firewood). This is because liquid fuels have a higher calorific value per unit volume vis-à-vis the solid fuels. The liquid fuels (ethanol, gelled ethanol and kerosene) burned cleaner (with less emissions) than the charcoal and firewood fuels.

The traditional Three-Stone Fire Stove had low carbon monoxide emissions and high particulate matter emissions compared to charcoal stoves.

The objectives of the study were achieved.

These results were documented and information stored in a database (Appendix 1).

5.2 RECOMMENDATIONS

1. In addition to the WBT, Controlled Cooking Tests (CCT) and Kitchen Performance Tests (KPT) should be carried out. Due to time constraint and limited resources, it was not possible to carry out all the tests. Carrying out these tests will help in understanding the performance of the stoves in real kitchen set ups while carrying out common cooking tasks.
2. There is a need to invest and carry out capacity building activities for local testing centers. This will ensure the expertise and quality is maintained through the use of standardized testing and manufacturing procedures. Making testing facilities available to local stove manufacturers will also create awareness and a better understanding of the performance of the stoves.
3. There is a need for local entrepreneurs' participation in the stoves manufacturing and design discussions and make commitments to improve their stoves performance, to make better cook stove with improved fuel and emissions efficiency. This can be done through workshops and seminars through which sensitization can be carried out.
4. Stove manufacturers many at times make a variety of multipurpose cook stove sizes and designs and that use both charcoal and wood. Each size and design of the stove performs in a different way and a separate analysis is required to make improvements. For this reason, fewer modifications are done if manufacturers only concentrate on one stove design. In turn this reduces the work load in improving the design of the stoves, link to carbon credit and carry out quality control and link to carbon finance.

5. There is a need to sensitize the general public on the need to use cook stoves in well ventilated environments. There is also a need to promote the use of liquid and gaseous fuels that burn more efficiently and with less emissions. This will in turn reduce the number of cases of infections and deaths resulting from indoor air pollution.

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APPENDICES

Appendix 1: Water Boiling Tests – Version 4.2.2 Data Entry Sheets

WATER BOILING TEST - VERSION 4.2.2				**TEST #**			
All cells are linked to data worksheets, no entries are required							
Stove type/model				Prototype -WOOD COOK STOVE			
Location				University Of Nairobi – Chiromo Campus			
Fuel description				FIREWOOD Eucalyptus Grandis (Rose Gum, Grand Eucalyptus)			
Wind conditions				Light breeze; Light breeze; Light breeze			
Ambient temperature				21.9;19.7; 24.5			
1. HIGH POWER TEST (COLD START)	**Units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time Taken to Boil Water Pot #1	min	40	42	37	40	2.5	6.3%
Temp-corrected Time Taken to Boil Water Pot #1	min	45	44	39	43	3.2	7.6%
Burning rate	g/min	14	12	12	13	1.0	8.3%
Thermal efficiency	%	17%	21%	21%	20%	2%	11.3%

Specific fuel consumption	g/liter	148	133	123	135	12.5	9.3%
Temp-corrected specific consumption	g/liter	167	139	130	145	19.2	13.2%
Temp-corrected specific energy cons.	kJ/liter	3,070	2,567	2,388	2675	353.6	13.2%
Firepower	watts	4,216	3,581	3,812	3870	321.2	8.3%
2. HIGH POWER TEST (HOT START)	**units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Time Taken to Boil Water Pot # 1	min	21	24	23	23	1.5	6.7%
Temp-corrected Time Taken to Boil Water Pot # 1	min	24	25	25	25	0.9	3.5%
Burning rate	g/min	17	16	16	16	0.8	5.1%
Thermal efficiency	%	23	24	24	24	1	2.6%
Specific fuel consumption	g/liter	94	100	94	96	3.5	3.6%
Temp-corrected specific consumption	g/liter	106	106	100	104	3.1	3.0%
Temp-corrected specific energy cons.	kJ/liter	1,948	1,948	1,849	1915	57.2	3.0%

Firepower	watts	5,240	4,832	4,783	4952	250.6	5.1%
3. LOW POWER (SIMMER)	**Units**	**Test 1**	**Test 2**	**Test 3**	**Average**	**St Dev**	**COV**
Burning rate	g/min	10	10	10	10	0.4	3.7%
Thermal efficiency	%	24	26	25	25	1	4.4%
Specific fuel consumption	g/liter	155	152	164	157	6.1	3.9%
Temp-corrected specific energy cons.	kJ/liter	2,859	2,804	3,021	2894	113.1	3.9%
Firepower	watts	3,096	2,952	3,180	3076	115.3	3.7%
Turn down ratio	--	1.36	1.21	1.20	1	0.1	7.2%

Appendix 2: Cook Stoves Codes

Local and Imported Charcoal and Firewood Cook Stoves

LOCALLY MANUFACTURED COOK STOVES			
	CHARCOAL COOK STOVES		
COOK STOVE CODE	COOK STOVE	SIZE	MANUFACTURER
CL0I	KCJ-CERAMIC	Small medium large	Keyo, Scode, GVEP, ISAK, Jua kali
CL02	KCJ SCODE	Medium	Scode
CL03	KCJ Ranen	Small	Keyo
CL04	KCJ - Vermiculite & Clay	Medium	Keyo
CL05	KCJ - Sawdust & Clay	Medium	Keyo
CL06	KCJ SCODE(Modified)	Medium	Scode
CL07	KCJ with Skirt	Small	Scode/GVEP
CL08	Keyo Uhai	Medium	Keyo/GVEP
CL09	Traditional metal stove	Various	Various
CLI0	GVEP Rocket Prototype Stove	Medium	GVEP
CL11	GVEP Rocket Prototype - MURANGA	Medium	GVEP
CLI2	GVEP Rocket Prototype - KISUMU	Medium	GVEP
CLI3	GVEP Prototype I	Medium	GVEP
CL14	KCJ Without skirt(2.5 LTRS)	Small	Various
CL 15	Traditional Metal stove (2.5LTRS)	Small	Various

A3.2	MULTIPURPOSE COOK STOVES		
	COOK STOVE	**SIZE**	**MANUFACTURER**
MPF 0I	SCODE Mazingira(wood)	Medium	Scode
MPF 02	SCODE Multipurpose Cook Stove With Pot Skirt(wood)	Medium	Scode
MPF 03	SCODE Multipurpose Cook Stove Without Pot Skirt(wood)	Medium	Scode
MPF 04	Mulitpurpose Cook Stove with Water Jacket(wood)	Medium	
MPF 05	GVEP Prototype 2(wood)	Medium	GVEP
MPF 06	SCODE KM Multipurpose Cook Stove (wood)	Medium	Scode
MPC 0I	SCODE Mazingira Cook Stove (charcoal)	Medium	Scode
MPC 02	SCODE Multipurpose Cook Stove With Pot Skirt(charcoal)	Medium	Scode
MPC 03	SCODE Multipurpose cook Stove Without Pot Skirt(charcoal)	Medium	Scode
MPC 04	Multipurpose Cook Stove with Water Jacket(charcoal)	Medium	
MPC 05	GVEP Prototype 2(charcoal)	Medium	GVEP
MPC 06	SCODE KM	Medium	Scode

	Multipurpose Cook Stove (charcoal)		
A3.3	**FIREWOOD COOK STOVES**		
	COOK STOVE	**SIZE**	**MANUFACTURER**
FL0I	Kuni Mbili	Large	N/A
FL02	Keyo Kuni Mbili	Medium	Keyo
FL03	Jiko Poa- With Skirt	Medium	N/A
FL04	Jiko Poa(red)	Medium	N/A
FL05	Gasifier	Medium	Various
FL06	Baker stove	Medium	Jonathan Baker
FL07	Carbon Zero Stove(CZK)	Medium	Carbon Zero Kenya
FL08	GVEP Rocket wood Stove	Medium	GVEP
FL09	Jiko Chap Chap - Single Pot	Medium	Jonathan Baker
FLI0	Jiko Chap Chap - Double Pot	Medium	Jonathan Baker
FL11	CZKA Stove	Medium	GVEP
FLI2	ISAK STD	Large	ISAK
FLI3	Institutional Stove	Large	GVEP
FL17	Kuni Mbili Stove (7L)	Large	Keyo
FLI4	3 Stone Fire	Various	N/A
FL15	GVEP Rocket wood stove - MURANGA	Medium	GVEP
FL16	GVEP Rocket wood stove - KISUMU	Medium	GVEP
FL17	VC-1(VERMICULITE+CLAY)	Medium	Narumoru
FL18	VC-2(VERMICULITE+CLAY)	Medium	Narumoru
FL19	VC-3(VERMICULITE+CLAY)	Medium	Narumoru

FL20	Carbon Zero Kuni Mbili	Medium	Cameroon

IMPORTED COOK STOVES			
CHARCOAL COOK STOVES			
A 3.4	**COOK STOVE**	**SIZE**	**MANUFACTURER**
	Stove	Size	Country of Origin
CI0I	Uganda Energy Foundation	Small	Uganda
CI02	Rafiki Yetu Jiko	Small	Tanzania
CI03	Burn Stove	Medium	U.S.A
CI04	Envirofit CH 5200	Various	China
CI05	Ecozoom Dura stove	Medium	U.S.A

CI06	Ecozoom Dura(24cm)with ridges	Medium	U.S.A
CI07	Ecozoom Dura(24cm)without ridges	Medium	U.S.A
CI08	Ecozoom Dura(28cm)with ridges	Medium	U.S.A
CI09	Ecozoom Dura(28cm)without ridges	Medium	U.S.A
FIREWOOD COOK STOVES			
FI0I	Ecozoom Dura(old)	Various	U.S.A
FI02	Teri Stove	Various	India
FI03	Enirofit G3300	medium	China
FI04	Enirofit Jiko Tosha G5000	medium	China
FI05	EZY Stove	Medium	China
FI06	Ecozoo Dura with Pot skirt	Medium	U.S.A
FI07	Ecozoom Dura with taller pot rests	Medium	U.S.A
FI08	Ecozoom Dura(new)	Medium	U.S.A

LIQUID FUEL COOK STOVES			
A3.5	**COOK STOVE**	**SIZE**	**MANUFACTURER**
L0I	Moto Poa -Gelled Ethanol Stove	medium	South Africa
L02	Baraka Ethanol Stove	Medium	Kenya
L03	Clean Cook Ethanol Stove	Medium	Sweden
L04	Good Fire pressurized kerosene stove	Medium	U.K.
L05	Kerosene Wick stove	Medium	China and India
L06	Bio Moto Cooker	Medium	Kenya

TRADITIONAL COOK STOVES	
A3.6	**COOK STOVE**
FL14	3-Stone Fire(4ltrs)
CL09	Traditional Metal

	Charcoal Stove
FL14(2.5)	3-Stone Fire(2.5ltrs)
CL 15	Traditional Metal Stove (2.5LTRS)
CL(7L)	Traditional Metal Stove (7LTRS)

Appendix 3: Firewood Cook Stoves Results

FIREWOOD COOK STOVES (IMPORTED AND LOCAL COOK STOVES)																							
Cook Stove type		FI05	FI04	FI03	FIOI	FI06	FI08	FI07	FL04	FL03	FL11	MPF 05	FL08	FL15	FL16	FL09	MPF 06	FL06	FLI0	FL17	FL18	FL19	FL20
Time Taken to Boil Water	Min	39	22	30	17	18	21	20	30	26	29	37	19	32	31	18	28	19	18	31	27	26	27
Burning rate	g/min	10	13	10	16	13	13	13	11	11	11	14	13	13	14	19	15	16	30	13	15	14	16
Thermal efficiency	%	27	29	33	30	37	31	29	30	31	27	17	28	20	20	20	22	23	18	23	24	23	23
Specific fuel consumption	g/liter	127	104	98	99	91	98	91	110	104	98	159	87	143	140	119	122	109	117	129	131	125	147
Fuel Consumption	g	532	505	411	440	413	489	442	482	466	441	723	396	646	628	571	563	510	969	543	549	527	654

CO_2	ppm	695	741	NA	756	691	825	713	NA	NA	783	672	732	696	750	793	N/A	N/A	1369	670	705	668	812
CO	ppm	13	33	20	30	34	48	27	22	25	15	4	11	9	15	8	8	21	23	5	9	8	13
Particulate Matter	μg/m^3	1049	1735	942	1222	2937	2985	2181	1242	1306	521	297	1151	309	648	561	670	1110	1330	221	295	262	946

Appendix 4: WBT Data Entry Spreadsheet

Water Boiling Test - General Information

Test & stove description

Name of Tester(s)	
Test Number or Code	
Date	
Test Location	
Stove Type/Model	
Manufactured by	
Description and Notes	

Ambient conditions

Air temperature (C)	
Air relative humidity (%)	
Local boiling point (C)	

Notes or description about stove or operation not included elsewhere on this form

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Fuel description

Your general description			
Fuel type	(Select from list)		
Fuel description	(Select from list)		
Average length (cm)			
Cross-sectional dimensions (cm x cm)			

Default values (looked up)

Gross calorific value	-	HHV, kJ/kg
Net calorific value	-	LHV,kJ/kg
Char calorific value	-	LHV,kJ/kg

If possible, enter a calorific value from measurements of local fuel below.

- [ ] Check box if you have a measured calorific value
- [ ] Check box if measured calorific value is for dry fuel

Measured gross calorific value		HHV measured, kJ/kg
Measured net calorific value		LHV, kJ/kg
Assumed net calorific value		LHV, kJ/kg

Values to be used for tests

Gross calorific value	-	HHV, kJ/kg
Net calorific value	-	LHV, kJ/kg

Description of firestarter (e.g. paper, fluid) and small wood or kindling
(note: Kindling should be weighed and reported with wood)

Description of operation during the high-power test

How is fire started?	
When do you add new fuel to the fire?	
How much fuel do you add at one time?	
How often do you feed the fire without adding fuel (e.g. push sticks)?	
Do you control the air above or below the fire? If so, what do you do?	

Description of operation during the simmering test

How is fire started?	
When do you add new fuel to the fire?	
How much fuel do you add at one time?	
How often do you feed the fire without adding fuel (e.g. push sticks)?	
Do you control the air above or below the fire? If so, what do you do?	

Fuel moisture content worksheet

If you are determining fuel moisture with the Delmhorst J-2000 or similar handheld moisture meter, take 3 pieces of fuel at random from the stock used for each test and measure each in three places along its length. Enter the results in the gray spaces below. The worksheet will automatically calculate average moisture content on a dry and wet basis.

If you are using another means to determine fuel moisture, enter the moisture content in the blue spaces next to the appropriate label (dry-basis or wet-basis).

Test-1 Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ___ wet-basis ___

Test-2 Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ___ wet-basis ___

Test-3 Instrument reading (% dry basis)

	1	2	3
Piece 1			
Piece 2			
Piece 3			

Average moisture content (%)
dry-basis ___ wet-basis ___

The Delmhorst J-2000 moisture analyzer measures fuel moisture on a dry basis. To find moisture on a wet basis, use the following equation:

$$MC_{wet} = \frac{MC_{dry}}{1 + MC_{dry}}$$

This spreadsheet does this calculation automatically if a value is entered in the dry-basis space. Output requires moisture content on a wet basis, so the conversion is very important.

Fuel moisture content worksheet

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Water Boiling Test - Test Entry Form

These values are not linked to the Test sheets. This sheet is provided so you can print an easy data entry form. You will have to enter these values in each Test sheet to obtain the calculations.

Air Temperature	
Wind Conditions	
Fuel Dimensions	
Moisture Content (wet basis)	
Dry Weight Pot 1	
Dry Weight Pot 2	
Dry Weight Pot 3	
Dry Weight Pot 4	
Weight Container for Char	
Local Boiling Point *	

* enter on General Information

Name of Testers

Date

Stove Type/Model

Test Number

Location

Fuel Type

Notes

	Cold Start		**Hot Start**		**Simmer**	
	Start	End	Start	End	Start	End
Time						
Weight of Wood						
Water Temperature, Pot 1						
Water Temperature, Pot 2						
Water Temperature, Pot 3						
Water Temperature, Pot 4						
Weight of Pot 1 with water						
Weight of Pot 2 with water						
Weight of Pot 3 with water						
Weight of Pot 4 with water						
Fire Starting Materials						
Weight of Charcoal + Container						