THERMAL PERFORMANCE OF KENYA DEFENCE FORCES MOBILE DIESEL COOKER

BY

WERE EZRA OMONDI

A THESIS SUBMITTED TO THE SCHOOL OF ENGINEERING, DEPARTMENT OF MECHANICAL & PRODUCTION ENGINEERING IN PARTIAL FULFILMENT FOR THE REQUIREMENTS FOR THE AWARD OF MASTER OF SCIENCE DEGREE IN ENERGY STUDIES

MOI UNIVERSITY

SEPTEMBER, 2017

DECLARATION

DECLARATION BY CANDIDATE

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/or Moi University.

Signature: ………………………… Date: ……………………………..

Were Ezra Omondi

TEC/PGMP/04/13

DECLARATION BY SUPERVISORS

This thesis has been submitted for examination with our approval as University Supervisors.

…………………………… Date: ………………………………

Eng. **Prof. Augustine Makokha**

Department of Mechanical and Production Engineering

Moi University - Kenya

…………………………… Date: ……………………………….

Dr. **Charles Nzila**

Department of Manufacturing, Industrial and Textile Engineering

Moi University – Kenya

DEDICATION

This research is dedicated to:

My wife Jane,

My late father, Moses Were

My mother Ludia

And

My children Florence, Braulio and Moses

Whose encouragement and love made me go this far.

ACKNOWLEDGEMENTS

Many individuals and institutions have contributed either directly or indirectly to the accomplishment of this study. Due to constraints of space, I will only mention a few by name.

To my supervisors, Eng. Prof. Augustine Makokha and Dr. Charles Nzila, thank you for the assistance, support, and guidance during the entire study period.

Thanks to Major General Lukas Tumbo in his capacity as the Managing Director of Kenya Ordnance Factories Corporation (KOFC) for accepting to have the study conducted at the Corporation.

Thanks to Mr Albert Ouma of EENOVATORS energy audit firm for his immense support in acquiring a flue gas analyser used the research.

Thanks to Sergeant Paul Tanui, Mr Elijah Rutto and Miss Valentine Waka of Kenya Ordnance Factories Corporation for their assistance in data collection.

My gratitude to all my friends and classmates at the Department of Mechanical and Production Engineering of Moi University for creating an inspiring atmosphere in which the research was done.

ABSTRACT

Kenya Defence Forces (KDF) developed a diesel and LPG mobile field cooker (DEFKITCH) in the year 2010 capable of cooking food for over two hundred soldiers within a cooking session of one hour. The equipment was intended to reduce high usage of firewood for cooking in order to save Kenyan forests. Its commercialization and mass production was launched in the year 2012 at Kenya Ordnance Factories Corporation (KOFC) in Eldoret. Since the cooker was invented, no experimental assessment had been done to ascertain its thermal performance and emission levels. The objective of this research was to experimentally evaluate the combustion and thermal efficiencies of the DEFKITCH cooker by comparing its thermal performance in Water Boiling Test (WBT) with other similar cookers like ARPA kerosene cooker;-analysing emission levels of the cooker and suggesting possible modifications aimed at improving DEFKITCH overall performance. Thermal efficiency was investigated for diesel fuel by conducting WBT. Parameters used were: heating time, temperatures and fuel consumption. Average thermal efficiencies computed from the results ranged from 60.37 percent to 65.86 percent using the 24 gallons cooking pots while a lower value of 42.69 percent was obtained using the 12 gallon pot on the same cooker. These values were found to be higher compared to the ARPA cooker which was an earlier model kerosene burner whose thermal efficiency was found to be 40.0 percent. However, this research established that LPG could not burn with sufficient flame to support WBT and therefore thermal efficiency could not be obtained. Average diesel consumption rate was found to be 0.8 litres per burner in one hour. Combustion efficiency of the cooker was determined using TESTO flue gas analyser and the overall value was determined as 69.0 percent while burning diesel and 46.5 percent while burning LPG. Emission levels for CO and CO_2 were determined as 172.7 ppm and 49,500 ppm (4.95 percent) respectively while using two burners on diesel. The CO level was found to be within the recommended maximum emission limit of 400 ppm air free basis according to National Comfort Institute Incorporation, 2008. The cooker was found to be economical in diesel consumption per unit amount of work and recommended for use without adaptor.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

BIS	Bureau of Indian Standards
DEFKITCH	Defence Field Kitchen
EGR	Exhaust Gas Recirculation
ERC	Energy Regulatory Commission
ESP	Environmental Soldier Program
FAME	Fatty Acid Methyl Esters
FAU	Formazin Attenuation Unit
GAL	Gallon
GHG	Green House Gas
GHV	Gross Heating Values
HPP	High Power Phase
KDF	Kenya Defence Forces
KNBS	Kenya National Bureau of Statistics
KOFC	Kenya Ordnance Factories Corporation
LPG	Liquefied Petroleum Gas
NEMA	National Environment Management Authority
NHV	Net Heating Value
NO_x	Nitrogen Oxides
PAH	Polycyclic Aromatic Hydrocarbons
pH	Potential of hydrogen
PM_{tot}	Total Particulate Matter
ppm	Parts per million
PRB	Porous Radiant Burner
R&D	Research and Development

SiC	Silicon Carbide
ToE	Tons of Oil Equivalent
VO	Vegetable Oils
VOC	Volatile Organic Compound
WBT	Water Boiling Test

LIST OF ABBREVIATIONS

C	Carbon
Cal	Calories
CO	Carbon monoxide
CO_2	Carbon dioxide
cSt	centistokes
J	Joules
kcal	kilo Calories
kg	kilogram
kW	Kilowatts
mg	milligrams
mV	millivolts
MJ	Mega Joules
O_2	Oxygen
˚C	Degree Celsius
%	percent

CHAPTER ONE

INTRODUCTION

1.1 Background and Motivation

The Kenya Department of Defence through Kenya Defence Forces (KDF) is committed to responsible energy use and sound environmental management through continuously improving use of energy in the most efficient, cost effective and in an environmentally sustainable manner in line with the Kenya vision 2030. The department had been involved in planting trees in government forests and within the camps in a program called Environmental Soldier Program (ESP) which was part of its strategy of ensuring that forest resources are conserved and maintained to reduce human and environment conflict and with the ultimate goal of mitigating global warming because Climate change is one of the severe problems that the world is facing today.

KDF set energy objectives to ensure efficient use, provide energy security and enhance environmental sustainability by:

a. Establishing effective energy and environment management systems.

b. Utilizing energy efficiently.

c. Encouraging behaviour change towards efficient energy use and environment conservation.

d. Incorporating energy efficiency into existing equipment and facilities, and in selection and purchase of new energy utilities.

e. Increasing use of renewable energy.

f. Minimising greenhouse gas emissions.

g. Continuously striving to achieve a green status. (KDF Energy Policy, 2010)

The main forms of energy used in the military camps for cooking included LPG and firewood, the latter was the major source of fuel for cooking both in the camps and in operation areas until the year 2010. The use of firewood in large quantities negated the gains achieved by KDF in the Environmental Soldier Program (ESP) because the trees planted in the forests ended up being used as firewood in the camps. It is for this reason that the KDF designed a field cooker branded Defence Kitchen (DEFKITCH) that used diesel as the main fuel but with a provision for using Liquefied Petroleum Gas (LPG) also. Diesel is the preferred fuel by KDF because it is readily supplied in operation areas.

The motivation for this thesis therefore came from the need to determine and document thermal and combustion efficiency of DEFKITCH cooker as is the requirement for all energy utilities. This work provides performance data which would allow the manufacturer to modify and adjust design parameters during fabrication in order to improve the cooker performance.

1.2 Energy for Cooking in Kenya

Traditional biomass-based fuels for cooking and heating are currently the most important source of primary energy in Kenya with wood fuel consumption accounting for 68.3% of total consumption (rural - 87.5%; urban - 10%; Kenya National Bureau of Statistics (KNBS), 2007). The role of agro forestry on small farms in providing firewood has increased while showing a decline in the other categories.

Kerosene and LPG are the main fossil fuels used widely in Kenyan homes for cooking. Kenya has not yet discovered any significant fossil deposits although exploration is ongoing. Kerosene is popular for lighting in the rural areas, and for both lighting and cooking in the urban areas. Nationally 13.2% of households use kerosene for cooking where approximately 44.6% of urban households use it for cooking (rural use: 2.7%) and 46.3% of urban households use it for lighting (rural: 86.4%). LPG national average coverage is 3.5% (urban - 11.9%; rural - 0.7%). Household LPG use in Kenya has been constrained by high costs and low supply rather than market (Ngigi, 2008).

1.3 Energy Mix in the Ministry of Defence

KDF is a major consumer of energy with energy sources mainly from grid electricity and petroleum products for vehicles and other utilities. The Government of Kenya is committed to a green economy and created a policy to encourage efficient energy use to reduce energy cost and to conserve the environment. Through the Energy Regulatory Commission (ERC), the Government encourages major energy consumers to conduct energy audits regularly to monitor consumption and reduce wastage. In one of the energy audits conducted by KDF in the year 2010 in its two barracks, the energy use pattern was found to be as shown in the table 1.1.

Table 1.1: Energy use in KDF (KDF Energy Audit Report 2010)

Energy Source	Unit of Measure	Kahawa	Embakasi	Total	Tons of Oil Equivalent/Yr (ToE)
Grid Electricity	Kwh/Yr	2,090,618	1,287,655	**3,378,273**	**291**
Diesel	Ltrs/Yr	11,733,532	3,792,347	**15,525,879**	**15,215**
LPG	Tons/Yr	418,789	543,208	**961,998**	**1,110,337**
Firewood	Tons/Yr	6,038,296	2,916,804	**8,955,100**	**2,879,065**
TOTAL					**4,004,908**

From the audit, it was observed that firewood and LPG were the main energy sources used in cooking by the Kenyan military. This trend contributed largely to deforestation because more firewood implied many trees felled to match the firewood requirements in the camps.

1.4 Old Cooking Technologies in KDF

The old cooking methods used in military camps posed several technical and environmental challenges which necessitated their abandonment. The following are the old cooking methods.

1.4.1 Open Fire Trench

This cooking method involved digging an open trench then placing metallic bars across the trench as shown in figure 1.1. During cooking, firewood logs were placed inside the trench underneath the metal bars with cooking pots placed on top of the metal bars. This method consumed a lot of firewood and involved huge energy losses. Typically, the amount of firewood shown in figure 1.2 below could last for only three days. The reaction from the cooks was that the system not only consumed a lot of firewood fuel but also posed a lot of danger and discomfort due to the high heat and smoke dissipated to the surrounding environment.

Massive heat loss in open fire trench

Figure 1.1: Photo of Open Fire Trench

Logs of wood ready to be used as firewood

Figure 1.2: Photo Showing Typical Amount of Firewood Expected to Last Three Days in Open Fire

1.4.2 Kerosene Cookers

KDF also imported kerosene cookers that failed to perform due to frequent breakdowns, lack of spare parts locally and high rate of fuel consumption. An example of such kerosene cookers whose usage was stopped due to frequent breakdown and high rate of fuel consumption was ARPA 2000 model.

1.5 Development of New Cooking Technologies at KDF

The Research and Development (R&D) branch in KDF proposed the use of energy saving wood stoves which reduced the firewood consumption and greenhouse gas emissions to the environment. The major achievement of the R&D branch was the invention of a mobile diesel cooker in figure 1.3 in the year 2010 that was designed for use both in operation areas and in the military camps. The equipment proved versatile, energy saving and reliable especially in operation areas where supply of gas and fire wood was found to be risky and impossible. The cooker, either three burner or two burner type was able to serve up to two hundred personnel with diesel consumption rate of as low as one litre of diesel per hour per burner which was found to economical compared use of firewood in open trench method. The equipment commonly referred to as DEFKITCH was built to either use gas or diesel but the primary fuel being diesel.

Figure 1.3: DEFKITCH **Two burner cooker.**

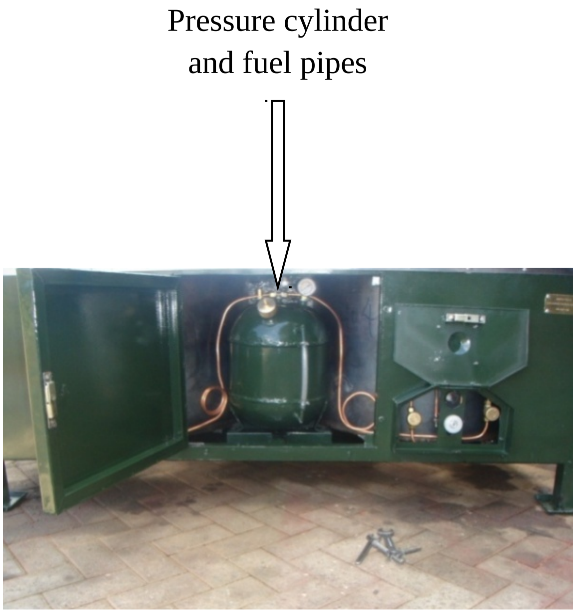


Figure 1.4: DEFKITCH **Fuel System**

The main components of the mobile cooker are the fire chambers, burners, fuel pressure cylinder (tank) and fuel pipes as indicated in figures 1.4 and 1.5. The fuel tank was a seventeen litre pressure cylinder fitted with a pressure relief valve, pressure gauge and a fuel outlet fitting. During operation, fuel was pressurized in the tank to a pressure between one and a maximum of three bars. After the burner had received pressurized diesel from the pressure cylinder, the fuel then passed through preheating coils before atomization through a nozzle where it was combusted with the aid of natural flow of air from the burner bottom base plate at the bottom of the fire chamber. When gas was used, the gaseous fuel was not preheated but directly passed through the nozzle for direct ignition. The heat produced from the burner was retained within an insulated fire chamber lagged to reduce heat losses where the cooking pot was placed but with a provision for flue gas escape. The cooking pot capacities used were twenty four gallons and twelve gallons depending on the amount of food to be prepared.

Figure 1.5: Diesel Burner inside the Fire Chamber

1.6 Problem Statement

The environment and its degradation due to greenhouse gases and other forms of pollution is a major topic of discussion in both political forums and around the kitchen tables of everyday people. Energy is one of the basic needs and a means to increase productivity which enhance employment opportunities and improve the quality of livelihood of people. The world energy scenario projects the deepening of the fuel energy crisis, the implications of which would be equally serious for both the developed and developing nations.

Good energy management practices require that energy sources are used efficiently and good environment conservation strategies require that energy utilities used produce little or no emission to the environment. The cost of energy in the country and indeed across the world has gone up in recent times and can only be expected to keep going up. The rising energy cost has spared no sector of industry or part of the world but most developed countries have quickly risen to the challenge and are diversifying their energy sources by most importantly trying to utilize the available energy resources as efficiently as possible.

DEFKITCH was fabricated in the year 2010 to use diesel as the primary fuel. However, its emission levels and efficiency had never been experimentally determined to assess if it was a good alternative to firewood in the military camps. This research sought to determine the cooker's thermal performance, both combustion and thermal efficiencies and emission levels while using diesel and LPG with a view of availing initial data and information to form basis for the cooker improvement.

1.7 Justification of the Study

The energy needs of Kenya are increasing at a rapid rate, and indigenous energy resources are limited and may not be sufficient in the long run to sustain meaningful economic development. The combination of high demand compounded by low use efficiency has contributed to energy shortage and deforestation as a result of overreliance on biomass. Efficient energy use aimed at reducing cost and adverse effects to the environment is the greatest concern of energy experts and environmental scientists.

The cost of fossil fuel is always increasing each day due to the increasing demand and increased cost of extraction (Wayne C. T., Steve D, 2007) therefore energy conversion devices like boilers, cook stoves and engines among others are supposed to be designed to use energy economically and in an environmental friendly manner.

Performance of energy consuming devices therefore must be determined to ensure energy is used efficiently and with less emission of greenhouse gases that contribute to the menace of global warming. In addition, any effort aimed at conserving the environment by using energy efficiently or adopting a renewable source of energy should be embraced by all energy consuming institutions including households.

As a result of the increased energy demand worldwide, efficient energy use is inevitable to cut on costs and mitigate global warming by reducing emission of greenhouse gases like carbon dioxide, methane and carbon monoxide to the environment. This calls for proper energy use in an environmental friendly manner. The DEFKITCH cooker had been in use since its invention in 2010 but its combustion and thermal performance had not been assessed experimentally. This research was aimed at determining and documenting its thermal performance in order to provide KDF and other users with the performance data of the cooker and to suggest performance improvement measures.

1.8 Objectives

1.8.1 General Objective

The general objective of this research was to assess thermal performance of DEFKITCH cooker.

1.8.2 Specific Objectives

The specific objectives of the research were to:

- Compare the DEFKITCH cooker thermal performance in Water Boiling Test with other similar cookers like ARPA kerosene cooker.
- Analyse the emission levels of the cooker using flue gas test on diesel and LPG.

- Evaluate combustion and thermal efficiencies of the DEFKITCH cooker using diesel and liquefied petroleum gas (LPG).
- Generate initial performance data for DEFKITCH diesel - LPG cooker.

1.9 Scope of the Study

This study was intended for DEFKITCH cooker fabricated by KDF to use diesel fuel or LPG. The cooker used in the research was borrowed from Kenya Ordnance Factories Corporation (KOFC) in Eldoret where the study was conducted through experiments on performance of the burner using diesel and liquefied petroleum gas and results compared with performance of kerosene cooker that was in use before.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Energy management has been an important tool to help organizations meet critical objectives for their short term survival and long-term success. Analysis and monitoring of performance of energy utilities like cookers is a requirement for efficient energy management and improvement of environment quality. Therefore this chapter presents a review of some of the studies accomplished to date which make available information on the performance of various cooking stoves. Also included is a brief discussion on the previous efforts by other researchers, aimed at determining the efficiencies of cooking stoves and ways to improve them. Hence this chapter provides knowledge and understanding on whose base this research work was built.

2.2 Principle of Combustion of fuels

Combustion is the rapid oxidation of fuel which results in the production of heat, or heat and light. For complete combustion of a fuel, there must be adequate supply of oxygen. Oxygen (O_2) is one of the most common elements on earth making up 20.9 percent of air. Rapid fuel oxidation results in large amounts of heat and fuels will burn in their normal state if enough air is present. Most of the air is nitrogen (apprimately79 percent) and oxygen (approximately 21 percent) with traces of other elements (McConkey and Eastop, 1993).

Nitrogen is considered to be a temperature reducing that dilutes the oxygen concentration but that must be present in the air to obtain the oxygen required for combustion. The presence of Nitrogen in the combustion air reduces combustion efficiency by absorbing heat from the combustion of fuels and diluting the flue gases. This reduces the heat of combustion available for doing work. It also increases the volume of combustion by-products, which then have to travel through the heat exchanger and up the stack faster to allow the introduction of additional fuel air mixture. The other adverse effect of Nitrogen in the air is that it can combine with oxygen particularly at high temperatures to produce oxides of nitrogen (NO_x), which are toxic pollutants.

The constituents of the fuel are Carbon, hydrogen and sulphur which combine with oxygen in the air to form carbon dioxide, water vapour and sulphur dioxide, releasing 8,084 kilo calories (kcal), 28,922 kcal and 2,224 kcal of heat respectively. Carbon may also combine with Oxygen to form Carbon Monoxide, which results in the release of a smaller quantity of heat (2,430 kilo calories per kilogram of carbon) Carbon burned to CO_2 will produce more heat per unit weight of fuel than when CO or smoke are produced. Each kilogram of CO formed means a loss of 5654 kcal of heat. (8084-2430) (Gordon F. C. and Rogers G F, 1992).

2.2.1 Calorific values of fuels

Fuels are substances which produce heat either by combustion or by nuclear fission /fusion and they can be classified as solid, liquid and gaseous fuels. Solid fuels include wood, coal, charcoal and coke. Liquid fuels include petrol, kerosene, diesel and alcohol while gaseous fuels include methane, propane, butane, hydrogen and coal gas among others.

Calorific value of fuels is the amount of heat evolved when a unit weight of fuel is completely combusted. It can be defined in two forms namely gross or higher calorific value and net or lower calorific value.

The gross calorific value (GHV) refers to the heat evolved when the water produced by combustion is condensed as a liquid. The net value gives the heat liberated when water is in the form of steam or water vapour.

Net calorific value (NHV) is the heat produced when unit mass of fuel is burnt completely and products of combustion are allowed to escape. The net calorific value (or the net heating value) is defined as the gross calorific value minus the latent heat of condensation of water (at the initial temperature of the fuel), formed by the combustion of hydrogen in the fuel.

The GHV and NHV for diesel are 46MJ/kg and 43.25 MJ/kg respectively while the GHV and NHV for LPG are 122 MJ/m^3 and 113 MJ/m^3 respectively (McConkey and Eastop, 1993). This research was based on DEFKITCH cooker which used Diesel and LPG as fuels, therefore the calorific values of the two fuels was useful in determination of thermal efficiency of the cooker.

2.3 Energy Utility efficiency

Boiler and other fired systems, such as furnaces and ovens, combust fuel with air for the purpose of releasing the chemical heat energy. The purpose of the heat energy may be to raise the temperature of an industrial product as part of a manufacturing process; it may be to generate high-temperature high-pressure steam in order to power a turbine, or it may simply be to heat a space so that the occupants will be comfortable. The energy consumption of boilers, furnaces, and other fire systems can be determined as a function of load and efficiency, expressed as shown in the following equations (Wayne C. T. and Steve D, 2007).

$$\text{Energy consumption} = \int (load) \times (1/efficiency)\, dt \qquad (2.1)$$

Therefore the cost of operating a burner or a fired system can be determined as:

$$\text{Energy cost} = \int (load) \times (1/efficiency) \times (fuel\ cost)\ dt \qquad (2.2)$$

In order to reduce burner or fired system energy consumption, one can reduce the load, increase the operating efficiency, reduce the unit fuel energy cost, or combinations of the three.

The efficiency varies as a function of the load and other functions, such as time or weather. In addition, the fuel cost may also vary as a function of time (such as in seasonal, time-of-use, or spot market rates) or as a function of load (such as declining block or spot market rates. Therefore, solving the equation for the energy consumption or energy cost may not always be direct (Wayne C. T. and Steve D, 2007).

2.4 Energy Balance Equations

To determine systems' efficiencies, balance equations are used in an analysis of a process which determines inputs and outputs to the system. For fired systems like boilers and cookers, the balance equations which may prove useful in the analysis are heat balance and mass balance.

2.4.1 Heat Balance

A heat balance is used to determine the performance of a system where all the heat energy enters and leaves a system. Since energy can neither be created nor destroyed, all energy can be accounted for in a system analysis. Energy getting into a system should be equal to energy leaving the system. Whether through measurement or analysis, all energy entering or leaving a system can be determined. In a simple furnace system, energy enters through the combustion air, fuel, and mixed-air duct. Energy leaves the furnace system through the supply-air duct and the exhaust gases (Gordon F. C and Rogers G. F, 1992).

2.4.2 Mass Balance

A mass balance is used to determine system efficiency where all mass enters and leaves a system. There are several methods in which a mass balance can be performed that can be useful in the analysis of a boiler or other fired system. In the case of a steam boiler, a mass balance can be used in the form of a water balance (steam, condensate return, makeup water, blow down, and feed water.) A mass balance can also be used for water quality or chemical balance and can also be used in the form of a combustion analysis (fireside mass balance consisting of air and fuel in and combustion gasses and excess air out). This type of analysis is the foundation for determining combustion efficiency and determining the optimum air-to-fuel ratio.

For analyzing complex systems, the mass and energy balance equations may be used simultaneously such as in solving multiple equations with multiple unknowns. This type of analysis is particularly useful in determining blow down losses, waste heat recovery potential, and other interdependent opportunities (Wayne C. T and Steve D, 2007).

2.5 Efficiency

There are different methods of efficiency measurement used in fired systems. The two primary methods of determining efficiency are the input – Output method and the heat-loss method which give an estimate of gross thermal efficiency as opposed to “net” efficiencies which would include the additional energy input of auxiliary equipment such as combustion air fans and fuel pumps.

2.5.1 Combustion efficiency

Combustion efficiency is determined by the heat losses due to exhaust gases. It is practically determined by analyzing the products of combustion in the exhaust gases. Typically measuring either carbon dioxide (CO_2) or oxygen (O_2) in the exhaust gas can be used to determine the combustion efficiency as long as there is excess air. Excess air is the air in excess of the amount required for stoichiometric conditions. In other words, excess air is the amount of air above that which is theoretically required for complete combustion. It is a requirement for complete combustion to take place.

The disadvantage of having excess air in a combustions process is that it results in heat losses as the excess air is being heated from ambient air temperatures to exhaust gas temperatures. Therefore while some excess air is required, it is also desirable to minimize the amount of excess air. Carbon dioxide can be used as a measure of complete combustion but it cannot be used to optimally control the air-to-fuel ratio in a fired system. Determining oxygen content in the exhaust gases is a direct measure of the amount of excess air and is a more common and preferred method of controlling the air-to-fuel ratio in a fired system (Wayne C. T and Steve D, 2007).

2.5.2 Thermal efficiency

Thermal efficiency of a stove may be defined as the ratio of heat actually utilized to the heat theoretically produced by complete combustion of a given quantity of fuel (which is based on the net calorific value of the fuel). Typical thermal efficiency of a cooker can be determined using Water Boiling Test (WBT) from which the thermal efficiency can be computed using the following formulas in table 2.1. (Bureau of Indian Standards, 2002).

Table 2.1: The Table of Heat Equations

Parameters	Equations	Equation Number
Thermal efficiency (Boiling)	$\frac{(T2 - T1) \text{ x } (Mp\ Cp + Mw\ Cw)}{Mf \text{ x } NHVf}$	(2.3)
Thermal efficiency (Simmering)	$\frac{M_W \times L_W}{M_f \times NHV_f}$	(2.4)

Where;

M_p = Mass of cooking pot in kg

M_w = Mass of water in kg

M_f = Mass of fuel

C_p = Specific heat capacity of cooking pot

C_w = Specific heat capacity of water

L_w = Latent heat of vaporization of water

T_2 = Final Temperature of water in ˚C

T_1 = Initial temperature of water in ˚C

NHV_f = Net heating value of fuel

Assumption: temperature of water and pot are equal at all times.

The following are thermal properties of stainless steel grade 304 and water used in the experiments (Gordon F. C and Rogers G, 1992).

- Specific heat of Stainless steel Grade 304 = 510 J/kgK.
- Specific heat of water = 4.187 kJ/kgK
- Latent heat of vaporization = 2270 kJ/kg

2.6 Factors Affecting Efficiency

According to McConkey, T.D., and Eastop, 1993, the efficiency of a cooker depends on the efficiency of the combustion process in the burner and complete combustion with the appropriate flame is necessary to release the maximum amount of energy available. The efficiency of combustion is affected by the ratio of air to fuel, the degree of atomization of liquid fuels, the degree of air and fuel mixing that takes place in the combustion zone, the flame shape, temperature and speed. The setting of these parameters is important and requires skill and instrumentation.

a) Air to fuel ratio

The process of combustion depends on an optimum mixture of air and fuel such that there is just enough oxygen to chemically bond with every carbon and hydrogen atom in the fuel called the stoichiometric ratio (James L. B, 2005). It is practically impossible to achieve the degree of fuel and air mixing required ensuring every molecule of oxygen finds a carbon or hydrogen molecule. Therefore a certain amount of excess oxygen is required to ensure that every carbon and hydrogen molecule is found by an oxygen molecule. The typical range of excess oxygen required to achieve complete combustion is generally 1 – 5 percent, depending on the combustion appliance. Since the amount of oxygen in the air is 20.9 percent, an approximate excess air requirement of 5 – 25 percent is needed for complete combustion to take place (McConkey and Eastop, 1993).

b) Atomization of the fuel

To achieve complete combustion of a liquid fuel, it must be dispersed into the combustion air in an even spray of fine droplets to increase the level of intimacy of the fuel and air. The droplets must be sufficiently small to allow for the combustion process to take place in the available time within the flame. The degree of atomization achieved depends on the burner design, the pressure of the fuel supply to the burner, the pressure of the atomizing air or steam and the viscosity of the fuel. It is generally accepted that the viscosity of the fuel must be below 20 centistokes (cSt) for adequate atomization to be achieved (Gordon F. C. Rogers G, 1992). .

c) Fuel-air mixing

The mixing of the fuel and air is a critical process that must be optimal to ensure that efficient combustion takes place. The fuel, whether gas or liquid, must be evenly dispersed in the combustion air stream such that the fuel and air can make intimate contact. Failure to achieve this results in un-burnt or partially burnt fuel leading to low efficiency of the appliance (McConkey and Eastop, 1993).

d) Flame shape and size

The combustion appliance design will dictate the required size and shape of the flame. The flame should be sized and shaped to reach the heat transfer zone without impinging on the refractory or firing tube. Short bushy flame that does not extend over the radiant heat transfer area will not be as efficient as a longer flame (Wayne C. T and Steve D, 2007).

2.7 Thermal and Combustion Efficiency of Diesel, LPG and other cookers

Different researchers have in the past experimented and detrmined both thermal and combustion effiencies of newly designed cookers, heaters and burners using diferrent sources of energy. Some of these reseach results were studied to provide a benchmark for methodology and results for comparison with this research.

2.7.1 Research on solar cookers

An investigation of thermal performance of a box type solar cooker was conducted on the double glazed solar cooker of aperture area of 0.245 m^2 with a fibre body. Optical efficiency and heat capacity of the cooker were then calculated using linear regression analysis for different load of water. The results obtained showed that efficiency and heat capacity are the critical design parameters that determine the thermal performance of the solar cooker (Kumar S, 2005).

Thermal and combustion effiencies were the main parameters determined in the experiments that were conducted for the assessment of thermal performance and efficiency of pyra-box solar cooker which is a low cost solar cooker (Tekle A, 2014). The energy efficiency of the cooker was experimentally evaluated in a clear day in January 2014 in Hawassa University, Ethiopia. Details of temperature distributions and their time dependences were measured. Temperature measurements were taken at intervals of 30 seconds with K-type thermocouples connected to a multi-channel digital data-logger. The maximum temperature obtained in a pot containing half liter of water was 94 °C and 88°C for pyra-box and conventional box cooker respectively. The research showed that average energy efficiency of conventional solar cooker and pyra-box cooker was about 15.4 per cent and 26.5 per cent respectively. At 50°C temperature difference they had 8 per cent energy efficiency difference and the study found that pyra-box cooker can increase an average of 11 per cent thermal efficiency by decreasing 25 per cent total collector area (Tekle A, 2014).

From the two analogies of the solar cookers, combustion and thermal efficiencies were found to be the main parameters that determined performance of the solar cookers and the same were the main focus in this research to analyze the DEFKITCH cooker performance. The time interval used in this research experiment was 3 minutes as opposed to the 30 seconds used in the solar cooker above due to the large volume of water, 50 liters used in this research.

2.7.2 Research on bio-fuel stoves

An investigation was conducted on two types of biodiesels and vegetable oil (VO) as potential fuels for gas turbines to generate power. Biodiesels produced from VO and animal fat were considered in this study. The problems of high viscosity and poor volatility of VO (soybean oil) were addressed by using diesel-VO blends with up to 30 per cent VO by volume. Gas chromatography/mass spectrometry, thermogravimetric analysis, and density, kinematic viscosity, surface tension, and water content measurements were used to characterize the fuel properties. The combustion performance of different fuels was compared experimentally in an atmospheric pressure burner with an air-assist injector and swirling primary air around it. Profiles of nitric oxides (NO_x) and carbon monoxide (CO) emissions were obtained for different atomizing airflow rates, while the total airflow rate was kept constant. The results show that despite the compositional differences, the physical properties and emissions of the two biodiesel fuels are similar. Diesel-VO fuel blends resulted in slightly higher CO emissions compared with diesel, while the NO_x emissions correlated well with the flame temperature. From the experiment, the results showed that the CO and NO_x emissions are determined mainly by fuel atomization and fuel/air mixing processes, and that the fuel composition effects are of secondary importance for fuels and operating conditions (Heena V. P et.al , 2009)

The work only concentreated on measuring CO and NO_x but ignored other emission such as CO_2, O_2 and SO_x which also determine effieciency of cookers.

A study was conducted on the performance of a domestic cooking wick stove using fatty acid methyl esters (FAME) from oil plants in Kenya. The study presented the performance of a wick stove using FAME fuels derived from oil plants: Jatropha curcus L. (Physic nut), Croton megalocarpus Hutch, Calodendrum capense (L.f) Thunb., Cocos nucifera L. (coconut), soya beans and sunflower. The tests were based on the standard water-boiling tests (WBT) and compared with kerosene. Some of the findings were that unlike kerosene all FAME fuels burned with odourless and non-pungent smell generating an average firepower of 1095 W with specific fuel consumption of 44.6 gram per litre (55 per cent higher than kerosene). The flash points of the FAME fuels obtained were typically much higher (2.3–3.3 times) than kerosene implying that they are much safer to use than kerosene. FAME fuels have potential to provide safe and sustainable cooking liquid fuel in developing countries (Agatha W. et.al, 2010).

Lalitpur N. (2001) did a study and found out the efficiency of biogas stove and for comparison, they also determined efficiency of LPG (Liquefied Petroleum Gas) and kerosene stove (pressure type and wick type). In their study, the efficiency of cook stoves was determined by calculating the heat gained by the water subjected for heating and amount of fuel consumed during this process. The experiment was done by heating of water from initial water temperature T_1°C to boiling point termed as High Power Phase (HPP). During this phase water in vessel gained energy from fuel with the help of burning stove and that value of energy is equivalent to energy required to raise the temperature of that mass of water from T_1°C to boiling point. In Low Power Phase predetermined weight of water at boiling point was subjected to boil for five minutes and energy gained by this water was calculated by multiplying latent heat of vaporization of water and mass of vaporized water. Fuel consumed during each process was the input energy for these phases. Overall efficiency was calculated by dividing output energy by input energy. They conclude that the efficiency of a given stove is not constant and could vary on the basis of surrounding conditions and quality of fuel used. A high value of efficiency could be obtained under controlled conditions. But in practice this value is normally lower than the value found in the controlled laboratory condition.

The study also concluded that the efficiency of stove depends upon following conditions; environmental conditions such as wind, temperature, pressure shape, specific heat capacity and weight of vessel, burner size of stove and size of bottom face of cooking vessel energy content of fuel and quality of fuel (Lalitpur N, 2001). These were the main conditions considered in determining the efficiency of DEFKITCH cooker. This research also employed the use of Water boiling test method for the determination of thermal efficiency.

In an experiment by Olubiyi O. D, 2014 that was designed, constructed to evaluate the performance of biogas burner with the aim of improving the efficiency was done by conducting the water boiling test. The efficiencies of the stove in water boiling and rice cooking were 21, and 60 per cent respectively. Also, flue gas analysis was carried out to establish the emissions of the stove. The combustion efficiency of the stove recorded by the flue gas analyser was 86.9 per cent. From the study, the following results were obtained -The potential of this stove can be maximized by improving the air/gas regulating mechanism. The percentage of O_2, CO_2 and excess air were constant for the flue gas analysis done on the three burners tested. This was because the machine worked on some preset values set during calibration for different kind of fuel (Olubiyi O. D, 2014).

The above work had a merit of using both water boiling test and rice cooking test unlike in this research that was limited to water boiling test only.

2.7.3 Liquefied petroleum gas stoves

In a study that was conducted by Jugjai S and Trewetasksorn, (2001) investigated the thermal efficiency improvement of an LPG gas cooker by a swirling central flame. They did thorough studies in an effort to improve the thermal efficiency of the cooker by reducing thermal inertia of the pan support and using the proposed porous medium technology to recover heat from flame radiation to preheat the secondary air entrained from the bottom of the burner. The experimental results showed that the thermal efficiency of the swirling central flame burner with conventional support is approximately 15 per cent higher than that of the conventional radial flow burner. They attributed this to the higher heat transfer coefficient between hot flue gas and vessel surface of the swirl burner than that of the conventional one. By replacing the conventional support of the developed swirl burner with a lighter one, whose mass was reduced by a factor of 3.7, the thermal efficiency could be increased by about 3 per cent. By using the proposed preheating secondary air support instead of the light support, the thermal efficiency could be further improved by 3 per cent. The predicted thermal efficiency obtained from the proposed model showed good agreement with the experiment (Jugjai S and Trewetasksorn, 2001).

Another study by Pantangi V. K. et.al 2011 was conducted to investigate the performance of a porous radiant burner (PRB) used for liquefied petroleum gas domestic cooking stoves. Since porous medium is known to be efficient in combustion, the team constructed a two-layer porous media for the study in which the combustion zone was made up of silicon carbide, and alumina balls to form the preheating zone. For a given burner diameter, the performances of the burner, in terms of thermal efficiency and emission characteristics, were analyzed for different equivalence ratios and thermal loads (wattages). The water boiling test as prescribed in the Bureau of Indian Standard (BIS): 4246:2002 was used to calculate the thermal efficiency of both the conventional LPG cooking stoves and the PRB. The maximum thermal efficiency of the LPG cooking stoves with a PRB was found to be 68 per cent which is 3 percent higher than that of the maximum thermal efficiency of the conventional domestic LPG cooking stoves. (Pantangi V. K. et.al 2011).

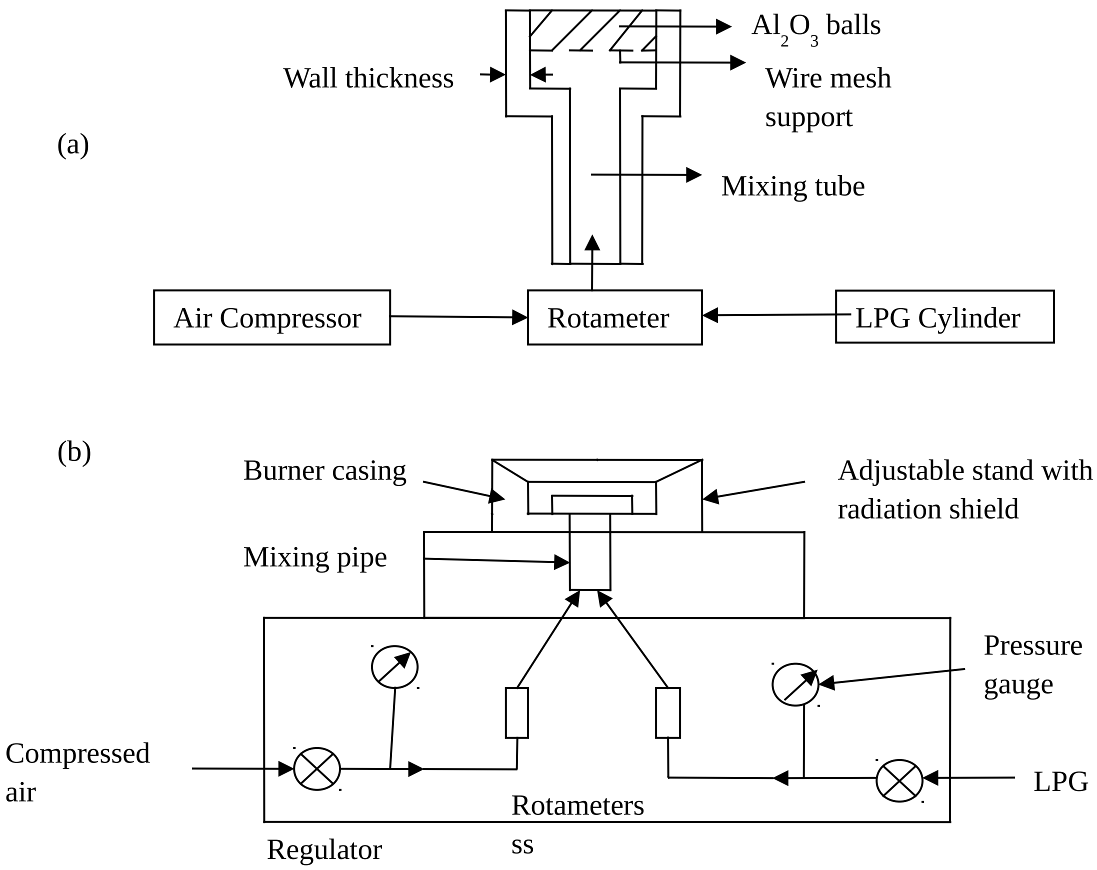


Figure 2.1: Schematics of the (A) Porous Radiant Burner and (B) The Experimental Set-Up

This study on DEFKITCH was conducted by using water boiling test and flue gas analysis just like the above work on LPG porous radiant burners.

Mishra N. K. et.al, (2013) conducted performance tests on porous radiant burner (PRB) shown in figure 2.2 used for medium - scale cooking applications of capacity 5-10 kW. The PRB chosen for the study was SiC-based porous burner. Liquefied petroleum gas (LPG) was used as a fuel. Effects of different heat inputs in the range of 5 - 10 kW on the thermal efficiency and emission levels of PRB were investigated. For the conventional LPG burner of 5-10 kW capacity, the measured value of thermal efficiencies was in the range of 30-40 per cent, and the CO and NO_x were in the range of 350-1145 parts per million (ppm) and 40 - 109 ppm, respectively. These emissions levels were well above the world health organization standards. Within range of parameters tested, the silicon carbide (SiC) based PRB yields the maximum thermal efficiency of about 50 per cent, which is about 25 per cent higher than the conventional stoves (Mishra N. K. et al, 2013).

Pores for spreading flames

Figure 2.2: Commercial PRB Burners used for Performance Test

Mohd Y. K. and Anupriya S, (2012) investigated the effects of using different design burner heads on the performance of LPG cooking stove. Burners of different material were used to study the effects of burner material on LPG stove performance. It was experimentally found out that thermal efficiency of stove using flat and flower face brass burners were higher as compared to regular cast iron burner.

The burner head was removed and replaced by different designs. Thermal efficiency was found out as per the Bureau of Indian Standard 10109:2002. When flower face burner was used, thermal efficiency of LPG stove was found to improve. The thermal efficiency of flat face brass burner was found to be highest at 58 per cent. The study was found useful since it provided the thermal efficiency for the gas burners based on different designs that offers a good comparison with the DEFKITCH cooker.

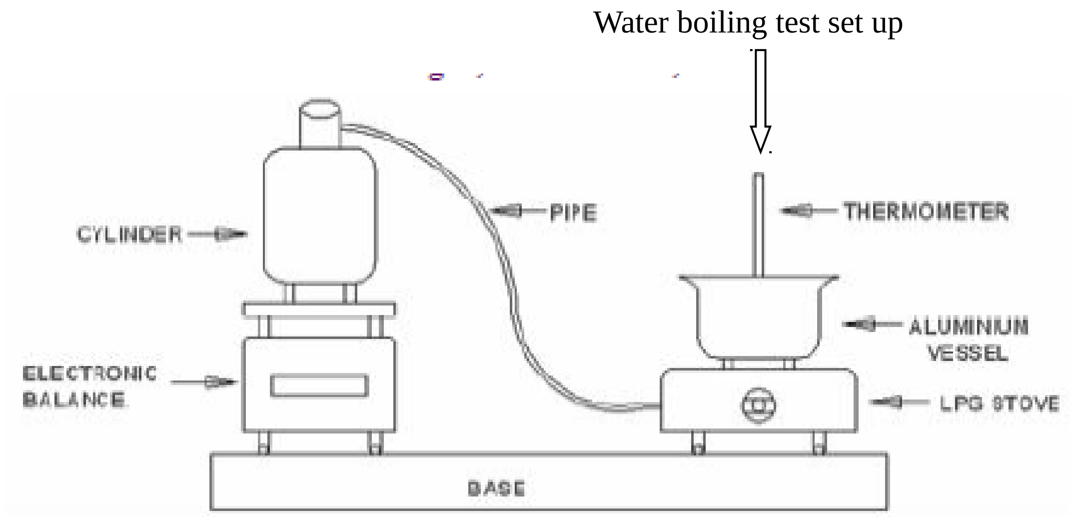


Figure 2.3: Water Boiling Experiment Set Up

The thermal efficiency of LPG stove for regular cast iron burner was found to be 48per cent. When flat face brass burner was used maximum thermal efficiency of 58 per cent was achieved. While thermal efficiency of 50 per cent was observed when face brass flower burner was used. Further, it was experimentally found out that thermal efficiency of LPG stove using regular brass burner was 4 per cent higher as compared to regular cast iron burner (Mohd Y. K. and Anupriya S, 2012).

2.7.4 Kerosene stoves

Murthy M. et al, (2011) conducted an investigation through an experiment on the horizontal type kerosene stove modified to burn higher percentage cotton seed oil blends with kerosene. In normal kerosene stove the copper coil is incorporated to absorb the heat radiated through burner and heat up the blend to reduce its viscosity. The heat which is utilized to heat up the blend is the waste heat. To achieve higher thermal efficiency using blends they set optimum pressure of 0.2 kg/cm^2 on normal kerosene stove and the test were performed on same. They found that the normal stove could burn with a maximum of 40 per cent blend with kerosene. (40 per cent cotton seed oil and 60 per cent kerosene). However, in the modified kerosene stove 70 per cent blend could be easily burnt and with a thermal efficiency of almost same as kerosene operated stove. Thermal efficiency tests were carried out on various blends and a comparison of performance of regular and modified stove obtained (Murthy M. et al, 2011).

2.7.5 Diesel cookers

Shi Yi-ping and Wang Yong-bin, (2005) studied development of heat exchange system for a diesel-hot-air stove of exhaust gas recirculation in greenhouses. The aim of the study was to increase thermal efficiency and reduce NO_x emission of the stove. Based on the technology of exhaust gas recirculation (EGR), a new method for increasing thermal efficiency of a diesel hot air stove from a greenhouse was proposed. The structure and principle of this EGR heat exchange system were also introduced. This method as well as its validity was proved by the diesel hot air stove tests. The optimized range of the EGR rate all the way is from 50 to 70 per cent, if the EGR rate is 60 per cent, the thermal utilization efficiency of the EGR heat exchange system of the stove was enhanced by 17.6 per cent as compared with no EGR rate. And pollution of the environment was reduced by EGR system. They concluded that the EGR heat exchange system of a diesel hot air stove is a good substitute for traditional heating system and that the EGR system is suitable for diesel hot air stove (Shi Yi-ping and Wang Yong-bin, 2005).

There has been a limited research work on the diesel cookers. However in the above research work, heat recovery from the exhaust gases was used for the purpose of increasing the efficiency and reducing the NO_x emissions which was found to be out of the scope of the DEFKITCH experiment.

2.7.6 Other energy utilities

A study was conducted by Li H. et al, (2006) on the thermal performances and CO emissions of gas-fired cooker-top burners. The experiment was carried out using a 4-factor and 3-level Box–Behnken design-method, utilizing a premixed gas-fired impinging-flame. A cooker-top burner, with circular nozzles with an inner diameter of 3 mm, was used in this experiment. Design parameters of the burner under consideration included Reynolds number, equivalence ratio, nozzle-to-plate distance, and jet-to-jet spacing. They reported their findings based on an analysis of the experimental data, variations of the thermal efficiency and the carbon monoxide (CO) emission with each of the above mentioned parameters. Multiple regression models of the thermal efficiency and the CO emissions were obtained in terms of all the major design parameters. Some of the 2-factor interactions on the thermal efficiency and the CO emissions were significant. Their findings are important for the designer of a fuel-efficient and environmentally-friendly cooker-top burner (Li H. et al, 2006).

Vishal R. and Sardeshpande D.S, (2010) studied thermal performance of a four pan jaggery processing furnace for improvement in energy utilization and proposed a procedure for thermal evaluation using mass and energy balance in order to establish furnace performance and loss stream analysis. The proposed method indicated that the theoretical energy required for jaggery processing is only 29 per cent of total energy supplied by bagasse combustion. The major losses were associated with heat carried in flue gas and wall losses. The study found that the air available for combustion depends upon the draft created by chimney in natural draft furnaces and that the oxygen content in the flue gas is a measure of degree of combustion (Vishal R. and Sardeshpande D.S, 2010).

Makmool U. et.al, (2007) conducted a research on performance and analysis by particle image velocimetry (PIV) of cooker-top burners which are used extensively in Thailand because of the rapid combustion and high heating-rates created by an impinging flame, which is characteristic of these types of burners. High thermal efficiency with low level of CO emissions was the most important performance criteria for the burners. In this research, a nationwide cooker-top burner performance survey and an implementation of a PIV technique to analyze the burner performance as well as advising local manufacturers were carried out. Experimental data were reported for the base line value of thermal efficiency of all the burners. The thermal performance parameters and dynamic properties of the flow field at a flame impingement area, i.e. velocity magnitude, turbulent intensity, vorticity and strain rate were also reported as a function of burner type, which was categorized into four types based on the configuration of the burner head: radial flow burners, swirling flow burners, vertical flow burners and porous radiant burners.

Christoffer B. et al (2011) studied stove performance, characteristics, and quantities of gaseous and particulate emissions for two different pellet stoves, varying fuel load, pellet diameter, and chimney draft. This approach was aimed at covering variations in emissions from stoves in use today. The extensive measurement campaign included CO, NO_x, organic gaseous carbon, volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), total particulate matter (PM_{tot}) as well as particle mass and number concentrations, size distributions, and inorganic composition. At high load, most emissions were similar. For stove B, operating at high residual oxygen and solely with primary air, the emissions of PM_{tot} and particle numbers were higher while the particles were smaller. On lowering the fuel load, the emissions of CO and hydrocarbons increased dramatically for stove A, which operated continuously also at lower fuel loads. On the other hand for stove B, which had intermittent operation at lower fuel loads, the emissions of hydrocarbons increased on slightly lowering the fuel load, while CO emissions increased sharply, due to high emissions at the end of the combustion cycle. The study showed that differences in operation and modulation principles for the tested pellet stoves, relevant for appliances in use today, affect the performance and emissions significantly (Christoffer B. et.al, 2011).

Walter M. B. et al. (1921) carried a study on gas burners by developing an atmospheric gas burner and an arrangement of apparatus and method of testing it. They studied the theory of flow of gas through different types of orifices, the principles governing the rate of injection of air into the burner, the design of the injecting tube, the rate of consumption of burners of different port areas, and the effect of adjustment of the air shutter. The rate of discharge of gas orifices of different types was found to vary greatly with a variation of the angle of approach and with the length of channel or tube of the orifice. Past research on burners found that for any given burner the ratio between the momentum of the gas stream and the momentum of the stream of the air-gas mixture entering the burner is always a constant, and this relation enables one to calculate readily the effect on the volume of air entrained when the gas pressure, gas rate, or specific gravity of the gas is changed.

Various types of burner orifice with different models of injection tubes were designed by Walter M. B. et al. (1921) and optimized. Experiments were also conducted with orifice position changed and the optimum injector was selected. A relation between burner tube and burner ports was used to find out the characteristics of satisfactory burner. With smaller size port, it was possible to turn the gas lower without causing a flash back. The study found an important co- relation between the area of the throat of the injecting tube and the area of the burner. The results of the tests showed that the area of the injector throat should be about 43 per cent of the area of the burner ports.

From the study on other cookers that are not using diesel or LPG, it was found out that the thermal efficiency, combustion efficiency and emission levels were the main performance parameters and the same parameters were also investigated in the DEFKITCH cooker to determine the performance.

Summary of relevant literature reviewed is show in table 2.2.

Table 2.2: Summary of Relevant Researches on Cooker Performance

Researchers	**Topic**	**Findings**
Kumar S. (2005)	Thermal performance of a box type solar cooker.	Efficiency and heat capacity were the critical design parameters for thermal performance
Heena V. P. et al. (2009)	Performance of biodiesels and vegetable oils as fuels for gas turbines.	CO and NO_x emissions were determined mainly by fuel atomization and fuel/air mixing processes.
Jugjai S. and Trewetasksorn (2001)	Thermal efficiency of LPG gas cooker by a swirling central flame	Thermal efficiency of the swirling central flame burner was approximately 15 per cent higher than that of the conventional radial flow burner
Agatha W. et al. (2010)	Performance of a domestic cooking wick stove using fatty acid methyl esters (FAME)	FAME fuels showed potential to provide safe and sustainable cooking liquid fuel in developing countries.
Vishal R and Sardeshpande D. S. (2010)	Thermal performance of a four pan jaggery processing furnace	Air available for combustion depended upon the draft created by chimney in natural draft furnaces. Oxygen content in the flue gas was used as a measure of degree of combustion.
Tekle A. (2014)	Thermal performance and efficiency of pyra-box solar cooker	Average energy efficiency of conventional solar cooker and pyra-box cooker was about 15.4 per cent and 26.5 per cent respectively.
Lalitpur N. (2001)	Efficiency of biogas, LPG and Kerosene for	Efficiency of stove was found to depend on conditions, such as wind,

	comparison	temperature, pressure, specific heat capacity and weight of vessel, size of bottom face of cooking vessel, fuel energy content.
Olubiyi O. D. (2014)	Performance of biogas burner.	The efficiencies of the stove in water boiling and rice cooking were 21, and 60 per cent respectively. The combustion efficiency was 86.9 per cent.
Pantangi V. K. et al. (2011)	Performance of a porous radiant burner (PRB) used for LPG domestic stoves.	The maximum thermal efficiency was found to be 68 per cent which is 3 percent higher than that of conventional domestic LPG stoves.
Mishra N. K. et al. (2013)	Performance of porous radiant burner PRB for medium - scale cooking applications.	Thermal efficiency was in the range of 30-40 per cent, and the CO and NO_x were in the range of 350-1145 ppm and 40 - 109 ppm, respectively.
Mohd Y. K and Anupriya S. (2012)	Effects of using different design burner heads on performance of LPG stove.	The thermal efficiency of flat face brass burner was found to be highest at 58 per cent.

2.8 Conclusion

Energy utilities like cookers must use fuels efficiently with minimum emissions to the environment. From the information presented in this chapter, it is apparent that a major impediment to proper energy management of diesel and LPG cooking stoves is lack of precise knowledge of their thermal and combustion efficiencies. Therefore it is expected that more research on diesel and LPG cooking stoves will continue to focus on efforts aimed at filling the above knowledge gap. As a contribution towards filling the aforementioned knowledge gap, this thesis made available the information of combustion and thermal efficiencies of a combined diesel and LPG field cooking stove manufactured and used by KDF through experimental studies.

CHAPTER THREE

EXPERIMENTAL MATERIALS, EQUIPMENT AND METHODOLOGY

3.1 Introduction

This chapter presents description of the experimental work undertaken for this thesis. The experimental equipment and measuring system components including instrumentation system are described first followed by discussion of experimental programs, measuring techniques, materials and procedures. Difficulties and challenges encountered during the course of experimental planning, execution and the success achieved are also noted here. The guiding principle for the assessment was the performance of DEFKITCH cooker using Water Boiling Test (WBT) with diesel and liquefied petroleum gas (LPG) in order to determine thermal efficiency and flue gas composition that lead to determination of combustion efficiency. The research was conducted at Kenya Ordnance Factories Corporation (KOFC) in Eldoret where the cookers were being manufactured. The data obtained from the experimental programs discussed in this chapter is analysed in subsequent chapters.

3.2 Experimental Equipment

The following equipment and tools were used in the research.

3.2.1 DEFKITCH cooker and cooking pots.

DEFKITCH cooker complete with cooking pots was acquired from Production department at Kenya Ordinance Factories Corporation (KOFC). The DEFKITCH used was a two burner cooker designed to use either diesel or LPG and it had fuel cylinder fitted with pressure gauge and a level sight glass. The three different sizes of cooking pots namely 12 gallon, 24 gallon heavy duty and 12 gallon light duty cooking pots shown in figure 3.1 (a) and (b) were availed for the tests. The pots were fabricated using grade 304 stainless steel with uniform wall thickness of 3 millimetres except for the heavy duty pot which had bottom wall thickness of 6 millimetres.

Figure 3.1(a): 12 gallon Pot

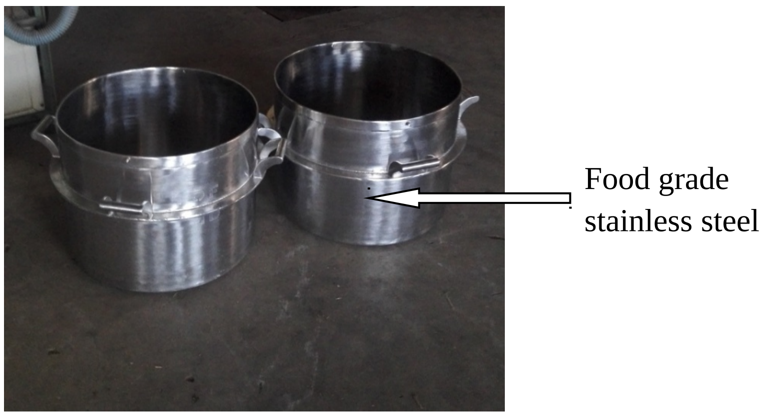


Figure 3.1(b): 24 gallon pots

3.2.2 Atomic absorption spectrophotometer

The spectrophotometer used was model AA-6300 manufactured by SHIMADZU shown in figure 3.2. The equipment was borrowed from chemical laboratory in the Quality Assurance Department at Kenya Ordnance Factories Corporation. The spectrophotometer was used in the research to test the composition of water to check if it was within the Kenya Standard requirement for cooking. The test was done by placing water samples in the holder. The sample was then aspirated by the nebulizer to allow minerals in the water to be absorbed by the cathode lights where the amount of absorption was directly proportional to each mineral concentration in the water.

Figure 3.2: Atomic Absorption Spectrometer at KOFC Physiochemical Laboratory

3.2.3 Thermometer and PH meter

A combined thermometer and pH meter in figure 3.3 below model HI-9025 microcomputer manufactured by HANNA INSTRUMENTS capable of measuring pH and temperature was also obtained from Quality assurance department at KOFC. The instrument has two probes for measuring temperature and pH level respectively. The probes were immersed into the water during the experiment to check the pH level of the water and also to measure temperature rise with time during the boiling tests. The readings were displayed on the screen of the instrument. The boiling time was measured using a stop watch.

Figure 3.3: Thermometer and pH meter

3.2.4 Flue gas analyser

A flue gas analyser model number 320 manufactured by TESTO in figure 3.4 was used to analyse flue gas composition, flue gas temperatures and in determination of cooker combustion efficiency. The gadget equipped with a wireless printer was hired from EENOVATORS Limited which is a registered energy audit firm in Nairobi. Its measurement range and resolution are as indicated in table 3.1.

Table 3.1: Flue Gas Analyser Measurement Ranges and Resolution

Measurement parameter	Measuring range	Resolution
O2	0 to 21%	0.1%
CO	0 – 4000 ppm	1 ppm
CO2	0 – 8000 ppm	1 ppm
Temperature	-40 – 1200 °C	0.1 °C
Efficiency	0 – 120%	0.1%

The flue gas composition measurement procedure was as follows:

a. The cooker was lit and allowed to burn for five minutes to allow the flame to stabilize.

b. On the flue gas analyser screen, fuel type was selected for both diesel and LPG respectively.

c. This was followed by zeroing of the equipment which was done with the probe placed outside the chimney.

d. The probe was then inserted in the chimney and start measurement button pressed.

e. Ten seconds was allowed to allow measurement stabilization then followed by pressing the stop measurement button.

f. The probe was the removed and readings printed from the wireless printer.

Figure 3.4: TESTO flue gas analyser (Hired from EENONATOTS limited)

3.2.5 Weighing machine

A weighing machine METTLER TOLEDO brand with measurement range of 500 kg and an accuracy of 0.01 kg shown in figure 3.5 was acquired from production department in KOFC for initial weighing of cooking pots and water to assist in computing heat gained during boiling. The machine was also used in weighing diesel in order to compute its density and hence mass of fuel consumed during the test.

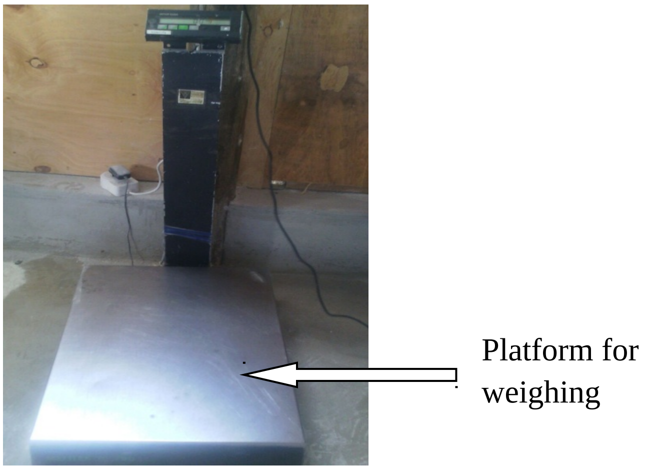


Figure 3.5: Weighing Machine at KOFC Production Department

3.2.6 Beaker

A one thousand cubic centimetre beaker was used in the experiment to measure the volume of diesel and water in order to determine their respective densities. An empty beaker was weighed, and then diesel was filled to 1000 cubic centimetres level. The weight of the beaker with diesel was recorded from which the density of the diesel used was determined. The same procedure was repeated to determine the density of water.

3.3 Experimental Materials

The materials used in the experiment were mainly water, diesel and LPG.

3.3.1 Water

The water used in the boiling test was collected from KOFC treated water supply system meant for drinking and use in production processes. The water was sampled and tested in the spectrometer in figure 3.2 and found contain dissolved minerals allowable for cooking according to Kenya Standards on water quality (KS 05-459) and had chemical composition as indicated in the table 3.1. One litre of water was weighed and its density determined as 1000 kg/m^3.

Table 3.2: Characteristics of water used in the boiling test

S/No	Parameter	Recommended limits (KS 05-459	Results
1	pH	6.5 -9.2	7.8
2	Turbidity	$\leq$ 25 FAU	1 FAU
3	Temperature	$\leq$ 25˚C	21.7˚C
4	Zinc	3 mg/l	0.4 mg/l
5	Iron	3 mg/l	0.05 mg/l
6	Lead	0.05 mg/l	0.001 mg/l
7	Hardness - (Calcium Magnesium)	25 mg/l	4 mg/l
8	Chlorine	0.2 - 0.6 mg/l	0.4 mg/l
9	Micro-organisms	Nil	Nil
10	Conductivity	$\leq$ 5 mV	-0.03 mV

3.3.2 Diesel and Liquefied petroleum gas (LPG)

The cooker was tested on the diesel and LPG. One litre of diesel fuel used in the experiment was weighed and its density determined as 800 kg/m^3. The burner was also tested using LPG in a six kilogram gas cylinder. Summary of properties of experimental materials is attached in Appendix E.

3.4 Experimental Methods and Procedures

3.4.1 Experimental Design

In water boiling test, temperature measurements were taken at initial time interval of 5 minutes from room temperate up to 20 minutes, then at reduced interval of 3 minutes up to 62 minutes and finally at interval of 2 minutes up to boiling point. Litres of fuel consumed measured as shown in the table 3.3. The tests were repeated 3 times for three pot sizes during boiling and simmering. For flue gas analysis, 4 sets of measurements were taken for both single burner and two burners as shown in appendix G.

Table 3.3: Water Boiling Test data collection sheet

Time (Min)	Temp (˚C)	Diesel Consumption (Ltrs)	Observation
0	21.1	0	
5	32.0		
10	38.9		
15	46.2		
20	53.5		
23	57.4		
26	62.0		
29	65.8		
32	69.9		
35	74.0		
38	77.8	0.5	
41	81.4		
44	85.1		
47	89.4	0.6	Boiling
50	90.0		
53	90.0		
56	90.1		
59	90.0		
62	90.0		
64	90.1		
66	90.1		
68	90.2		
70	90.1		
92	90.1	1.2	Evaporation– 5.5 Liters (5.5kg)

3.4.2 Experimental Procedure

In determination of the cooker's performance, water boiling test and flue gas analysis were used to obtain thermal and combustion efficiencies respectively.

3.4.2.1 Water Boiling Test for thermal efficiency and diesel consumption

Water Boiling Test (Set up and its schematic shown in figure 3.6 and 3.7 respectively) was used to find thermal efficiency and rate of diesel consumption. 50 litres of water was heated to boiling point at standard conditions in 24 gallon light duty, 24 gallons heavy duty and 30 litres in 12 gallon cooking pots using the diesel and LPG and measurements of burner temperatures and diesel consumption rate was done during water boiling test by use of the graduated fuel sight gauge fitted on to the fuel cylinder. The 12 gallon pot was inserted into the fire chamber by use of an adapter because its diameter was smaller than the chamber diameter while the 24 gallon pots were inserted without adapters. The tests were done in Eldoret at atmospheric pressure is 0.8 bars and room temperature of between 22.1˚C to 22.3˚C. The combusting diesel was pressurized by use of hand pneumatic pump to 2.5 bars which is the design operating pressure for the cooker. The cooking pot and water were weighed and initial water temperature was determined before boiling.

In the boiling phase, water was first heated from an initial average temperature (T_1) of 21.7 °C to boiling point of 90.1 °C. The boiling point was noted through bubbling of water without temperature increase. During this phase water in the cooking pot gained energy from fuel with the help of the burner and that value of energy is equivalent to energy required to raise the temperature of that mass of water from T_1°C to boiling point.

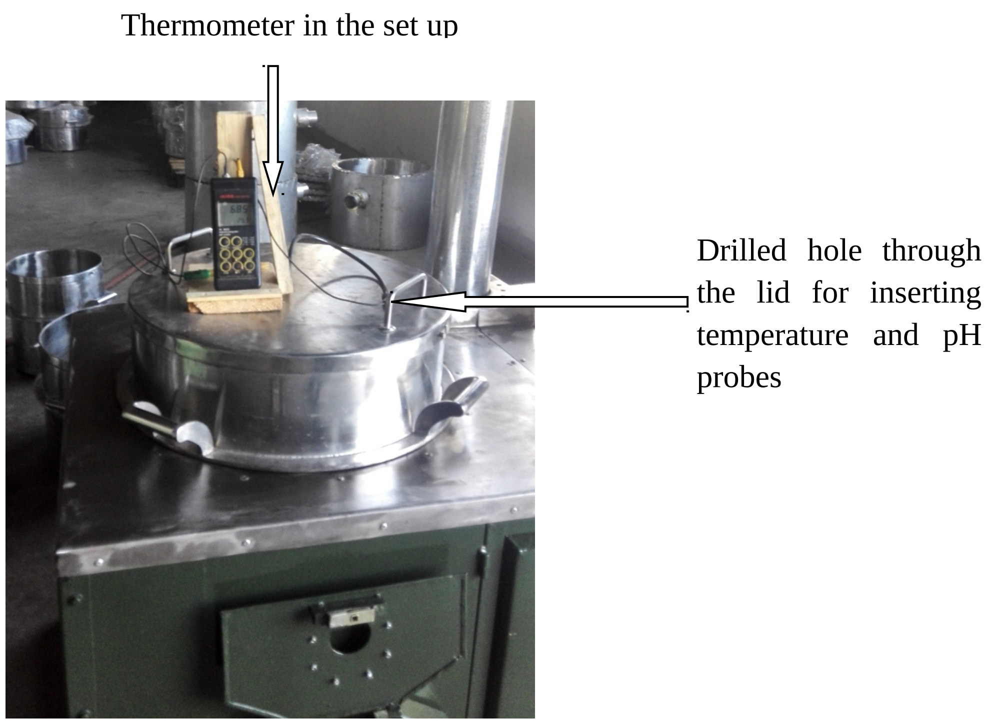


Figure 3.6: Water boiling test set up for DEFKITCH

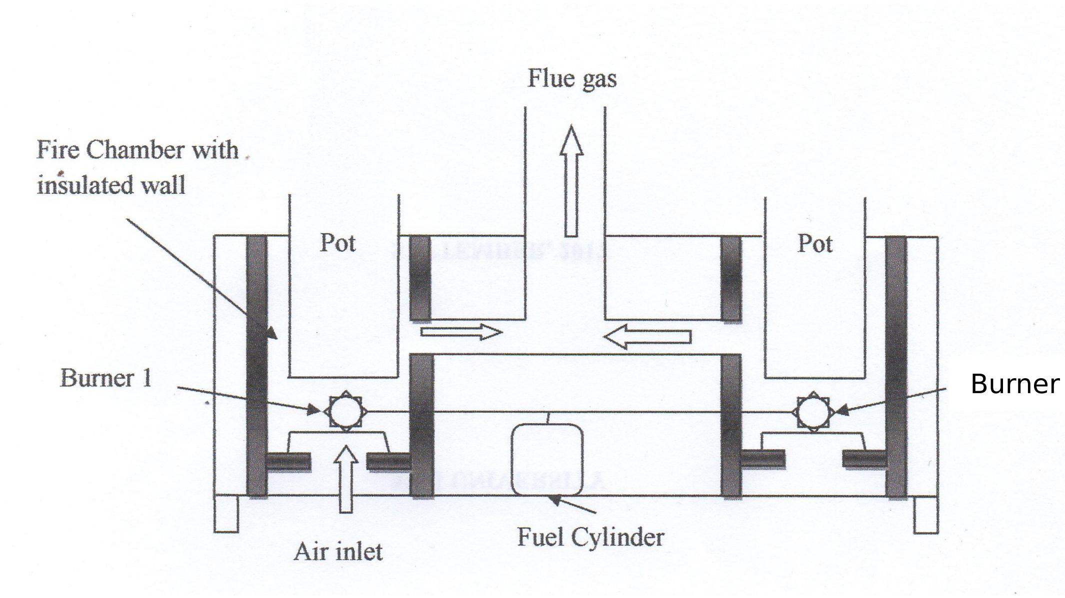


Figure 3.7: Schematic of DEFKITCH cooker

Equation 2.3 was then used to compute thermal efficiency during boiling.

$$\frac{(T2 - T1) \times (Mp\ Cp + Mw\ Cw)}{Mf \times NHVf}$$

Sample calculation for 24 gallon Light duty in Test 1 in appendix A:

Initial Temperature, $T_1 = 21.1\ ^{\circ}C$

Final Temperature, $T_2 = 89.4\ ^{\circ}C$

Mass of Pot, $M_p = 35.1$ kg

Specific Heat Capacity of pot, $C_p = 510$ J/kg/K

Mass of Water, $M_w = 50$ kg

Specific Heat Capacity of Water, $C_w = 4187$ J/kg/K

Mass of Fuel, $M_f = 0.48$ kg

Neat Heating Value of Fuel, $NHV_f = 43$MJ/kg

Thermal Efficiency (boiling) = $\frac{[89.4-21.1] x [(35.1\ x\ 510)+(50\ x\ 4187)]}{0.48\ x\ 43\ x\ 10^6}$

= 0.752

In the simmering phase, predetermined weight of water at boiling point was then subjected to boil for 30 minutes (which was found sufficient to allow reasonable amount of water to evaporate) and energy gained by this water was calculated by multiplying latent heat of vaporization of water and mass of vaporized water. Fuel consumed during each process was recorded from the graduated sight glass of the fuel cylinder as input energy for these phases.

The cooker’s thermal efficiency was determined by calculating the heat gained by the water subjected for heating and amount of fuel consumed during this process (BIS 2002). Equation 2.4 was then used to compute thermal efficiency during simmering.

$$\frac{M_W \times L_W}{M_f \times NHV_f}$$

Mass of evaporated water, Mw = 5.5 kg

Latent Heat of vapourization of water, Lw = 2270 kJ/kg

Mass of fuel consumed, Mf = 0.48 kg

Thermal efficiency (simmering) = $\frac{5.5 \ x \ 2270 \ x \ 10^3}{0.48 \ x \ 43 \ x \ 10^6}$

= 0.6049

Overall thermal efficiency was calculated by dividing output energy by input energy. The analysis consisted of heat gained by cooking pot and three replications of different amounts of water was employed throughout the experiments for different cooking pot sizes and averages of thermal efficiency obtained. For comparison of thermal efficiency, a similar test was conducted on the ARPA model of field cooker.

3.4.2.2 Flue gas test for combustion efficiency

For each set up as shown in figure 3.8, flue gas composition was also measured using flue gas analyser to determine the combustion efficiency and emission levels of greenhouse gases. The flue gas meter probe was inserted in the flue gas pipe and measurement of combustion efficiency was allowed to stabilise before readings were taken. The results were then transmitted to the wireless printer for printing. This procedure was done using diesel and LPG. The following parameters were measured and their effect on thermal and burner combustion efficiencies was analysed based on the heat generated by the burner and the energy potential of the fuel used.

a. Exhaust gas temperatures.
b. Fire chamber temperatures

c. Flue gas composition

The combustion efficiency test was conducted in Nairobi near Jomo Kenyatta International Airport where atmospheric pressure and ambient temperature were 1.024 bars and 32°C respectively.

The collected data from WBT and flue gas analysis were then analysed using graphs and calculations.

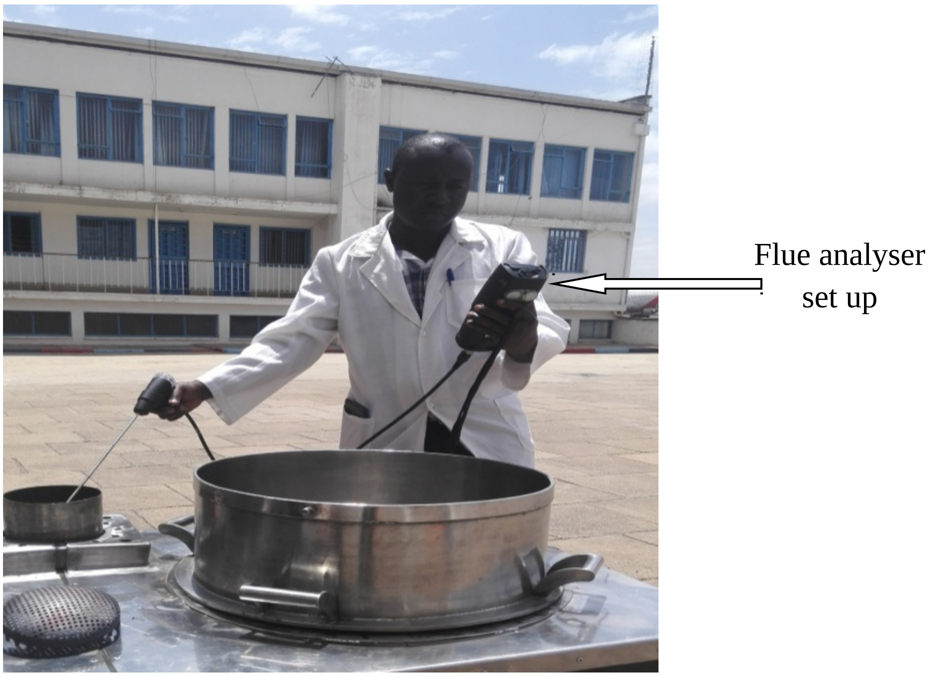


Figure 3.8: Experimental Set up for Flue Gas Measurements

3.4.2.3 Difficulties encountered

Acquiring the flue gas analyser was difficult since it was not available within Eldoret town hence delaying the experiments as the one that was used was found in Nairobi. The flue gas analyser finally acquired again was not capable to measure (NO_x and SO_x) and therefore was a challenge.

The other difficulty was the inability of DEFKITCH cooker to work with LPG since it did not burn well and therefore the flame produced was not sufficient for the water boiling test.

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Introduction

This chapter describes the results of the water boiling tests and flue gas analysis experiments conducted on DEFKITCH cooker while burning diesel and LPG. The water used in the tests was tested and found to be within the recommended requirements of human drinking water. However, water boiling test could not be conducted using LPG because the burner as design could not properly burn the gas to produce sufficient heat for cooking.

4.2 Water Boiling Tests Results

These tests were conducted in order to determine water heating time and fuel consumption rate from which thermal efficiency of DEFKITCH was calculated. From the results of water boiling tests conducted using 24 gal light duty cooking pot; it was observed that the temperature of water rose uniformly from an average of 21.7 ˚C to an average boiling point of 90.1 ˚C for Eldoret region. After boiling, the temperature remained almost constant at 91 ˚C which is attributed to change of phase of water to vapour a process that takes place without increase in temperature. The average flame temperature of the burner while using diesel was 1500˚C. The raw data obtained from water boiling tests are attached in Appendix A, B and C.

After the water boiling tests, graphs of heating time against water temperatures were plotted for all the 24 gallon heavy duty, 24 gallon light duty and the 12 gallon cooking pots as shown in figure 4.1.

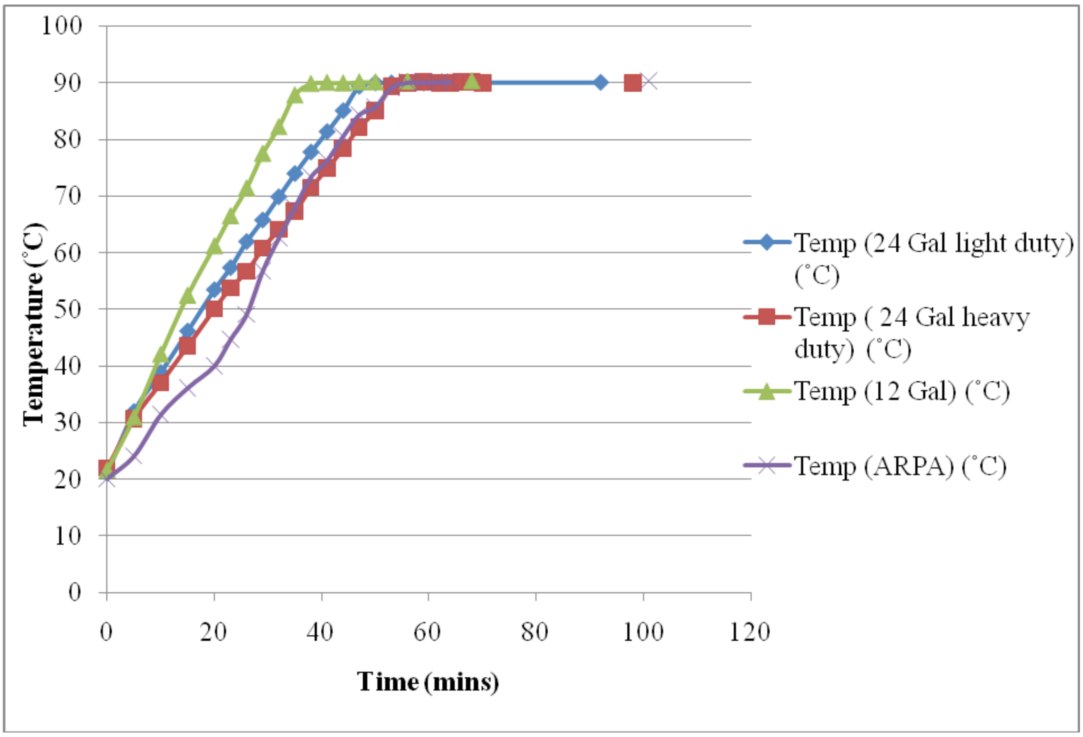


Figure 4.1: Heating curves on the 24 gal light pot, 24 gal heavy pot, 12 gal pots and ARPA

The gradients of the boiling curves varied with the 12 gallon pot being steeper likely due to the lower mass of water of 30 kg and that of the pot of 21.7 kg compared to the 24 gallon pots. This implied less time and energy was needed to raise the temperature of water to boiling point.

The mass of the 24 gallon heavy duty pot which was the heaviest at 41.8 kg compared to the 24 gallon light duty of 35.1 kg contributed to slower heating rate of water in the heavy duty pot as depicted by the lower gradient of its heating curve despite the fact that the two pots had same diameter.

For comparison, water boiling curve for the ARPA kerosene cooker that was in use in KDF before the development of DEFKITCH cooker was also plotted in the same graph as shown in figure 4.1.

4.2.1 Diesel consumption rate

During the water boiling test, the average diesel consumption was observed to be 0.8 litres in one hour when operating at tank pressure of 2.5 bars for the three types of cooking pots namely 24 gallon light duty, 24 gallon heavy duty and 12 gallon. The fuel consumption for ARPA cooker was found to be 1.2 litres of kerosene per hour. The consumption of the fuel was found to be lower than consumption in ARPA cooker due to the small size of the nozzles that is approximately 0.6mm therefore leading to build up of pressure that result into atomization of the fuel. Therefore when the fuel is atomised under pressure its rate consumption tends to be low since it is released in small quantity of vapour for the burning process and fuel air mixing is sufficient. (McConkey and Eastop, 1993)

4.2.2 Thermal efficiency obtained from diesel

The comparison of thermal efficiencies of the cooker using the three sizes of cooking pots is shown in Figure 4.2. A summary of thermal efficiencies from boiling and simmering tests is presented appendix F.

The thermal efficiency of the cooker using 24 gallon light duty cooking pot was found to be 65.86 percent on average which implies that 34.14 percent of heat energy was being lost through conduction in fire chamber walls and top plate and also through convection to heat the surrounding air. This value dropped to 60.37 percent while using 24 gallon heavy duty cooking pot which was attributed to heat energy lost through conduction by the thick walled bottom of the pot. Thermal efficiency obtained using 12 gallon cooking pot was 42.69 percent. This massive decrease in thermal efficiency was attributed to energy loss through conduction from the cooking pot to the 9.4 kg stainless steel pot adapter used in supporting the pot in the fire chamber. Since the pot diameter is smaller than the fire chamber diameter, the adapter is used to hold the small pot on to the cooker. This therefore makes the 12 gallon pot not energy efficient on the cooker.

The boiling time in the 24 gallon light duty pot was observed to be lower at an average of 46 minutes in the first two experiments as compared with an average of 53 minutes in the 24 gallon heavy duty cooking pot. Despite using the same amount of water in the two cooking pots, the boiling time was longer on the heavy duty pot due to the heat energy used to initially preheat the double walled bottom of the pot.

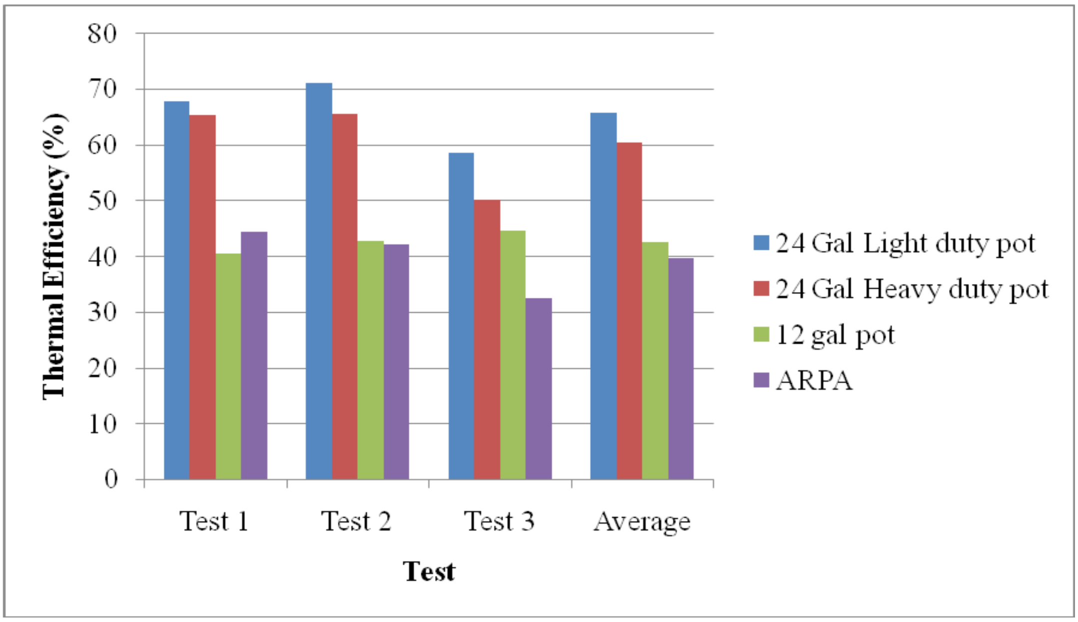


Figure 4.2: Comparison of Efficiencies on Different Pots on Diesel

4.2.3 Thermal performance on liquefied petroleum gas

The cooker was tested using both 6 kg cylinder and 13 kg cylinder but the burner flame was found to be too weak to provide sufficient temperature to cook or perform water boiling test using the heavy gauge cooking pots designed for diesel cooking. The design of the burner did not perform well with LPG because of the long gap between the atomizing nozzle and the fire plate of the burner. The burner was constructed using stainless steel pipes of 9 mm internal diameter which is too large to be used as gas pipes for cooking as opposed to brass material which are common for gas burners (Mohd Y. K. and Anupriya S, 2012). This may have also contributed to the poor performance of the burner on LPG and therefore this burner was found to be inappropriate to be used for cooking using LPG.

4.3 Flue Gas Test

From the flue tests conducted on the two burner DEFKITCH cooker at an ambient temperature of 33.5 degrees Celsius, the composition of flue gas was summarised in Table G1 in appendix G. From the flue gas analysis conducted on the two burner DEFKITCH cooker with one burner on followed by two burners simultaneously at an ambient temperature of 33.5 degrees Celsius, the composition of the flue gas found was summarised as shown in the error bar graphs in figures 4.3 to 4.10.

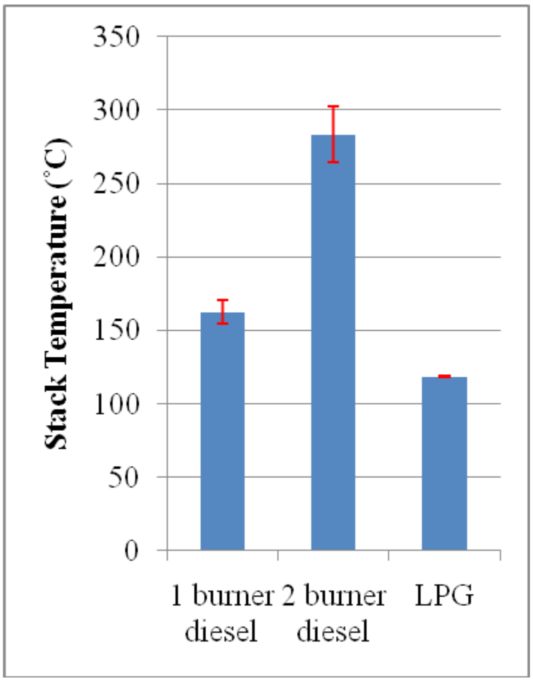


Figure 4.3 Graph of Stack Temperatures

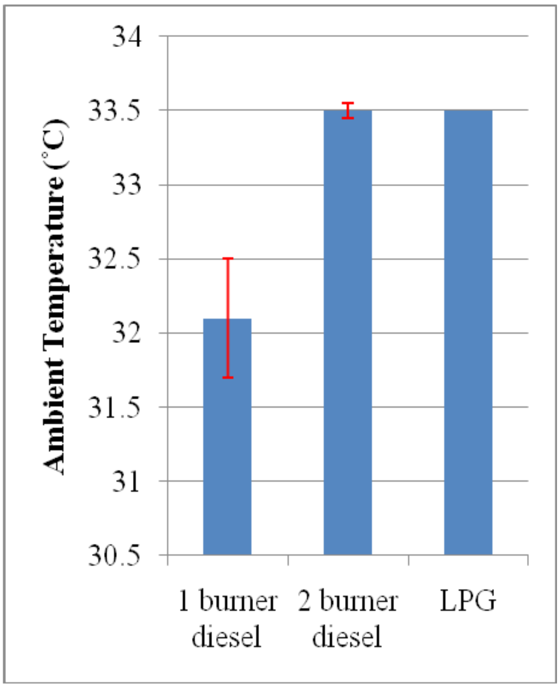


Figure 4.4 Graph of Ambient Temperature

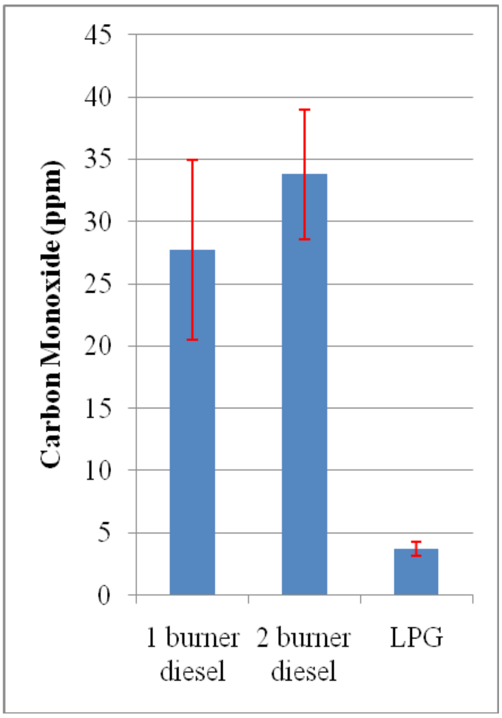


Figure 4.5: Graph of CO Emission

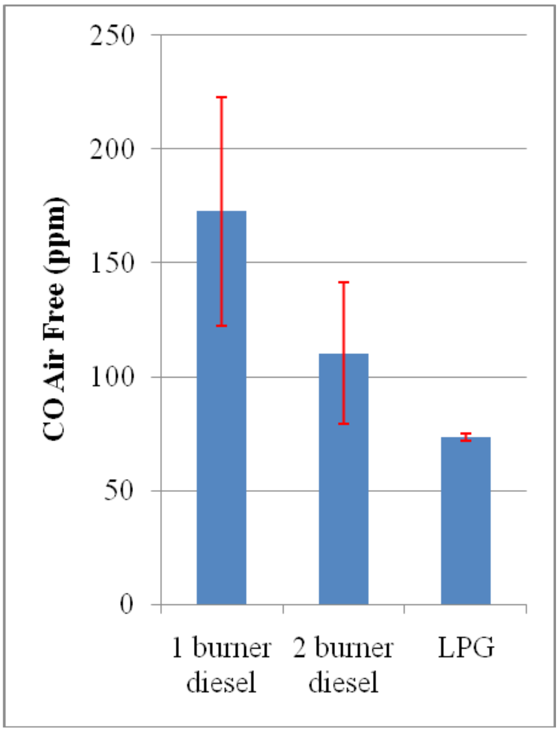


Figure 4.6: Graph of CO Air free in Flue **Gas**

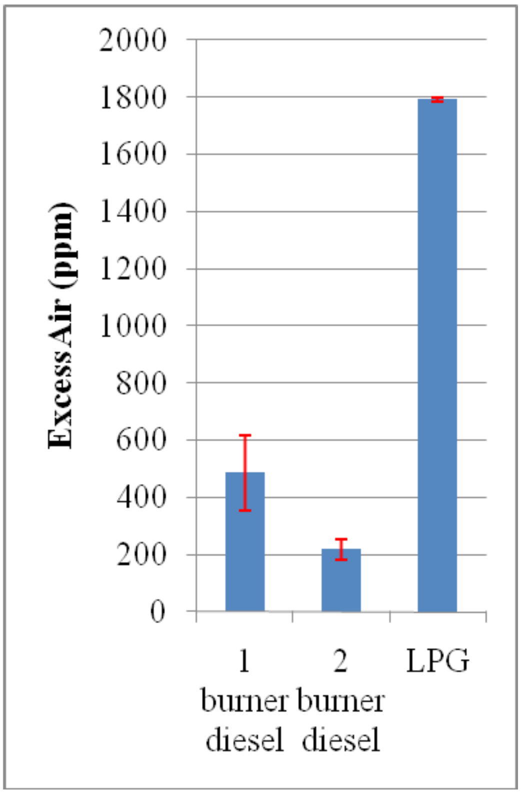


Figure 4.7: Graph of Excess air in Flue Gas

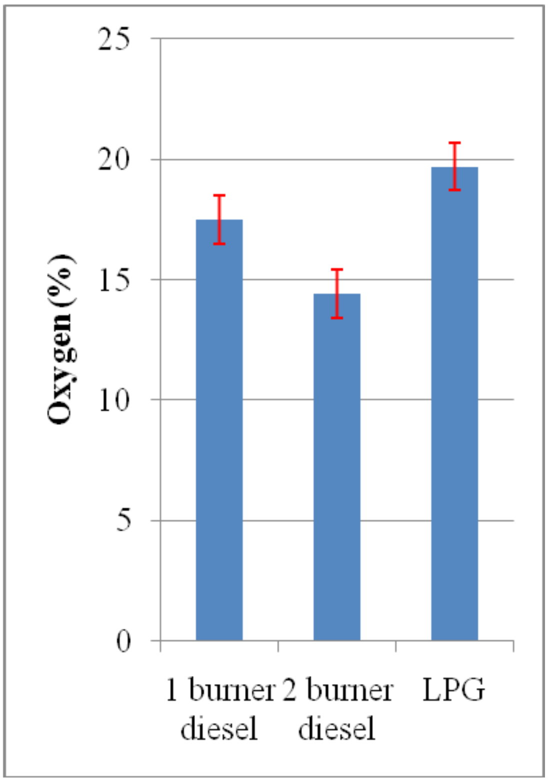


Figure 4.8: Graph of Oxygen in Flue Gas

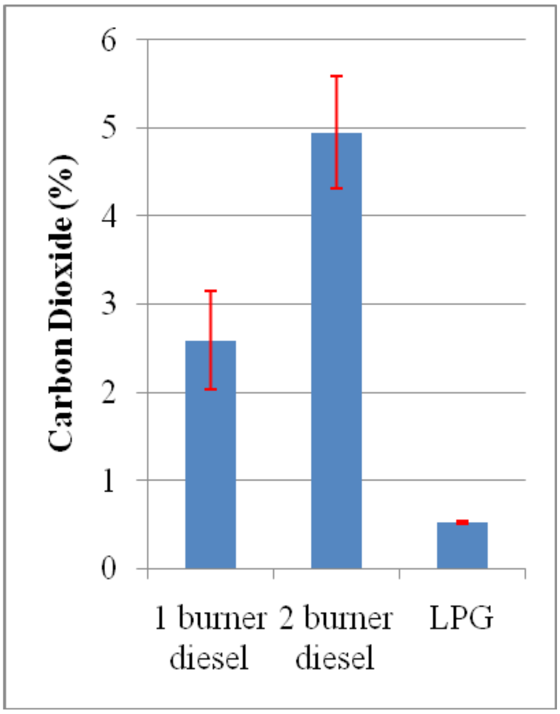


Figure 4.9: Graph of CO_2 in Flue Gas

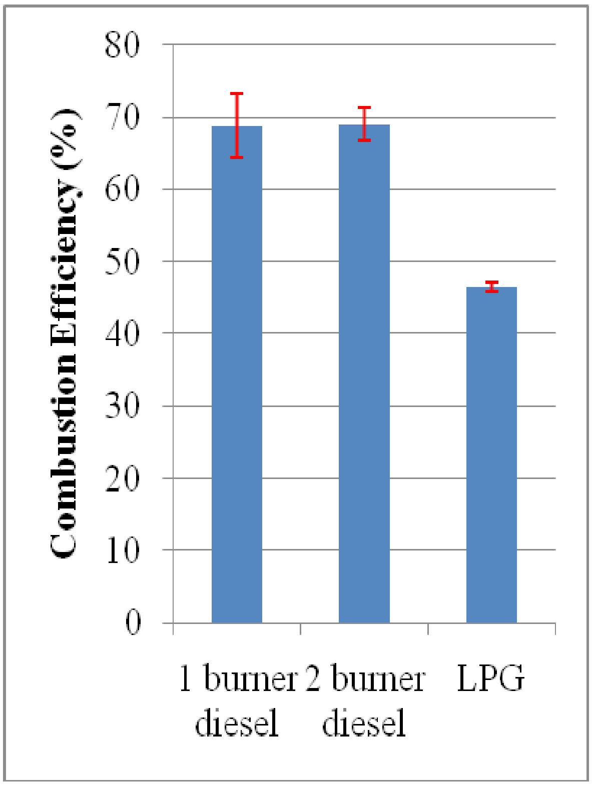


Figure 4.10: Graph of Combustion Efficiency

4.3.1 Combustion efficiency

The average combustion efficiency of the two burner DEFKITCH cooker was found to be 69 percent while using diesel either on a single burner or on two burners. The combustion efficiency of the cooker while using LPG was found to be 46.5 percent which was low compared to the efficiency obtained while burning diesel. This low efficiency is attributed to the design features of burner like the large gap between the nozzle and the fire plate which is about 100 mm which was observed to be unsuitable for burning gas. According to Mishra N. K. et al, 2013, thermal efficiency of LPG radiant burners falls in the range of 3- to 40 percent. However, the highest value of 58 percent is achievable in flat faced burners using LPG (Mohd Y. K and Anupriya S, 2012)

4.3.2 Carbon monoxide

Diluted carbon monoxide level in the flue gas was found to be 27.7 ppm for single burners on diesel (figure 4.5) while the value of CO air free was found to be 172.7 ppm average. The average values of CO air-free for two burners was 110.3 ppm. The CO levels obtained from LPG were found to be lower at 73.3 ppm. Detailed flue gas test result is attached in appendix G. This trend was observed to be within the recommended maximum limits of 400 ppm air free basis according to National Comfort Institute Incorporation, 2008.

4.3.3 Carbon dioxide

CO_2 increased on using two burners which implied that better combustion of the cooker was achieved using two burners running concurrently as opposed to using a single burner. Complete combustion of any fuel takes place in excess air with production of CO_2 and no CO. (Gordon F. C. and Rogers G. F,1992).

4.3.4 Oxygen and excess air

The presence of O_2 in the flue gas meant that more air (20.9 percent of which is O_2) was supplied than was needed for complete combustion to occur therefore some O_2 is left over. The value of excess air in the flue gas was observed to reduce from 486.3 ppm using single burner to 217.6 ppm while using two burners. This was attributed to increase fuel supply due to the introduction of the second burner but with limited air supply from natural aspiration hence more air was consumed in the combustion process.

4.3.5 Stack temperature

The flue gas temperature of the cooker increased from 162 .4 ˚C when using a single burner to 283.4 ˚C when using two burners on diesel. This increase was attributed to the introduction of the second burner which meant more heat directed to the chimney stack. These temperatures were high enough to prevent water formation in the chimney; however the rise in temperatures obtained on two burners indicated that more heat energy was being lost through exhaust gases and this could be tapped to recover waste heat for higher efficiencies.

4.4 Other observations

It was observed that the field kitchen burner produced a lot noise similar during operation. This noise may negatively affect cooks and the people near by the kitchen.

4.5 Conclusion

From literature review, most cookers have combustion and thermal efficiencies of 86.7 percent and 50 to 60 percent respectively while DEFKITCH cooker's highest thermal and combustion efficiencies were found to be 65.86 and 69.0 percent respectively.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusion

The results obtained in this work lead to the following conclusions:

1. Thermal efficiency of the diesel burner was determined using water boiling test and the value was found to range from 60.37 percent to 65.86 percent using the 24 gallons cooking pots while a lower value of 42.69 percent was obtained using the 12 gallon pot on the same cooker. These values were found to be close to the thermal efficiencies of the LPG cookers in the reviewed literatures whose efficiency ranged from 58 percent to 68 percent. The difference in thermal efficiency could be due to different ambient condition under which the experiments were done.

2. Combustion efficiency of the cooker was determined using TESTO flue gas analyser. The overall combustion efficiency was found to be 69 percent while burning diesel and 46.5 percent while burning LPG.

3. Emission levels for CO and CO_2 were determines as 172.7 ppm and 49,500 ppm (4.95) percent while using two burners on diesel. These were found to be within the recommended emission levels. However, the equipment had the limitation of measuring all the flue gases, therefore NO_x and SO_x were never determined.

4. Average diesel consumption per burner was found to be 0.8 litres in one hour for the KDF cooker which is enough to prepare a meal for approximately two hundred people in a cooking session of one hour. The equipment was found to be economical in diesel consumption per unit amount of work and is a better

substitute to using firewood for cooking food for a large group of people especially in remote location like in military operation areas.

5. Research on KDF diesel field cooker had never been done before; therefore this work provided technical data on its performance. It also added to the database of previous research on performance of various types of cook stoves and other energy utilities. The cooker performance on diesel was compared to the ARPA kerosene cooker that existed in KDF before and was found to be higher than that of ARPA by 64.65% in thermal performance.

From this research work, the following were suggested to improve DEFKITCH's efficiency:

- The design of the 12 gallon cooking pot need to be changed to eliminate the use of pot adapter in order to increase the thermal efficiency while cooking in the 12 gallon pot.
- Liquefied petroleum gas should not be used on the burner because it not effective and is less efficient unless the burner design is changed.
- The waste heat from the flue gas need to be tapped by means of a heat exchanger to preheat water during the initial cooking for use subsequent cooking processes. This will improve the efficiency of the cooker.
- The noise generated from the burner to the surrounding environment need to be minimised by use of noise absorbing materials in the body of the field cooker.

5.2 Recommendations

The present research provided valuable information on the performance of DEFKITCH cooker. However, recommendations for further work do suffice.

- Further experiments on flue gas needed to be conducted to determine NO_x and SO_x emission levels from the cooker on both diesel and LPG.
- More research needed to be conducted to determine the optimum sizes and mass of cooking pots that can achieve higher (improved) thermal efficiencies.
- Further research needed to be conducted on the cooker to determine the possibility of using biodiesel
- Further experiments are needed to reduce emissions and to review burner design for efficient use of LPG.

REFERENCES

Agatha, W., et al. (2010). Performance of a domestic cooking wick stove using fatty acid methyl esters (FAME) from oil plants in Kenya. *Biomass and Bioenergy* Volume 34, Issue 8, August 2010, (pp. 1250–1256).

Bureau of Indian Standards 10109. (1999 & 2002). *Oil pressure Stoves (Standard)*. First and Second Revision (pp.5-10).

Christoffer, B., et al. (2011). Stove Performance and Emission Characteristics in Residential Wood Log and Pellet Combustion, Part 1: Pellet Stoves. *Energy Fuels*.11, 25 (1), (pp 307–314) DOI**:** 10.1021/ef100774x Publication Date (Web): January 5, 2011.

Gordon, F. C., & Rogers, G. F. (1992). *Engineering Thermodynamics: Work and Heat Transfer : SI Unit.* (4th ed). Longman Scientific & Technical.

Heena, V. P., et al. (2009). Combustion Performance of Biodiesel and Diesel-Vegetable Oil Blends in a Simulated Gas Turbine Burner. *J. Eng. Gas Turbines Power* 131(3), 031503 (Feb 06, 2009) (11 pages) doi:10.1115/1.2982137

James, L. B. (2005). *Combustion analysis: An Essential Reference for The Advanced Technician*. *(Applications Guide).* Testo Incorporation.

Jugjai, S.T., & Trewetasksorn. (2001). Thermal efficiency improvement of an LPG gas cooker by a swirling central flame. *International Journal of Energy Research*, Vol. 25, Issue 8, (pp. 657–674, 25).

Kenya Defence Forces (KDF) Energy Audit Report (2010).

Kenya Defence Forces Energy Policy Document (2010).

Kenya National Bueau of Statistics (KNBS) Baseline Report 2007.

Kenya Standards (1996). *Water Quality and Effluent Monitoring Guidelines (Standard).* KS 05 – 459: Para 1: Schedule 2, (pp 26 – 41).

Kumar, S. (2005). Estimation of design parameters for thermal performance evaluation of box type solar cooker, *Science Direct*, *30* (7), 1117-1126.

Lalitpur, N. (2001). Efficiency Measurement of Biogas, Kerosene and LPG Stoves. *International Journal of Innovative Research in Science, Engineering and Technology* (IJIRSET). Volume 3, Special Issue 4, April 2014

Li, H., et al. (2006). Thermal performances and carbon monoxide emissions of gas-fired cooker-top burner. *Applied Energy,* 83(12), 1326-1338.

Makmool, U., et al, (2007). Performance and analysis by particle image velocimetry (PIV) of cooker-top burners in Thailand. *International Journal of Energy Research*, Vol. 32, Issue 8, (pp. 1986-1995).

McConkey, A., & Eastop, T. D. (1993). *Applied Thermodynamics For Engineering Technologists*. (5th ed). Longman Singapore publishers.

Mishra, N. K., et al. (2013). Performance Tests on Medium-Scale Porous Radiant Burners for LPG Cooking Applications. *International Journal of Emerging Technology and Advanced Engineering* Volume 3, Special Issue 3: ICERTSD 2013. 126-130.

Mohd, Y. K., & Anupriya, S. (2012). Performance of Insulated LPG Burner with Ball Bearings as Porous Medium. *PJST ISSN: 2249- 5487*.VOl.2 (1), Jan-June-2012 (IJIRSET).

Murthy, M., et al. (2011). *Clean Energy and Technology (CET)*. IEEE First Conference on Date of Conference: 27-29 June 2011. Print ISBN: 978-1-4577-1353-8 , 145 - 150.

National Comfort Institute Incorporation (2008). *Carbon Monoxide levels and Risks*. www.cloudhvac.com

Ngigi, A. (2008). *Kenya Country Baseline report and Workplan.* KNBS

Olubiyi, O. D. (2014). "Design, Construction And Performance Evaluation Of A Biogas Burner." An Msc Thesis Submitted to the Postgraduate School, Ahmadu Bello University Zariain Partial Fulfilment of the Requirements for the Award of Masters of Science (M.Sc) Degree In Mechanical. *International Journal of Innovative Research in Science, Engineering and Technology* (IJIRSET). Volume 3, Special Issue 4, April 2014.

Pantangi, V.K., et al. (2011). Studies on porous radiant burners for LPG (liquefied petroleum gas) cooking applications. *Energy* 36 (2011) 6074e6080 (IJIRSET)

SHI, Yi-ping., & WANG, Yong-bin. (2005). The development of heat exchange system for a diesel-hot-air stove of exhaust gas recirculation in greenhouses. *Journal of Ningbo Polytechnic*; 2005-02.

Tekle, A. (2014). Experimental Assessment on Thermal Performance and Efficiency of Pyra-Box Solar Cooker. *Journal of Energy Technologies and Policy* www.iiste.org ISSN. 2224-3232. (Paper) ISSN 2225-0573 (Online) Vol.4, No.7.

Vishal, R. Sardeshpande, D. S. (2010). *Thermal performance evaluation of a four pan jaggery processing furnace for improvement in energy utilization*. Volume 35, Issue 12. (pp.4740-4747). The 3rd International Conference on Sustainable Energy and Environmental Protection, SEEP 2009.

Walter M. B., et al. (1921). *Design of Atmospheric Burners*. Technologic Papers of The Bureau of Standards, September 6 1921. IJIRSET Vol 3, Special Isssue 4, April 2014.

Wayne, C. T., & Steve, D. (2007). *Energy management Hand book,*. (6th Edition pp 89-116). The Fairmont press Inc.

APPENDICES

Appendix A: Water Boiling Test Results for 24 Gal Light Duty Pot

<u>TEST 1</u>
Room Temp = 19.1 ˚C
Mass of Pot = 29.9 kg
Mass of Pot + Lid = 35.1 kg
Mass of Water = 50 kg

Table A1: Temp Measurements

Time (Min)	Temp (˚C)	Diesel Consumption (Ltrs)	Observation
0	21.1	0	
5	32.0		
10	38.9		
15	46.2		
20	53.5		
23	57.4		
26	62.0		
29	65.8		
32	69.9		
35	74.0		
38	77.8	0.5	
41	81.4		
44	85.1		
47	89.4	0.6	Boiling
50	90.0		
53	90.0		
56	90.1		
59	90.0		
62	90.0		
64	90.1		
66	90.1		
68	90.2		
70	90.1		
92	90.1	1.2	Evaporation– 5.5 Liters (5.5kg)

<u>TEST 2</u>
Room Temp = 21.8 ˚C
Mass of Pot = 29.8 kg
Mass of Pot + Lid = 35 kg
Mass of Water = 50 kg

Table A2: Temp Measurements

Time (Min)	Temp (˚C)	Diesel Consumption (Ltrs)	Observation
0	22.1	0	
5	30.5		
10	43.1		
15	50.3		
20	59.7		
23	62.8		
26	67.6		
29	71.2		
32	75.4	0.5	
35	80.2		
38	84.0		
41	87.3		
44	90.8	0.75	Boiling
47	91.0		
50	91.0		
53	90.9		
56	91.0		
59			
62			
64	91.0		
66			
68			
70			
89	91.0	1.25	Evaporation– 6.2 Liters (6.2 kg)

<u>TEST 3</u>
Room Temp = 22.4 ˚C
Mass of Pot = 29.7 kg
Mass of Pot + Lid = 35 kg
Mass of Water = 50 kg

Table A3: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	22.0	0	
5	30.0		
10	36.2		
15	42.2		
20	48.0		
23	51.5		
26	54.8		
29	58.7		
32	61.5		
35	64.5		
38	67.5		
41	70.7		
44	74.3	0.5	
47	77.3		
50	81.0		
53	84.6		
56	87.3		
59	90.1	0.75	Boiling
62	90.2		
64	90.1		
66	90.0		
68	90.1		
70			
104	90.1	1.35	Evaporation– 5.2 Liters (5.2kg)

Appendix B: Water Boiling Test Results for 24 Gal Heavy Duty Pot

<u>TEST 1</u>
Room Temp = 22.0 ˚C
Mass of Pot = 36.6 kg
Mass of Pot + Lid = 41.8 kg
Mass of Water = 50 kg

Table B1: Temp Measurements

Time (Min)	Temp (˚C)	Diesel Consumption (Ltrs)	Observation
0	22.0	0	
5	30.7		
10	37.0		
15	43.5		
20	50.1		
23	53.8		
26	56.7		
29	60.8		
32	64.1		
35	67.3	0.5	
38	71.5		
41	74.9		
44	78.4		
47	82.2		
50	85.1		
53	89.4	0.7	Boiling
56	90.0		
59	90.1		
62	90.0		
64	90.0		
66	90.1		
68	90.1		
70	90.0		
98	90.0	1.2	Evaporation– 5.0 Liters (5.0kg)

<u>TEST 2</u>
Room Temp = 20.5 ˚C
Mass of Pot = 36.6 kg
Mass of Pot + Lid = 41.8 kg
Mass of Water = 50 kg

Table B2: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	20.3	0	
5	30.2		
10	37.4		
15	43.2		
20	50.4		
23	54.7		
26	59.1		
29	63.1		
32	67.0	0.5	
35	71.2		
38	75.1		
41	79.0		
44	82.5		
47	87.0		
50	90.4	0.75	Boiling
53	90.5		
56	90.5		
59	90.4		
62			
64			
66	90.3		
68			
70			
95	90.5	1.25	Evaporation – 5.2 Liters (5.2 kg)

<u>TEST 3</u>
Room Temp = 21.3 ˚C
Mass of Pot = 35.9 kg
Mass of Pot + Lid = 41.1 kg
Mass of Water = 50 kg

Table B3: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	20.0	0	
5	29.8		
10	37.0		
15	43.2		
20	49.6		
23	53.0		
26	56.4		
29	60.0		
32	63.7		
35	68.0	0.5	
38	71.1		
41	74.4		
44	77.5		
47	80.7		
50	84.2		
53	87.2		
56	90.5	0.8	Boiling
59	90.5		
62	90.4		
64	90.4		
66	90.3		
68	90.2		
70			
101	90.4	1.55	Evaporation– 4.7 Liters (4.7 kg)

Appendix C: Water Boiling Test Results for 12 Gal Pot

<u>TEST 1</u>
Room Temp = 21.4 ˚C
Mass of Pot = 18.9 kg
Mass of Pot + Lid =21.8 kg
Mass of Water = 30 kg

Table C1: Temp Measurements

Time (Min)	Temp (˚C)	Diesel Consumption (Ltrs)	Observation
0	21.7	0	
5	31.0		
10	42.1		
15	52.5		
20	61.2	0.3	
23	66.5		
26	71.4		
29	77.5		
32	82.2		
35	87.8		
38	89.8	0.6	Boiling
41	90.0		
44	89.9		
47	90.1		
50	90.1		
53			
56	90.2		
59			
62			
64			
66			
68	90.3	1.3	Evaporation – 3.8 Liters (3.8 kg)

TEST 2
Room Temp = 20.1 ˚C
Mass of Pot = 18.9 kg
Mass of Pot + Lid = 21.8 kg
Mass of Water = 30 kg

Table C2: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	20.7	0	
5	32.1		
10	39.2		
15	49.5		
20	58.6		
23	64.0		
26	69.2		
29	73.0		
32	79.5	0.5	
35	83.9		
38	88.7	0.6	Boiling
41	89.0		
44	89.2		
47	89.1		
50	90.0		
53	90.0		
56			
59			
62			
64			
66			
68	89.9	1.2	Evaporation – 3.7 Liters (3.7 kg)

TEST 3
Room Temp = 21.6 ˚C
Mass of Pot = 18.8 kg
Mass of Pot + Lid = 21.7 kg
Mass of Water = 30 kg

Table C3: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	20.6	0	
5	31.6		
10	41.5		
15	50.8	0.2	
20	59.3		
23	64.5		
26	70.1		
29	75.6		
32	80.7		
35	85.0		
38	89.9	0.7	Boiling
41	90.0		
44	90.0		
47	90.2		
50	90.1		
53	90.1		
56			
59	90.2		
62			
64			
66			
68	90.4	1.2	Evaporation – 3.8 Liters (3.8 kg)

Appendix D: Water Boiling Test Results for ARPA Cooker

TEST 1
Room Temp = 19.1 ˚C
Mass of Pot = 27.5 kg
Mass of Pot + Lid = 33.1 kg
Mass of Water = 50 kg

Table D1: Temp Measurements

Time (Min)	Temp (˚C)	Diesel Consumption (Ltrs)	Observation
0	20.1	0	
5	24.1		
10	31.4		
15	36.1		
20	40.0		
23	44.7		
26	49.1	0.5	
29	56.8		
32	62.6		
35	68.0		
38	73.4		
41	76.3		
44	80.6		
47	84.4		
50	85.8		
53	89.2		
56	90.1	1.2	Boiling
59	90.1		
62	90.2		
64	90.2		
66			
68			
70			
101	90.4	1.8	Evaporation– 4.6 Liters (4.6 kg)

<u>TEST 2</u>
Room Temp = 21.0 ˚C
Mass of Pot = 27.5 kg
Mass of Pot + Lid = 33.1 kg
Mass of Water = 50 kg

Table D2: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	20.3	0	
5	23.5		
10	27.3		
15	32.0		
20	36.8		
23	41.3		
26	45.2	0.5	
29	51.1		
32	56.4		
35	61.0		
38	66.1		
41	73.4		
44	78.7		
47	81.5		
50	84.9		
53	86.3		
56	89.2		
59	90.3	1.3	Boiling
62	90.3		
64	90.2		
66	90.3		
68			
70			
104	90.4	2.0	Evaporation– 5.2 Liters (5.2 kg)

<u>TEST 3</u>
Room Temp = 21.4 ˚C
Mass of Pot = 27.5 kg
Mass of Pot + Lid = 33.1 kg
Mass of Water = 50 kg

Table D3: Temp Measurements

Time (Min)	**Temp (˚C)**	**Diesel Consumption (Ltrs)**	**Observation**
0	22.1	0	
5	24.0		
10	26.4		
15	30.3		
20	35.2		
23	38.7		
26	43.0	0.5	
29	48.4		
32	53.0		
35	58.5		
38	62.9		
41	67.0		
44	73.8		
47	75.9		
50	79.9		
53	83.6		
56	86.3		
59	88.8		
62	90.6	1.2	Boiling
64	90.6		
66	90.6		
68	90.5		
70			
107	90.5	2.2	Evaporation – 4.2 Liters (4.2 kg)

Appendix E: Heat Capacity and Density of Experimental Materials

Density Measurements

- Mass of Empty beaker = 0.6 kg
- Mass of Beaker + Diesel = 1.4 kg
- Mass of Beaker + Water = 1.6 kg
- Volume of Beaker used = 1000 cm^3
- Density of Water **(ρ_w)** = 1000 kg/m^3
- Density of Diesel **(ρ_d)** = 800 kg/m^3
- Atmospheric Pressure (Eldoret) = 0.8 bars

Thermal Properties of materials used in the experiments [2]

- Specific heat of Stainless steel Grade 304 = 510 J/kg/K.
- Net calorific value of diesel = 43MJ/kg. or 34.4 MJ/L.
- Net calorific value of kerosene = 43 MJ/kg or 34.4 MJ/L
- Net calorific value of LPG = 113 MJ/m^3
- Specific heat of water = 4.187 KJ/kgK
- Latent heat of vaporization of water = 2270 kJ/kg

Appendix F:

Table F1: Thermal Efficiency Results

Pot	**Thermal Efficiency (%)**						
	Test 1		**Test 2**		**Test 3**		**Average**
	Boiling	Simmering	Boiling	Simmering	Boiling	Simmering	
24 Gal Light duty pot	75.20	60.49	60.50	81.83	59.97	57.19	65.86
24 Gal Heavy duty pot	64.56	65.99	62.67	68.63	59.00	41.35	60.37
12 gal pot	45.11	35.82	45.04	40.69	39.33	50.15	42.69
ARPA	38.36	50.59	35.41	49.02	37.54	27.72	39.77

Table F2: Summary of Thermal Efficiencies

Pot	**Thermal Efficiency (%)**			
	Test 1	**Test 2**	**Test 3**	**Average**
24 Gal Light duty pot	67.85	71.17	58.58	65.86
24 Gal Heavy duty pot	65.28	65.65	50.18	60.37
12 gal pot	40.47	42.87	44.74	42.69
ARPA	44.48	42.22	32.63	39.77

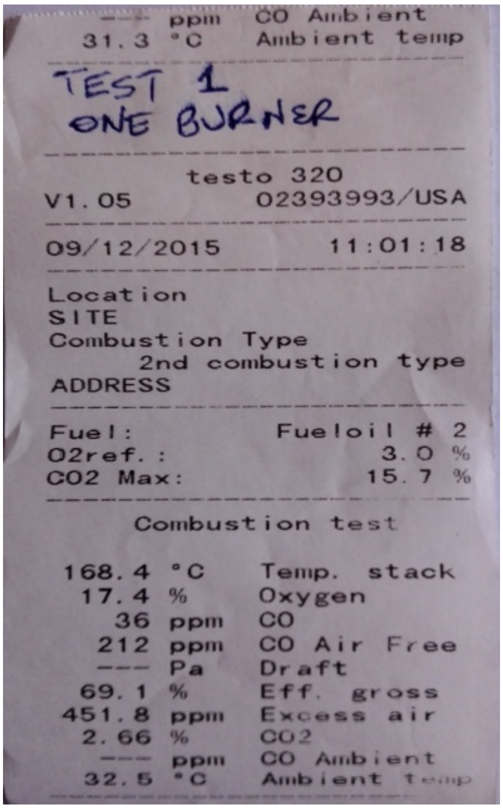
Appendix G: Flue Gas Test Results

Table G1: Flue gas test summary

Parameter	Burners	Unit	Test 1	Test 2	Test 3	Test 4	Average	Standard Deviation
Temperature of stack	1 burner diesel	˚C	168.4	153.5	165.2	-	162.4	7.84
	2 burner diesel	˚C	279.6	258.3	296.8	298.7	283.4	18.78
	LPG	˚C	118.3	119.0	118.5	-	118.6	0.36
Oxygen (O_2)	1 burner diesel	%	17.4	18.3	16.8	-	17.5	0.75
	2 burner diesel	%	15.3	14.8	13.6	13.7	14.4	0.83
	LPG	%	19.8	20.1	19.2	-	19.7	0.46
Carbon Monoxide (CO)	1 burner diesel	ppm	36	24	23	-	27.7	7.23
	2 burner diesel	ppm	41	34	30	30	33.8	5.19
	LPG	ppm	4	4	3	-	3.7	0.58
CO Air free	1 burner diesel	ppm	212	190	116	-	172.7	50.29
	2 burner diesel	ppm	152	116	86	87	110.3	31.12
	LPG	ppm	73	75	72	-	73.3	1.53
Excess air	1 burner diesel	ppm	451.8	633.0	374.1	-	486.3	132.85
	2 burner diesel	ppm	251.1	242.6	186.3	190.3	217.6	34.02
	LPG	ppm	1800.0	1790.8	1800.5	-	1791.1	5.46
Carbon dioxide (CO_2)	1 burner diesel	%	2.66	1.99	3.11	-	2.59	0.56
	2 burner diesel	%	4.23	4.61	5.52	5.44	4.95	0.63
	LPG	%	0.53	0.50	0.52	-	0.52	0.02
Ambient Temperature	1 burner diesel	˚C	32.5	31.7	32.2	-	32.1	0.40
	2 burner diesel	˚C	33.5	33.4	33.5	33.5	33.5	0.05
	LPG	˚C	33.5	33.5	33.5	-	33.5	0.00

Combustion efficiency	1 burner diesel	%	69.1	64.2	73.1	-	68.8	4.46
	2 burner diesel	%	65.6	70.3	70.4	69.6	69.0	2.28
	LPG	%	46.0	47.3	46.1	-	46.5	0.72

Flue Gas Test Results Print Outs


--- ppm CO Ambient
31.3 °C Ambient temp

TEST 1
ONE BURNER

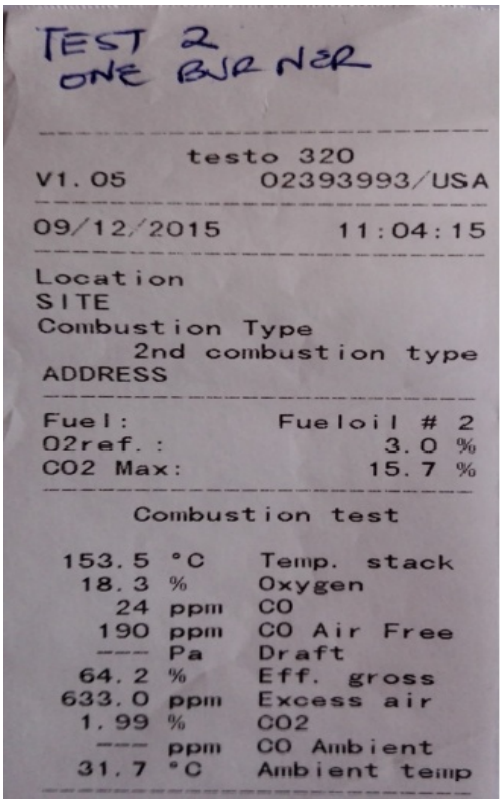
testo 320
V1.05 02393993/USA
09/12/2015 11:01:18

Location
SITE
Combustion Type
2nd combustion type
ADDRESS

Fuel:	Fueloil # 2	
O2ref.:	3.0	%
CO2 Max:	15.7	%

Combustion test

168.4	°C	Temp. stack
17.4	%	Oxygen
36	ppm	CO
212	ppm	CO Air Free
---	Pa	Draft
69.1	%	Eff. gross
451.8	ppm	Excess air
2.66	%	CO2
---	ppm	CO Ambient
32.5	°C	Ambient temp


TEST 2
ONE BURNER

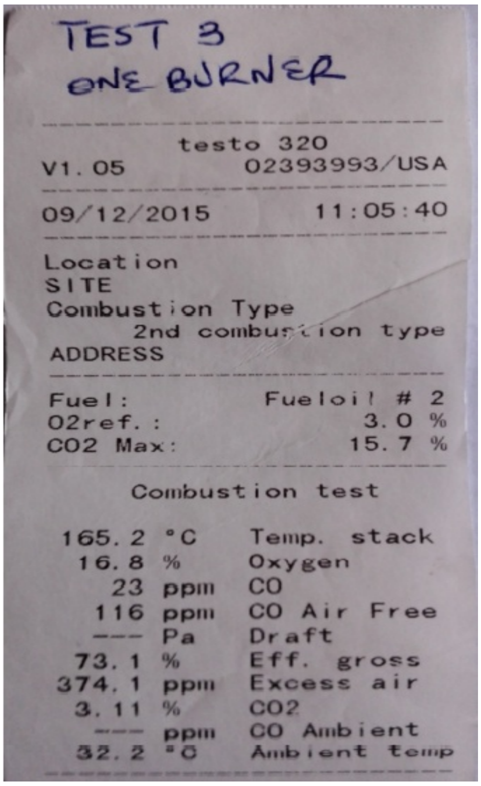
testo 320
V1.05 02393993/USA
09/12/2015 11:04:15

Location
SITE
Combustion Type
2nd combustion type
ADDRESS

Fuel:	Fueloil # 2	
O2ref.:	3.0	%
CO2 Max:	15.7	%

Combustion test

153.5	°C	Temp. stack
18.3	%	Oxygen
24	ppm	CO
190	ppm	CO Air Free
---	Pa	Draft
64.2	%	Eff. gross
633.0	ppm	Excess air
1.99	%	CO2
---	ppm	CO Ambient
31.7	°C	Ambient temp


TEST 3
ONE BURNER

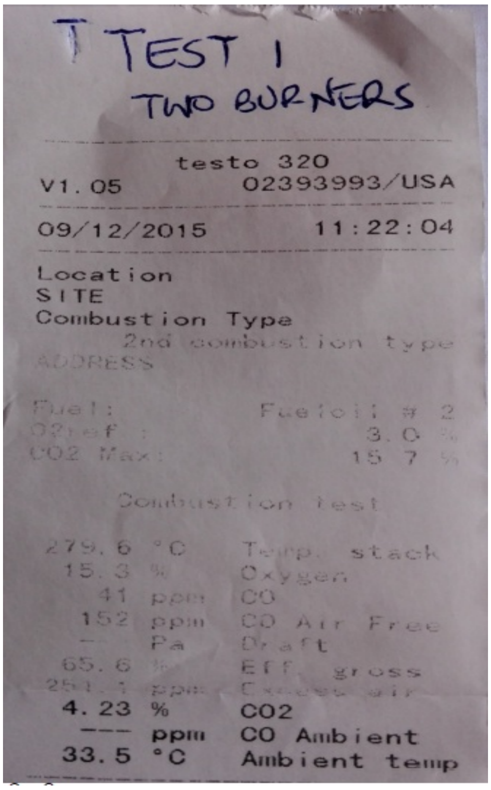
testo 320
V1.05 02393993/USA
09/12/2015 11:05:40

Location
SITE
Combustion Type
2nd combustion type
ADDRESS

Fuel:	Fueloil # 2	
O2ref.:	3.0	%
CO2 Max:	15.7	%

Combustion test

165.2	°C	Temp. stack
16.8	%	Oxygen
23	ppm	CO
116	ppm	CO Air Free
---	Pa	Draft
73.1	%	Eff. gross
374.1	ppm	Excess air
3.11	%	CO2
---	ppm	CO Ambient
32.2	°C	Ambient temp


TEST 1
TWO BURNERS

testo 320
V1.05 02393993/USA
09/12/2015 11:22:04

Location
SITE
Combustion Type
2nd combustion type
ADDRESS

Fuel:	Fueloil # 2	
O2ref.:	3.0	%
CO2 Max:	15.7	%

Combustion test

279.6	°C	Temp. stack
15.3	%	Oxygen
41	ppm	CO
152	ppm	CO Air Free
---	Pa	Draft
65.6	%	Eff. gross
251.1	ppm	Excess air
4.23	%	CO2
---	ppm	CO Ambient
33.5	°C	Ambient temp

Flue Gas Test Results Screenshots