

**PERFORMANCE OF WASTE LUBRICATION
OIL BURNER FOR PROCESS HEATING IN
SMALL TO MEDIUM ENTERPRISES**

BERNARD OTIENO OWITI

**MASTER OF SCIENCE
(Mechanical Engineering)**

**JOMO KENYATTA UNIVERSITY OF
AGRICULTURE AND TECHNOLOGY**

2015

**Performance of Waste Lubrication Oil Burner for Process
Heating in Small to Medium Enterprises**

Bernard Otieno Owiti

**A thesis submitted in partial fulfilment for the Degree of Master
of Science in Mechanical Engineering in the Jomo Kenyatta
University of Agriculture and Technology**

2015

DECLARATION

This thesis is my original work and has not been presented for a degree in any other university.

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

Bernard Otieno Owiti

This thesis has been submitted for examination with our approval as the university supervisors.

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

Dr. (Eng) Hiram M. Ndiritu

JKUAT, Kenya

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

Dr. Benson B. Gathitu

Technical University of Kenya

DEDICATION

I dedicate this work to my loving family. A special feeling of gratitude to my wife Beatrice and children Patrick and Jane. Their encouragement motivated me to work even harder in this research. I also dedicate it to my late parents, Mr. Patrice Owiti and Mrs. Jane Owiti.

ACKNOWLEDGEMENTS

Thanks be to God the Almighty, first and foremost, for giving me the opportunity to do this research. May I sincerely thank my supervisors Dr. (Eng.) Hiram Ndiritu and Dr. Benson Gathitu who guided and supported me throughout the research period. I am also very grateful to the Government of Kenya through JKUAT for offering me a scholarship to do MSc. in Mechanical Engineering.

I would like to thank Kenyatta University Chemistry department for allowing me to carry out some tests in their laboratory which contributed partly to the success of this research. I also want to thank National Environment Management Authority (NEMA) for the important information it provided regarding handling of wastes in general and waste oils in particular. Food Science Department of JKUAT and Ministry of Roads (Material Testing Department) of Kenya also played critical roles in determining Waste Lubrication Oil (WLO) properties for use in this research.

Finally, I want to extend my gratitude to the staff members, technicians and technologists of the department of mechanical engineering and Engineering workshops (JKUAT) for their assistance during this period.

TABLE OF CONTENTS

DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF TABLES	ix
LIST OF FIGURES	xi
LIST OF APPENDICES	xiii
LIST OF ABBREVIATIONS	xiii
NOMENCLATURE	xvi
ABSTRACT	xviii
CHAPTER ONE	1
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Handling and Management of WLO in Kenya	4
1.3 Waste Lubrication Oils Contaminants and Specification	5
1.4 Problem Statement	6
1.5 Justification	7
1.6 Objectives	8
1.7 Outline of Thesis	9

CHAPTER TWO	10
2.0 LITERATURE REVIEW	10
2.1 Overview	10
2.2 Properties of Liquid Fuels in General	10
2.3 Utilization of Waste Lubrication Oils for Energy Generation	11
2.4 Sources of Waste Lubrication Oils	12
2.4.1 Uses of Waste Lubrication Oils	13
2.4.2 Re-refining and Recycling of WLO	17
2.5 Burners	19
2.5.1 Background	19
2.5.2 Gas Fuel Burners	20
2.5.3 Liquid Fuel Burners	23
2.5.4 Fuel Atomizing Nozzles	24
2.6 Fuel Combustion Process and Emissions	26
2.6.1 Background	26
2.6.2 Stoichiometric Combustion	28
2.6.3 Flame Temperature	29
2.6.4 Flame Speed	30
2.6.5 Flame Stability	31
2.6.6 Emissions from Fuel Oil Burners	33
2.7 Summary of Gaps	34
CHAPTER THREE	36
3.0 EXPERIMENTAL DESIGN AND METHODOLOGY	36
3.1 Background	36

3.2	Design of Waste Lubrication Oil Burner	36
3.2.1	Combustion Reactions of Waste Lubrication Oil	39
3.3	Waste Lubrication Oil Burner Setup	41
3.3.1	Waste Lubrication Oil Burner Body	41
3.3.2	Nozzle Selection	42
3.3.3	Fuel Pump Selection	43
3.3.4	Fuel Reservoir	44
3.3.5	WLO Flow Measurement	45
3.3.6	Air Supply System	45
3.4	Safety	47
3.5	Performance Parameters	48
3.5.1	Fuel Heating Value	48
3.5.2	WLO Burner FirePower (FP)	50
3.5.3	Emissions Test	51
3.5.4	Temperature Measurement	52
3.6	Determination of Burner Theoretical Emissions	52
3.6.1	Overview	52
3.6.2	Combustion of WLO by Volume	53
3.6.3	Theoretical CO ₂ Emission Determination at 12% Excess Air	54
3.7	Theoretical CO Emission Determination at 12% Excess Air	55
3.7.1	Adiabatic Flame Temperature for WLO Fuel	56
3.8	Uncertainty Analysis	58
3.8.1	Background	58
3.8.2	Instrumental Uncertainties	59
3.8.3	Experimental Uncertainties	60

CHAPTER FOUR	63
4.0 RESULTS AND DISCUSSION	63
4.1 Background	63
4.2 Waste Lubrication Oil Analysis	63
4.3 Comparison of Heating Water by Electric Heater and WLO Burner	66
4.4 Waste Lubrication Oil Burner Firepower	66
4.5 Combustion Emissions	68
4.5.1 Overview	68
4.5.2 Carbon Dioxide	68
4.5.3 Carbon Monoxide	70
4.5.4 Unburnt Hydrocarbon (UHC)	73
4.6 The Burner Flame Temperature	77
4.6.1 Actual Flame Temperature	77
4.6.2 Adiabatic Flame Temperature (AFT)	79
CHAPTER FIVE	82
5.0 CONCLUSIONS AND RECOMMENDATIONS	82
5.1 CONCLUSIONS	82
5.2 RECOMMENDATIONS	84
REFERENCES	86
APPENDICES	94

LIST OF TABLES

Table 1.1	Oil Import in Kenya Between the Year 2003 and 2010	3
Table 1.2	Waste Oil Specifications	5
Table 2.1	Waste Lubrication Oils Composition	11
Table 3.1	Typical Properties of Waste Lubrication Oil	40
Table 3.2	Oil Atomizing Nozzle Table	43
Table 3.3	Volumetric Analysis of WLO Dry Combustion Products	54
Table 3.4	Standard Deviation for Specific Fuel Consumption Values	62
Table 4.1	Properties of CI Engine Waste Lubrication Oil	64
Table A.1	Burner Firepower Data	95
Table A.2	CO ₂ Experimental and Analytical Emission Results	96
Table A.3	CO Experimental and Analytical Emission Results	97
Table A.4	UHC Experimental and Analytical Emission Results	98
Table A.5	Flame Temperature Results	99
Table B.1	Test Results for WLO from Compression Ignition Engine	100
Table B.2	Air Supply Blower Calibration Results	102
Table C.1	Ultimate Analysis of Waste Lubrication oil	104
Table C.2	Fuel Carbon and Oxygen Flow Rates	106
Table C.3	Combustion Air Flow Rates	106
Table D.1	WLO Dry Combustion Products Volumetric Analysis	110
Table D.2	Analytical CO ₂ Emission (% Volume) for 12, 20 and 30% EA	110
Table D.3	Experimental CO ₂ (% volume) Emission Data	111
Table D.4	Experimental CO (% volume) Emission Data	111
Table D.5	Experimental UHC (ppm) Emission Data	111
Table D.6	Theoretical CO ₂ (% volume) Emission Data	112

Table D.7	Theoretical CO (% volume) Emission Data	112
Table D.8	Theoretical Unburnt HC (ppm) Emission Data	113
Table D.9	Reactants and Products Masses for WLO Combustion	114
Table D.10	Combustion Products C_p Values for 12% EA	114
Table D.11	Combustion Products C_p Values for 20% EA	114
Table D.12	Combustion Products C_p Values for 30% EA	115
Table D.13	Adiabatic Flame Temperature for WLO Fuel	115

LIST OF FIGURES

Figure 2.1	Facilities Generating Waste Oils	13
Figure 2.2	Recuperative Gas Burner	21
Figure 2.3	Recuperative Burner Test Gas Nozzle	22
Figure 2.4	Recuperative Burner Flame	22
Figure 2.5	Internal Mix Air Atomizing Nozzle	25
Figure 2.6	External Mix Air Atomizing Nozzle	26
Figure 2.7	Combustion Process	27
Figure 2.8	Effects of Fuel Combustion on Emissions and Flame Temperature	28
Figure 2.9	Flame Temperature Variation with Distance from Burner Head	30
Figure 2.10	Flame Speed for Different Combustible Gases	32
Figure 2.11	Flame Appearance at Various Furnace Temperatures	33
Figure 3.1	Schematic Illustration of the Designed Burner	37
Figure 3.2	Pictorial Illustration of the Designed Burner	38
Figure 3.3	Pictorial View of the Assembled Burner	38
Figure 3.4	Waste Lubrication Oil Burner Body	42
Figure 3.5	The Danfoss BFP11 Oil Pump	44
Figure 3.6	The Oval Gear Digital Flow Meter	45
Figure 3.7	The Air Flow Bench Used for Blower Calibration	46
Figure 3.8	Constant Volume Bomb Calorimeter	49
Figure 3.9	The MEXA - 544GF Emissions Analyzer	51
Figure 3.10	TDS - 530 Data Logger	52
Figure 4.1	Firepower Variations with Fuel Pump Flow Rate	67
Figure 4.2	CO ₂ Emission Variation with Fuel Flow Rates and SR Values .	69
Figure 4.3	CO Emission at Various SR Values and Fuel Flow Rates	71
Figure 4.4	UHC Emission Variation with Fuel Flow Rates and SR Values .	74

Figure 4.5	Combined Emission Versus Fuel Flow Rate at SR1.12	75
Figure 4.6	Combined Emission Versus Fuel Flow Rate at SR1.20	76
Figure 4.7	Combined Emission Versus Fuel Flow Rate at SR1.30	76
Figure 4.8	Flame Temperature Variation with Fuel Flow Rates and SR . . .	78
Figure 4.9	WLO Adiabatic Flame Temperature at Various Excess Air Values	80
Figure A.1	Firepower Variations with Fuel Pump Flow Rate	95
Figure A.2	CO ₂ Emission at Various Fuel Flow Rates and SR Values	96
Figure A.3	CO Emission at Various SR Values and Fuel Flow Rates	97
Figure A.4	UHC Emission at Various Fuel Flow Rates and SR Values	98
Figure A.5	Flame Temperature at Various Fuel Flow Rates and SR Values .	99

LIST OF APPENDICES

Appendix A:	RESULTS DATA	95
Appendix B:	PRELIMINARY WORK	100
Appendix C:	BURNER DESIGN CALCULATIONS	103
Appendix D:	WLO BURNER THEORETICAL EMISSIONS AND ADI- ABATIC FLAME TEMPERATURE DETERMINATION .	109

ABBREVIATIONS

WLO	Waste Lubrication Oils
EGR	Exhaust Gas Recirculation
CI	Compression Ignition
IEA	International Energy Agency
PCBs	Polychlorinated Biphenyls
ppm	Parts Per Million
EPA	Environmental Protection Agency
PAHs	Polycyclic Aromatic Hydrocarbons
GHG	Green House Gas
AFT	Adiabatic Flame Temperature
RTP	Room Temperature and Pressure
POC	Products Of Combustion
IC	Internal Combustion
BTE	Brake Thermal Efficiency
BSFC	Brake Specific Fuel Consumption
LPG	Liquified Petroleum Gas
NMP	N-methyl-2-pyrrolidone
EA	Excess Air
SC	Stoichiometric Combustion
FBC	Fluidized Bed Combustion
AFBC	Atmospheric Fluidized Bed Combustion
PFBC	Pressurized Fluidized Bed Combustion
ACFBC	Atmospheric Circulating Fluidized Bed Combustion
mw	Molar Weight
NO_x	Nitrogen Oxide Compounds

SO_x	Sulphur Oxide Compounds
SR	Stoichiometric Ratio
PM	Particulate Matter
TOE	Tonnes of Oil Equivalent
IMF	International Monetary Fund
HHV	Higher Heating Value
LHV	Lower Heating Value
UHC	Unburnt Hydrocarbons
SMEs	Small to Medium Enterprises
WBT	Water Boiling Test
DLF	Diesel Like Fuel
B	Burner
BMEP	Brake Mean Effective Pressure
HEP	Hydroelectric Power
SI	Spark Ignition
TLV	Threshold Limit Value
LNB	Low NO _x Burner
HFO	Heavy Fuel Oil
LDO	Light Diesel Oil
HRR	Heat Release Rate
DC	Direct Current

NOMENCLATURE

ϕ	Diameter
Δ	Change
H	Enthalpy
C_p	Specific Heat Capacity at constant Pressure
wt	Weight
t	Test time
h	Hour
T	Torque
\dot{m}	Mass Flow Rate
Tm	Temperature
f	Fuel
\dot{V}	Volume Flow Rate
\dot{n}	Molar Mass Flow Rate

Subscripts

m	Mass
th	Theoretical
exp	Experimental
R	Reactants
P	Products
s	Sample
C	Carbon

w	Water
t	Time
cap	Capacity

ABSTRACT

Waste oil is a major output from lubrication process and there is a need to establish safe mechanisms of disposal of this hazardous waste to protect the environment from pollution. This research, therefore, focuses on supplementing energy demand through waste oil combustion as well as minimizing waste oil disposal problems.

An oil fired burner was designed, fabricated and its performance analyzed. The main aim of this burner was to burn waste lubrication oil (WLO), with less emissions, to generate process heat for utilization in Small to Medium Enterprises (SMEs) as well as offer its safer disposal solution. Air and fuel flow regulators were incorporated to control reactants' flow during combustion and investigate reactants flow regulation influence on emission levels as well as optimize combustion and heat generation. Results from this study showed that there was a reduction in carbon monoxide (CO) and unburnt hydrocarbons (UHC) concentration with increasing excess air. CO reduction was attributed to the fact that excess air enhanced formation of more oxygen radicals during chain initiation process which enabled conversion of more CO formed during chain branching process to CO₂. UHC emission reduction was as a result of more oxygen oxidizing fuel and therefore more fuel converted to combustion by-products of CO₂ and H₂O. The low emissions concentration, high calorific value of WLO and high flame temperatures achieved confirmed that combustion of WLO is able to supplement energy demand and at the same time offer safe disposal solution.

This research work can be applied in industrial boilers, heating process water in restaurants and hotels as well as heating in workshops. It also avails data and standards that can be utilized successfully in the design of real systems.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

Rising Energy prices across many regions have led to major shifts in energy supply sources and the overall trade balances. The share of energy expenditures in household income in the European Union reached a high of nearly 8% in 2008 [1]. This called for more energy sources exploration to try and reduce these huge costs as well as avail more surplus energy for both domestic and industrial applications. Climate change, pollution and energy insecurity are among the major problems associated with energy supply and addressing them requires great changes in the energy infrastructure [2]. Even with improvements in energy efficiency, it is still expected that the global energy demand will double by the year 2050. This is inevitable due to expected global population growth, global economic growth, continued urbanization and increased demand on mobility and other energy dependent services. World energy demand is growing much faster than expected leading to a widening gap between supply and demand for electric energy [3]. This therefore, calls for the need to diversify energy generation by utilizing more of the existing sources as well as exploring new energy sources.

Energy cost and scarcity in Kenya continue to pose a major challenge to industrialization efforts even as the country is set to realize its vision 2030. Extensive investments in new generation capacity are required to meet the growing energy demand in Kenya and other developing countries [4]. Alternative cheap sources of energy must therefore be sought. Among them are the Waste Lubrication Oils (WLO) which can be utilized efficiently in process heating by Small to Medium Enterprises (SMEs). Arumugam et

al [5] propose the use of waste oils from automobiles, industries and cooking as energy sources to supplement energy demand since they have high heat values. Sale of light diesel vehicles are rising, and automakers are adding more diesel models to their product lineups and this trend is likely to continue. This increase in automobiles implies an increase in lubrication oil use and subsequent waste lubrication oil generation [6]. Waste in general refers to any material rejected as unfit for further use [8]. Waste oil on the other hand is defined as any oil that has been refined from crude oil or mixtures containing synthetic oil which has been used and is therefore contaminated [9]. A major characteristic of WLO is that they contain both physical and chemical impurities hence require an application i.e burning at high combustion temperatures to take care of these impurities safely [10,11]. WLO originate from various sources including: automobiles, hydraulic systems, turbines, transformers, industrial sector among others [12].

The contaminants in WLO have adverse environmental and health impacts. Waste oils are generally considered hazardous and as such must be disposed off in accordance with the United States Environmental Protection Agency (EPA) regulations [13]. The presence of degraded additives, contaminants, and by-products of degradation render WLO more toxic and harmful to health and environment than virgin base oils [4]. WLO are therefore a health hazard and can pose great threats to human life and environment if poorly managed [10,11]. In the year 2000, about 4930 kilotonnes of base oils were consumed in Europe, of which about 65% was automotive oil and less than 35% industrial oil [14]. It is expected that waste oil generation from this was in the same proportion but it was not clear the total amount generated. One main challenge in waste oil research is that no clear criteria exist to establish the total quantity of oil that is recoverable as waste. It was estimated that only less than 45% of available waste oil was collected worldwide in 1995 while the rest was either misused or disposed

of improperly into the ecosystem by the end users [15].

Currently, developing countries consume a limited share of the world's commercial energy but the faster income growth due to improving economies and subsequent increase in population will lead to a corresponding rise in energy demand. The 1998 edition of the International Energy Agency's (IEA) World Energy Outlook (WEO) aimed to identify and discuss the major issues and uncertainties affecting the world energy demand and supply up to the year 2020. The outlook projected that the world energy demand would grow by 65% and CO₂ emissions by 70% between the year 1995 and 2020 unless new policies are put in place [16].

Transport sector is the largest consumer of petroleum products followed by manufacturing and power generation sectors [17]. This implies that the amount of WLO is continuously increasing since the main consumers of oil are rapidly expanding. Table 1.1 shows the trend in Kenya oil import between the year 2003 and 2010 [18].

Table 1.1: Oil Import in Kenya Between the Year 2003 and 2010

Year	Imports (in billion US\$)	change (%)
2003	0.879	-
2004	1.119	+27.30
2005	1.341	+19.84
2006	1.745	+30.13
2007	1.919	+9.97
2008	3.051	+58.99
2009	2.192	-28.15
2010	2.673	+21.94

From the table, it is clear that oil demand has been rising which could be attributed to growth in population and the economy. This projects a huge increase in WLO in future and with this expected large quantities, another reliable energy source is developing to

supplement energy demands.

1.2 Handling and Management of WLO in Kenya

WLO is burned in many combustion systems like industrial boilers, institutional boilers, space heaters, cement and lime kilns and steel production blast furnaces [12]. These oils have an advantage of being cheaper than the conventional oils used in combustion and are readily available in garages and oil change service centres, vehicle dismantlers, machine shops and food restaurants [5]. Its properties, composition and proper management must be considered to enable its safe burning for energy generation.

The National Environment Management Authority (NEMA), Kenya [19], outlines the guidelines to assist waste oil handlers meet their use and disposal requirements under the Environmental Management and Coordination (waste management) regulations of 2006. Under the Environmental Management and Coordination (water quality) regulations of 2006, the effluent discharge standard for oil and grease is zero since the impact of oil on drinking water can be devastating. NEMA advocates for an efficient collection and transportation systems for waste oils as well as promotion of an eco-friendly technologies for recycling waste oils. NEMA also educates people on waste oils handling hazards and gives clear guideline on waste oils management. Above that, NEMA accepts the use of WLO as fuel for industrial boilers, hotel boilers, furnaces and in steel processing plants provided that they are handled safely.

1.3 Waste Lubrication Oils Contaminants and Specification

WLO contain a lot of contaminants which arise due to the numerous additives added to the virgin lubrication oils to impart the desired lubrication properties. At the end of these oils' useful life, they become WLO and additives become contaminants. These contaminants include both chemical and metallic parts (which result due to wear between the lubricated parts i.e engine cylinder walls and the piston). These contaminants especially the metallic particles influence greatly the oil atomization and combustion due to their interruption of the heat transfer in micro scale.

Waste oils can be categorized as on-specification or off-specification. An on-specification waste oil is a crankcase used oil with no additive or simply not a blended mixture. Used oil specification knowledge helps in determining which method to use in its disposal. Waste oil which is not tested for on-specification status, or whose specification knowledge is not clear must be managed as off-specification. For an oil geared towards energy recovery to qualify as an on-specification waste oil, its contaminants content and properties must not exceed any of the limits shown in Table 1.2 [9, 10]

Table 1.2: Waste Oil Specifications

Constituent	Allowable Level (Maximum)
Arsenic	5 ppm
Cadmium	2 ppm
Chromium	10 ppm
Lead	100 ppm
sulfur	variable, mostly 1.0%
polychlorinated biphenyls (PCBs)	variable, mostly 2.0 ppm
Flash point	38°C minimum
Total organic halogens as chlorine	1000 or 4000 ppm

1.4 Problem Statement

Energy insufficiency is a major problem in industrial development of any country. Population of the world is increasing rapidly and technology is improving rapidly. This has in turn put pressure on the world energy demand. Existing energy sources can not sustain the energy requirement due to their limited nature and the growth of SMEs which require substantial amount of energy.

Hydroelectricity is the main form of renewable source of energy world wide. In Africa, it is recorded that effects of climate change affect severely Hydroelectric Power (HEP) plants more so in areas of low annual rainfall. Climate change results in increasingly unpredictable weather patterns making HEP plants ineffective and unreliable due to reduced dam reservoir inflows to non-sustainable levels during dry seasons [20]. In Kenya, energy deficit is experienced in form of frequent power rationing and outages. HEP highly relied on as the main renewable energy source in the country decreases in output annually due to constantly reducing rainfall and droughts. Kenya's hydropower base contributes about 55% of national energy requirements. This contribution is endangered by rainfall decline and therefore the nation may be forced to explore other energy sources to sustain its industrial operations . Masinga dam which is one of the Seven Forks dams has its HEP output decreasing yearly due to decline in average dam water level at the rate of 0.58 m annually [20].

WLO are very toxic in nature and with increase in their generation, careful attention must be given to their disposal. Oil is a form of pollution that harms plants and animals, damages rivers, groundwater and soil as well as destroying natural habitat and drinking water supplies. It is the most commonly reported type of water pollution that

causes over 16% of all pollution incidents annually [21]. WLO are usually contaminated with Polychlorinated Biphenyls (PCBs), heavy metals or carcinogenic Polycyclic Aromatic Hydrocarbons (PAHs) and are therefore a health hazard [8]. However, burning WLO at temperatures above 800⁰ C eliminates formation of most of the toxic compositions from it since they occur at combustion temperatures of between 750 - 800⁰ C [22]. Reduction of toxic elements therefore requires design and fabrication of a WLO combustion system that will achieve combustion temperatures well above 800⁰ C.

SMEs play a key role in any country's economy. According to the 2006 economic survey, SMEs sector contributed over 50% of new jobs created in the year 2005 in Kenya. Despite their significance, statistics show that three out of five SMEs fail within their first few months of operation. Among the challenges contributing to this failure is the unreliability and energy shortage for industrial process heating, melting metals, boiling water, cooking among others [23].

The challenges outlined above require research and exploration of alternative and supplementary sources of energy for SMEs and also explore safer ways to dispose off WLO. This research seeks to design an efficient waste oil burner that can be applied to steam production and energy generation for process heating in SMEs as well as reduce emissions to the environment.

1.5 Justification

The level and intensity of energy use in a country is a key indicator of its economic growth and development. The Kenya vision 2030 identifies energy as one of the infrastructure enablers of its social and economic pillars. Sustainable, affordable and reliable

energy for all citizens is a key factor in the realization of the vision. The overall energy policy objective in Kenya is to ensure affordable, sustainable and reliable energy supply to meet the national and county development needs while protecting and conserving the environment [24]. However, scarcity of energy has been a hindrance to the industrial development.

Quantity of WLO is set to increase in Kenya with further industrialization and population growth. This is a potential source of supplement energy for the current energy bank in Kenya and the rest of the world. With this expected increase in WLO output, proper disposal methods should be looked into carefully to avoid pollution of environment, water and soil degradation. Improper disposal of WLO by burning in incinerators, kilns and open air results in emissions of carbon dioxide (CO_2), oxides of nitrogen (NO_x), oxides of sulphur (SO_x), particulate matter (PM), unburnt hydrocarbons (UHC) and carbon monoxide (CO). CO_2 , a greenhouse gas (GHG), is responsible for global warming which has contributed greatly to the world climate change. Waste lubrication oils have a lot of untapped energy that can be used to boost energy needs for SMEs in Kenya. Proper utilization of WLO for energy generation is a potential way to supplement energy requirements as well as provide a safer path for its disposal.

1.6 Objectives

The general objective of this research is to design and fabricate a waste oil burner for steam and utility heat generation. The designed burner is expected to minimize toxic emissions from WLO combustion to the environment. This general objective will be achieved through the following specific objectives:

1. To design a waste oil burner for performance optimization.
2. To investigate the influence of WLO fuel flow parameter on the burner performance.
3. To investigate the influence of stoichiometric air composition on the burner performance.

1.7 Outline of Thesis

This thesis has five chapters. The current chapter is introduction to the research which presents a general overview of the existing problem related to energy crisis and WLO disposal. Existing literature review on WLO re-refining methods, utilization of WLO and WLO burner design is highlighted in Chapter 2.

Experimental set up and the measured parameters to determine performance of WLO burner are outlined in Chapter 3. Results of emissions, flame temperatures and burner firepower are discussed in Chapter 4. Chapter 5 has conclusions derived from the determined performance parameters and recommendations for further work on WLO combustion for process heat generation.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Overview

Against the challenges of waste oil disposal and emission associated with its combustion, efforts to come up with better utilization and disposal methods have been ongoing in terms of waste oil burner designs, ways of collecting and disposing of this waste as well as re-refining processes for its reuse as lubricant. A lot of WLO is generated from lubrication process and this large quantity is very important for energy source reserves. This is a readily and cheaply available energy source that can be utilized for a two fold advantage, energy supplement due to its high energy content and solving its disposal problem [27]. Handling WLO poorly poses great threats to human health and the environment [12]. This chapter analyzes the processes and challenges associated with WLO collection, disposal, utilization, waste oil burners and improvements that have been undertaken.

2.2 Properties of Liquid Fuels in General

Liquid fuels like furnace oils, light diesel oil (LDO), kerosene, and diesel among others are predominantly used in industrial combustion applications [28]. For this combustion to be carried out effectively and efficiently, various properties of liquid fuels, WLO included, must be known. Gomez-Rico et al [27] tested properties of WLO and found the chemical composition to be as shown in Table 2.1. From the table, it is clear that fuel carbon part of WLO takes a greater percentage of its composition. This justifies the fact that WLO has high energy content and can be used comfortably for energy

Table 2.1: Waste Lubrication Oils Composition

Constituents	% weight	Chemical Symbol	Atomic wt (g/mole)
Carbon	85.35	C	12
Hydrogen	13.25	H ₂	2
Oxygen	0.09	O ₂	32
Nitrogen	0.9	N ₂	28
Sulphur	0.46	S	32
Water	0	H ₂ O	18
-	-	CO ₂	44
-	-	SO ₂	64
Ash	0.05	-	-

generation. Again, the very harmful parts of it (nitrogen and sulphur) were in trace quantities and as such were left out in combustion equation even though they still pose great pollution threats. Its lower heating value (LHV) was found to be 48.17 MJ/kg.

2.3 Utilization of Waste Lubrication Oils for Energy Generation

There exist many ways by which waste lubrication oils can be utilized. WLO can be reprocessed, reclaimed and regenerated into base oil to produce base oil with same lubrication quality. One gallon (3.8 kg) of WLO can be re-refined into 2.3 kg of base lubrication oil. Similarly, WLO can be reprocessed into fuel for furnaces, or power plants to generate electricity for homes, schools and businesses [29]. Durrani [29] argues that one liter of WLO contains about 8000 kJ of energy which is sufficient to light a 100 watts bulb for 24 hours or even to operate a 1000 watts electric water heater for 2 hours. This implies that waste lubrication oils are potential energy generators for process heat required in workshops, foundry, hotels and restaurants.

2.4 Sources of Waste Lubrication Oils

A wide variety of crude petroleum can be processed, blended and formulated to produce a range of products that are used in many areas e.g lubrication, cutting processes, transmission and braking systems. Such oils require replacement over time once they have reached their useful life expectancy [30]. It is from these applications and replacement that waste oils are generated. Waste oils are generated in service stations, garages, new car dealer showrooms and automotive fleet service areas in the automotive sector. Such oils are highly flammable and contain toxic ingredients as well [4]. A major and continuing source of waste oil in this sector is from lubrication [31]. Many transformers which are integral components in power generation, transmission and distribution use oil as internal coolant. These transformers and capacitors use oils with low water absorption properties suitable for electrical insulation and heat transfer. This also offers an added insulation and protection against arcing. These oils are normally replaced after a long time but when this is done, waste oil is generated [31]. Other sources of waste oil are from lubrication of machinery used in mining processes. Figure 2.1 illustrates various sources of waste lubrication oil as generated [17].

Figure 2.1 shows the WLO generated from all engine-run equipment and hydraulic machines. This indicates that WLO results from many facilities utilized in day-to-day operations and hence there can never be a shortage of WLO at any given moment.

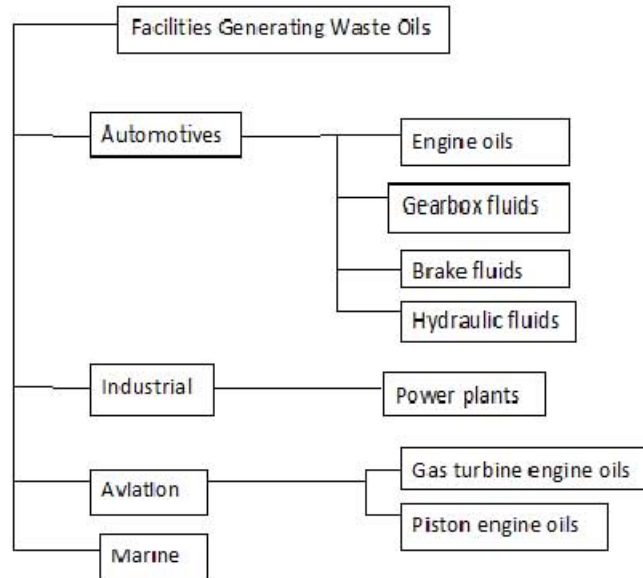


Figure 2.1: Facilities Generating Waste Oils

2.4.1 Uses of Waste Lubrication Oils

Currently, WLO are utilized in many areas some of which are not accepted by the United States Environmental Protection Agency (EPA). Each of the individual application has its own drawbacks which may render it inappropriate in application. Some of these applications are discussed as follows:

WLO can be used as fuel in cement and lime kilns, in brick works and metallurgical furnaces [32]. High combustion temperatures and absorption properties of cement, lime and clay destroy hazardous hydrocarbons while heavy metals, sulphur and chlorides are absorbed. However, modern plants are equipped with sophisticated gas cleaning systems that minimize other possible air pollution effects making the method very expensive.

WLO can also be used for co-firing in a boiler where 10 - 25% of it is mixed with heavy fuel oil (HFO) to serve as a fuel supplement in a boiler. Vorapot et al [33] investigated heat recoveries from waste lubricants and found that they could efficiently be burned in many types of boilers and burners. It was established that a heating boiler fueled by waste lubricants offered great benefit in terms of cost saving for transportation and disposal of these wastes as well as the required fuel for the boiler. However, before mixing waste lubricants with HFO, water and suspended solids in them must be removed first and this gives rise to an additional process before combustion. This application also comes with other combustion problems like burner fouling, higher particulate emission, ash residue and combustion emissions (CO, SO_x and NO_x).

Heino Vest [32] mixed unrefined WLO in small quantities with diesel fuel and used it in CI engines. Results showed that power generated was slightly lower than that generated with pure diesel and the process also added a lot of impurities to the diesel fuel thus increasing combustion emissions. Heino Vest also found out that WLO could be used as timber protecting agent. This is a very common practice in most African countries where fencing posts and roofing timber are soaked in used oil to resist termite attack. This provides an avenue for WLO to leach into underground water as well as to destroy soil. Oil concentration as low as one part per million (ppm) can contaminate drinking water [4]. This is a practice that further contributes to environmental pollution and has potential of affecting health of plant and animals. It is essential that appropriate disposal mechanisms (like burning under controlled parameters to generate heat energy and control emissions) are embraced.

WLO can be burned in space heaters to heat rooms like garages, workshops, and green

houses among others. Giovanna et al [34] explains that this route of disposal of WLO has not been taken in large scale by many countries except in UK where burning of WLO accounts for disposal of approximately 200 kilotonnes annually. Giovanna further states that special stand alone space heaters must be designed for this purpose so as to minimize combustion emission. This disposal method provides an economic heating source especially when the waste oil is disposed off at the point of generation. However, the method has negligible application in tropical regions since space heating and cooling are not major problems in these areas.

Other applications include using re-refined WLO as fuel in internal combustion engines (ICEs) without any form of blending. Orphan et al [35] and Pritinika et al [36] separately examined the use of Waste oils as an alternative fuel in a single cylinder, four-stroke, air cooled, naturally aspirated direct injection diesel engine at different speeds. Various engine performance parameters like brake thermal efficiency (BTE), brake mean effective pressure (BMEP), torque (T) and brake specific fuel consumption (BSFC) were tested. Results showed a marginal increase in the BTE, BMEP and torque but a marginally low BSFC compared to that of a normal diesel fuel. However, before using WLO as fuel it had to be re-refined through a complex pyrolytic distillation process which recovered 80% of it as useful fuel and the other 20% rejected as residue. This fuel had to be separated again to light and heavy fuels according to characteristics and distillation test results and these fuels were named Gasoline like fuel (GLF) and Diesel like fuel (DLF) respectively. From engine test results, DLF generated more SO_x, NO_x and CO to the environment compared to normal diesel fuel. This application has some drawbacks such as increasing level of harmful emissions even though it addresses energy shortage.

WLO oil can as well be re-refined and reused for lubrication purposes in refineries similar to the ones for refining crude oil. Basel convention [31] recommended subjecting WLO to regeneration processes including steps for separation of heavy metals, combustion byproducts and substances arising from original use e.g Polychlorinated Biphenyls (PCBs) and Polycyclic Aromatic Hydrocarbons (PAHs) which are the main contaminants in WLO prior to reuse for lubrication. The removed contaminants become part of waste streams that must be disposed off in an environmentally sound manner in accordance to the relevant environmental legislation and standards. This process is lengthy and quite expensive and is therefore not economically viable. The re-refined WLO possess inferior lubricating properties like viscosity which affect their performance.

In some countries like Botswana, it is reported that WLO are smeared on cattle to act as protective medicine against ticks and in other countries they are sprayed on the ground to suppress dust [32]. This method is not friendly to the environment and health in general. Finally, Waste oil may be used to produce hydrogen and light hydrocarbons as gaseous fuel by pyrolysis in a heated microwave. Shiung et al [37] pyrolysed waste automotive engine oil in a continuous stirred bed reactor using microwave energy as the heat source. 41% of gases were recovered which were found to contain up to 86% concentrations of light aliphatic hydrocarbons. Hydrocarbons in these gases could among other applications be reformed to produce hydrogen for use as a second-generation fuel. WLO was mixed with a highly microwave absorbent material like particulate-carbon that absorbed microwave energy to generate sufficient thermal energy required to achieve the temperatures needed for extensive pyrolysis to occur. Results showed that hydrogen content of the waste oil was nearly twice the amount available from wood biomass and about 3% higher than that of vegetable oils. This

demonstrates that additional hydrogen components exist in WLO and their combustion would further increase the energy content compared to that of biomass fuel. However, substantial amounts of pyrolysis gases were only produced at temperatures above 350° C. At 350° C and below, only small amounts of the pyrolysis gases were observed and no pyrolysis oils were observed after 1 hour of reaction. A higher temperature is supposed to enhance cracking of hydrocarbons into smaller molecules to yield more pyrolysis gases but the reverse was observed at temperatures between 500 and 550° C. This was because the volume increase that accompanied the phase change from liquid to gas created an increase of pressure that drove pyrolysis volatiles out of the reactor. Also, the small residence time due to higher temperatures in the microwave decreased waste oil cracking thereby yielding more oil than gaseous fuel. Apart from the problem of more oil generation than gaseous fuel, this is a very important fuel generation process through gasification. This therefore is an area requiring further research to open up more heat energy generating sources.

2.4.2 Re-refining and Recycling of WLO

Lubricants possess properties like viscosity, volatility, thermal and oxidative stability, load carrying ability, solubility and other physical, mechanical and chemical properties. Additive properties are also added to lubricants by incorporating special additives such as corrosion inhibitors, rust preventives, extreme pressure agents, oxidation inhibitors among others [38]. WLO collected contain both physical and chemical impurities thus require re-refining before recycling [39]. They can be recycled by reusing after treatment, blending with base engine oils for use as lubricant, fuel for boilers among others. Due to the increasing necessity for environmental protection coupled with the strict environmental legislation, disposal and recycling of WLO must be carried out in ac-

cordance with united states EPA requirements. A brief summary of WLO re-refining processes is presented as: Acid-clay used oil refining process where Jelena et al [15] mixed waste lube oil with concentrated sulphuric acid to remove most of the impurities. The process was not able to reduce sulphur concentration low enough to produce desired base oil group for lubrication [40].

Another method is the Vaxon-Process where Gabor et al [39] used chemical treatment, vacuum distillation and solvents to refine WLO. However, the major challenge of the process was that the cracked end products contained sulphur that required further treatment to reduce sulphur content which complicated the whole process [14]. Vacuum distillation and hydro-treatment of waste oils are energy demanding processes due to the high overpressures, deep vacuums and high temperatures involved making the process costly [15].

Solvent extraction process was done by Ahmad et al [41] who used hydrocarbon solvents to refine used lubrication oil. However, in the process of achieving high saturates concentration by selectively extracting aromatic compounds, the process also removed valuable products from the total lube oil available in the used oil thereby giving lower yields [40]. Jelena et al [15] re-refined Waste mineral insulating oil from transformers using solvent extraction method by subjecting it to a three-stage mixer-settler extraction procedure using N-methyl-2-pyrrolidone (NMP). This process had to undergo several stages to achieve a fully re-refined waste oil to a near virgin base oil.

2.5 Burners

2.5.1 Background

Environmental regulations and current energy crisis are increasingly driving the high demand for development of low-pollutant emissions and high-efficiency industrial and domestic combustion systems. Various types of burners and combustion systems have been studied and developed for industrial and domestic applications [42]. Process heaters pose unique challenges for burner designers. Unlike most other process equipment, they employ a lot of parameters to operate properly and efficiently. Some of these parameters affecting burner operation and combustion emissions include: fuel composition, process chemistry (reactions), operating conditions e.g temperatures, pressures, excess O₂, firing rates, among others [43]. A prior knowledge of these parameters is required to be able to design an oil burner that will optimize combustion and heat energy generation. A part from these parameters, flame type knowledge is required in burner designs. Mathew [44] observed that combustion under high temperatures and pressures emits nitrogen dioxide which is a reddish brown gas and this contributes greatly to the formation of ground level Ozone and acid rain. Investigations performed on fuel combustion have shown that there are two important groups of influential parameters: fuel type and burner characteristics. The most important conclusions of these investigations is that each fuel type requires a defined burner for its combustion and concrete operating parameters for optimal work [45].

There exist two main types of burner categorized according to the type of fuel burnt: Fuel oil burners and gas burners. A fuel oil burner is a device used to burn oil in heating appliances like boilers, furnaces, water heaters among other appliances. Such burners can be pressure atomizing gun type, horizontal or vertical rotary type, or mechanical

or natural draft vaporizing type.

In most oil burners, oil is supplied under pressure to an atomizing nozzle to produce a fine cone-shaped spray and to which air is added by a motor-driven fan. As the cone-shaped spray emerges from the nozzle, ignition is initiated by an electric spark to start the burner. In commercial-industrial types of burners, heavier fuel oil that requires mechanical atomization is used. Several types of burners have been developed in the past depending on fuel used and purpose. These include:- gas burners, oil burners, coal burners and wood burners. Bunsen burner is the most frequently used gas burner in domestic gas boilers but it has two major challenges. Firstly, if thermal efficiency is increased to improve heat exchange rate, incomplete combustion and soot accumulation in the heat exchanger may occur due to flame instability resulting from fallen condensed water generated on the heat exchanger surface. Secondly, combustion chamber size increases due to increased flame length. Bunsen burner releases relatively high NO_x emissions resulting from an increase in residence time in the high-flame temperature zone compared to that of premixed flame [42].

2.5.2 Gas Fuel Burners

These types of burners use gaseous fuels. In many cases the burner and heat exchanger are separate and this has posed a number of challenges concerning the construction of air supply system and the necessity to insulate hot air piping. This led to the development of a recuperative burner which is a compact equipment assembled in one body with burner, heat exchanger and the stack. This design sought to reduce NO_x emission and air preheat temperatures through Exhaust Gas Recirculation (EGR)

which helped in reduction of combustion temperatures thereby reducing thermal NOx and air preheat temperatures as well. Park et al [46] studied design of a recuperative burner and its effect as far as the stated problems were concerned. They mainly studied nozzle design and the aspect of gas/air mixing and stability. The gas nozzle was made using heat-resistant steel alloy while the main body was made of mild steel. The nozzle system consisted of gas nozzle and flame stabilizer which were one body and a gas ejection ring attached to the nozzle body. Air bulk velocity of the nozzle exit was designed to be 15 - 20 ms⁻¹ at the preheated temperature of 300° C and fuel gas velocity of the nozzle holes were to be 20 - 25 ms⁻¹. Some portion of the fuel gas ejected in the nozzle holes was premixed with air and made a flame just after the nozzle exit while the other portion flowed with air down the furnace as diffusion flame type. When this burner was tested, NOx content in the exhaust gases was found to be about 100 ppm at high air preheat temperature of 500° C. Figures 2.2, 2.3 and 2.4 below show the recuperative burner, test gas nozzle and recuperative burner flame as designed by Park and his fellow researchers.

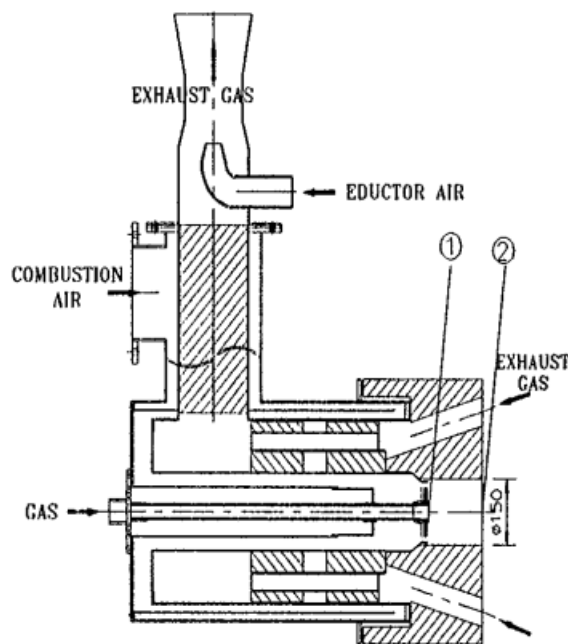


Figure 2.2: Recuperative Gas Burner

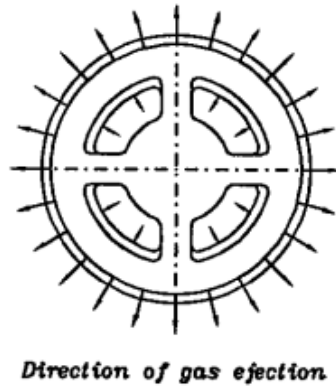


Figure 2.3: Recuperative Burner Test Gas Nozzle

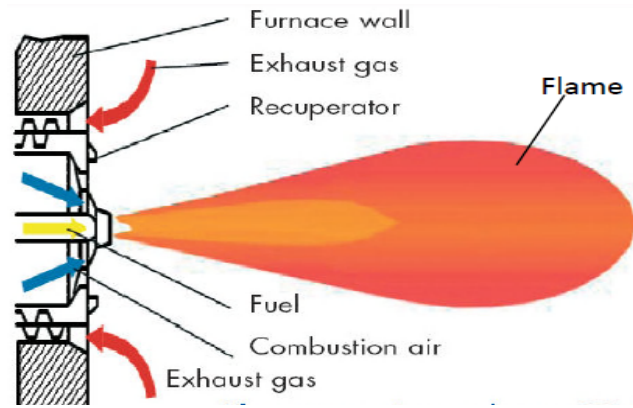


Figure 2.4: Recuperative Burner Flame

Baukal et al [43] did tests on NO_x reduction in burners and found out that reburn is one technique that is required for this reduction. Methane reburn was conducted and some of it was injected in the burner exhaust gas after the primary combustion zone where the gases were at a lower temperature. These created fuel-rich conditions that were not favorable for NO_x formation. As exhaust gases from combustion process flowed through the fuel-rich reducing zone, NO_x was reduced back to nitrogen (N₂). Any CO and other unburned fuels in the reaction zone were then burnt downstream at temperatures below those at the main combustion chamber. These lower temperature reactions were much less favorable for NO_x formation and thus the net effect was reduced NO_x emission. However, the challenges with this technique were: It was difficult

to get proper injection of the reburn gas into the exhaust products. Again, the reburn zone needed modification to sustain combustion at lower temperatures. Finally, to be able to take advantage of some of the energy produced during reburn, a heat recovery system needed to be added in the whole process which was an extra cost.

2.5.3 Liquid Fuel Burners

These burners are used to combust liquid fuels ranging from light kerosene to heavy fuel oil. Most conventional liquid fuel burners are spray types in design which pose a number of challenges as observed by Jugjai et al [47]. Such challenges include low combustion density, incomplete combustion with high emissions of CO and NO_x, relatively low and non uniform heat flux among others. Jugjai et al proposed the introduction of porous burner in combustion systems instead of spray burner systems. Problems associated with existing porous burners were also pointed out i.e the research focused on combustion with relatively high volatile liquid fuels only ignoring heavier fuels like the heavy fuel oils and waste oils. Moreover, atomization obtained by high pressure injector was required. The porous burner was therefore less efficient than conventional spray burners.

Srivastava et al [48] studied Low NO_x Burner (LNB) and explained that this type of burner achieved limited NO_x formation by controlling stoichiometric and temperature profiles of the combustion process. This control was achieved by imposing a predetermined aerodynamic distribution and mixing of fuel and air. They used air staging for heavy-oil turbulent diffusion flames. Air staging involved adding some of the combustion air (oxidizer) downstream of the main combustion zone through a secondary

inlet to enhance further combustion at lower temperatures. Staged combustion delayed complete mixing of fuel and air within the furnace design constraints, this reduced the overall temperature within the combustion chamber because combustion occurred in stages and the LNB could provide up to 50% NO_x reduction. However, LNB developed longer flames that required deeper furnaces to avoid flame impingement on furnace walls facing the burner. A retrofit situation required LNB adjustments which affected the system's NO_x reduction capability in some cases. In other situations, LNB retrofits resulted in changed heat transfer patterns within the furnace, increased corrosion of the furnace walls and increased furnace fouling.

2.5.4 Fuel Atomizing Nozzles

The main purpose of an oil burner is to promote efficient fuel oil combustion. This can only be achieved through very fine fuel atomization, proper fuel/air mixing, high combustion temperatures and sufficient residence time in the combustion chamber. Fuel vaporization to very fine particles occurs in extremely short time when exposed to high temperatures. Fine atomization also increases droplets surface area thereby enhancing proper fuel/air mixing and complete combustion [49].

Oil atomizing nozzles can be categorized according to the number of atomizing orifices i.e single point nozzle, multi point nozzle and adjustable spray nozzle [5]. A part from this classification, nozzles can also be classified according to the method of atomization. These are steam atomizing nozzles, air atomizing nozzles and fuel pressure atomizing nozzles. Air atomizing nozzles are categorized into internal and external mix nozzle set ups depending on where fuel atomization occurs. In internal mix nozzle set up, fuel

is atomized by pressurized air within the nozzle. In this case the nozzle has a mixing chamber where atomization occurs. This type of set up is the most common due to its flexibility and a wide range of flow rates, spray patterns and drop sizes can be achieved by adjusting fuel and air pressures. In the external mix nozzle set up, fuel is atomized outside the nozzle orifice and the two fluids exit from separate orifices. This enables pressure values to be adjusted independently and fuel flow rate easily controlled. It is also possible to obtain finer atomization with this set up than with internal mix nozzle set up because of the ability to increase air pressure while maintaining the desired fuel flow rate. This is the reason why an external mix nozzle set up was chosen in this research. Shown in Figures 2.5 and 2.6 below are the internal and external mix nozzle set up respectively [49].

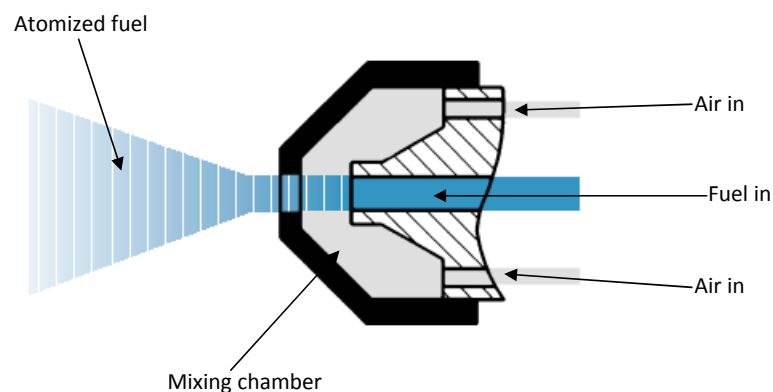


Figure 2.5: Internal Mix Air Atomizing Nozzle

Burner design is very crucial in determining the level and amount of emissions during a combustion process. The nature of fuel atomization by the burner in oil-fired boilers utilized in power generation is a major factor in determining the quantity and size distribution of particulate emissions. Poor atomization yields large fly ash particles and a higher particulate loading as the fuel droplets may be quite large and thus difficult to burn completely. Good atomization is achieved by smaller burner nozzle orifices that

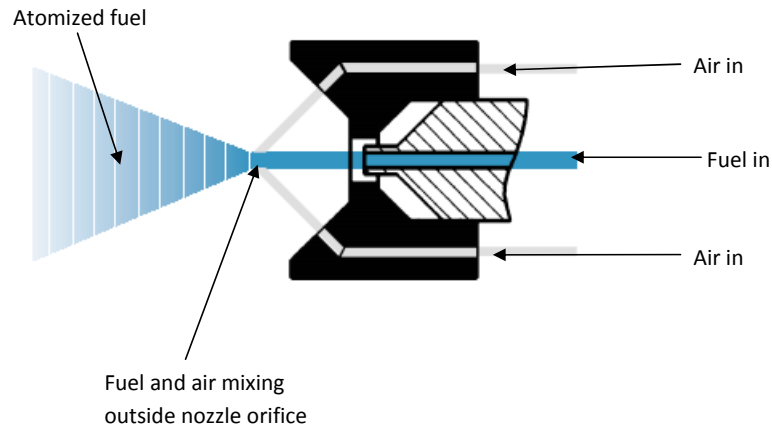


Figure 2.6: External Mix Air Atomizing Nozzle

contribute to a more complete fuel combustion [50]. Air atomizing burner is capable of operating at lower excess air levels and thus provides more efficient combustion with less emissions of NO_x, SO_x, CO, UHC and PM [51]. From the various types of burners discussed above, several gaps arise which need to be addressed to come up with better burner designs to achieve efficient combustion. These are: the challenge of fuel and oxidizer regulation during combustion to achieve a near stoichiometric reaction, existing challenges of NO_x and flame impingement on combustion chamber walls. Again, most burner designs focussed mainly on light liquid fuels ignoring heavier fuels like HFO and WLO which require more attention in terms of fuel and air flow and atomization for efficient combustion.

2.6 Fuel Combustion Process and Emissions

2.6.1 Background

Combustion refers to rapid oxidation of fuel leading to production of heat, light and combustion products (CO₂ and water). Combustion of WLO is similar to burning any

other liquid, solid or gaseous fuel and chemical reactions involved are the same. Oil is a very complex mixture of compounds containing carbon (over 80%), hydrogen (about 15%) and other elements in small quantities (e.g O₂, CO₂, sulphur, water vapour, ash etc) [52]. Carbon and hydrogen in fuel combine with O₂ in air to form CO₂ and water vapour respectively releasing 33.85 MJ/kg and 121.1 MJ/kg of heat respectively. Complete combustion occurs when reaction of fuel and oxidizer is stoichiometric and all reactants consumed. However, this is difficult to achieve and therefore an excess amount of air is used to ensure complete or near complete combustion. This air is referred to as excess air and is expressed as a percent of the required air. Combustion process can be represented by the diagram shown in Figure 2.7 below [52]:

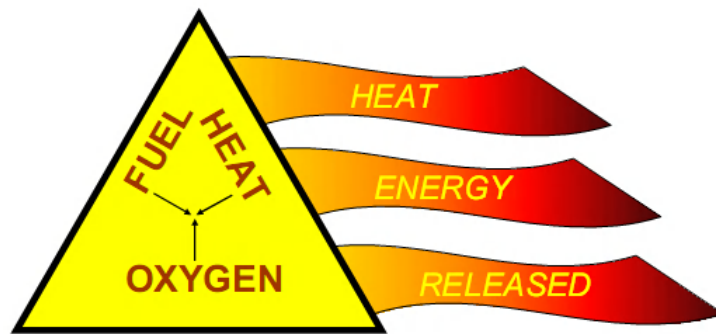


Figure 2.7: Combustion Process

The triangle illustrates three essential elements required for self-sustaining combustion i.e fuel, oxidizing agent (O₂) and heat. Fuel and oxygen are the reactants while heat ignites the mixture and sustains combustion.

2.6.2 Stoichiometric Combustion

The efficiency of a boiler or furnace depends on the efficiency of the combustion system. The amount of air required for complete combustion of fuel depends on elemental components of the fuel mainly Carbon and Hydrogen. This amount of air is called stoichiometric air. Ideal combustion process for burning 1 kg of a typical fuel oil containing 86% carbon, 12% hydrogen and 2% sulphur theoretically requires 14.1 kg of air. This is the minimum air that would be required for perfect mixing of fuel and air. However, it is difficult to tell when stoichiometric combustion occurs. Most combustion processes occur at either air deficit (rich burn) or excess air supply (lean burn) and these have their varied effects on CO and NO_x emissions as well as flame temperature. With 30% excess air combustion, the designed burner required 17.43 kg of air to completely burn 1 kg of WLO. Figure 2.8 shows effects of lean and rich fuel combustion [53].

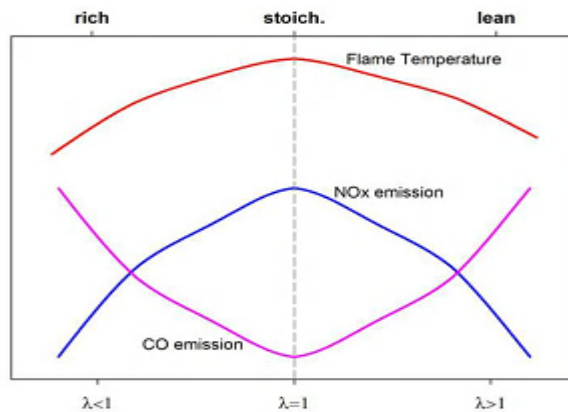


Figure 2.8: Effects of Fuel Combustion on Emissions and Flame Temperature

Where λ is the ratio between air and fuel used during combustion.

Stoichiometric reaction of fuel and combustion air is very necessary as it enables determination of the required quantity of combustion air, amount and composition of combustion products, flame temperature and fuel economy. Fuel combustion process is

highly affected by fuel heating value, amount of combustion air, air preheating temperature, oxygen enrichment in the combustion air and the exhaust gas temperature [54].

2.6.3 Flame Temperature

Theoretical combustion temperature is difficult to determine empirically, and it corresponds to the temperature that would be reached by combustion products if the heat released during stoichiometric combustion were exclusively used to heat them. This is called adiabatic flame temperature. However, this situation does not occur in practice mainly due to:

- heat transfer from combustion products to the surrounding environment.
- CO₂ and water vapour reduction to CO, H₂ and O₂ at temperatures above 1700⁰ C

Maximum flame temperature is reached in premixed combustion with air in excess of stoichiometric amounts. By preheating air/fuel mixture, flame temperature can be increased by 25⁰ C to 40⁰ C. The burner in this research employs premix combustion technique where combustion reactants (fuel and combustion air) mix before entering combustion chamber. Therefore, the above problems can never be avoided and as such very difficult to achieve adiabatic flame temperature. A typical graph of temperature variation as a function of distance from burner head is shown in Figure 2.9 [55].

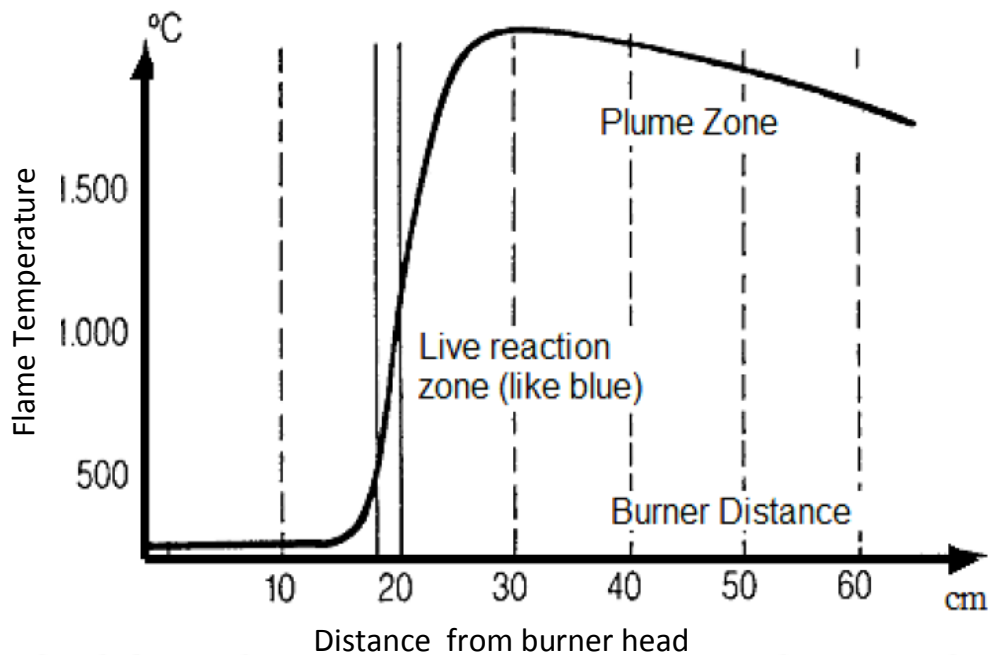


Figure 2.9: Flame Temperature Variation with Distance from Burner Head

2.6.4 Flame Speed

Flame front advances as air/fuel mixture exits the burner head, producing combustion products of the mixture. The reaction between fuel and air can only occur at a certain speed and this speed depends on the reaction rate (chemical) and the degree of flame turbulence (physical). Hence, if the flame is turbulent the mixture will burn more quickly. Furthermore, flame speed varies according to fuel/oxidant ratio of the premixture called primary aeration rate.

Flame speed is an essential factor in proper combustion and better energy use from fuels. It is therefore necessary to have a stable flame front and this is achieved when reactants transport velocity is equal to flame speed. If fuel is supplied at a higher speed than flame speed then liftoff (movement forward) will occur. Again, lower fuel supply speed compared to flame speed leads to flashback (movement backward) will occur.

Other factors affecting flame speed include: fuel nature and temperature of the mixture (combustible gas and air). Fuel nature dictates its reaction speed relative to flame speed and this influences formation of unburnt hydrocarbon (UHC) emission during combustion. Lower flame speeds compared to fuel reaction speed leads to more UHC emission generation. This means less mass fraction of the fuel is burnt and much of it passes to the exhaust unburnt [56]. This could be a possible reason for much UHC emission generation during WLO combustion in this research. Both fuel reaction speed and combustion products flame temperature have a direct influence on flame speed. When reaction speed is higher than flame speed, more fuel will be burnt and more efficient combustion achieved yielding higher flame temperatures. Figure 2.10 shows flame speed for different combustible gases as a function of percent primary air in relation to theoretical air (stoichiometric air) [55].

2.6.5 Flame Stability

To keep the flame attached to burner port, an equilibrium must be reached between fuel-air mixture exit velocity and flame propagation speed. Frequently, flame instability arises as a result of pressure variations in fuel supply to the burner or in combustion air. An increase in fuel pressure generates increased pressure of the mixture and increased exit velocity thereby producing flame detachment or liftoff. A decrease in fuel pressure generates a decrease in exit velocity of the mixture which produces flashback. This phenomenon is very relevant to premix burners. Fluctuations in combustion air supply produce oscillating flames which cause strong pressure variations in the combustion chamber.

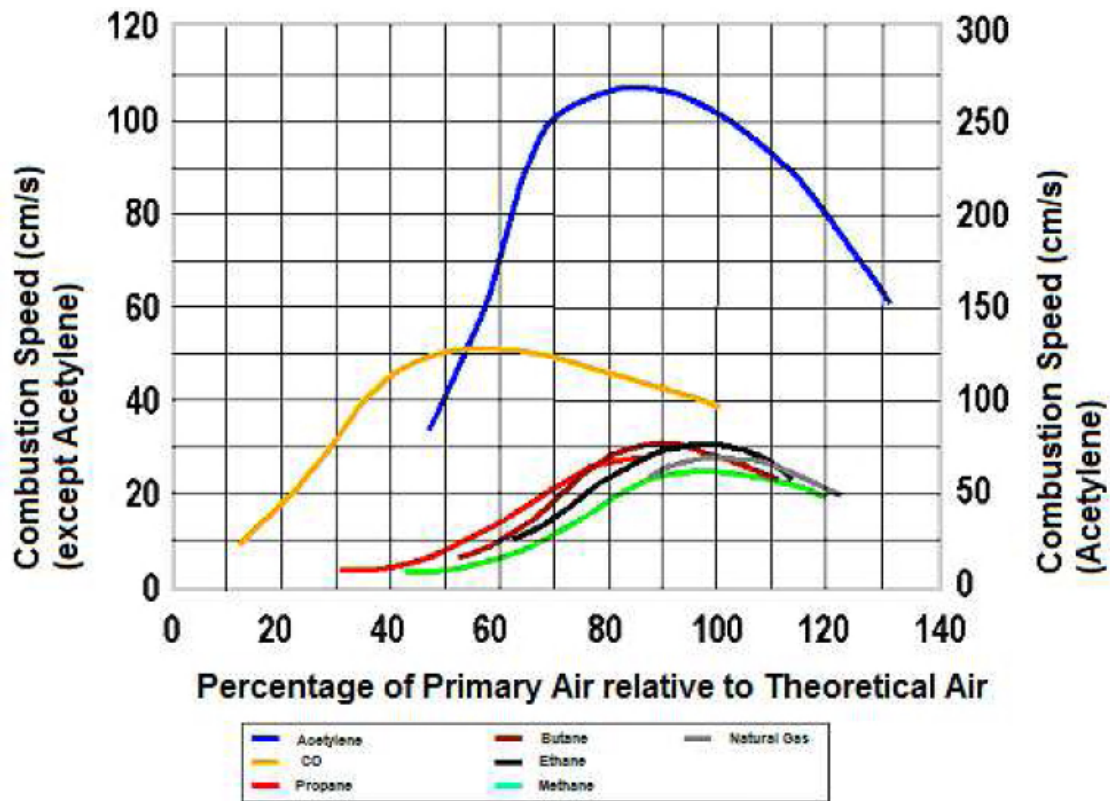


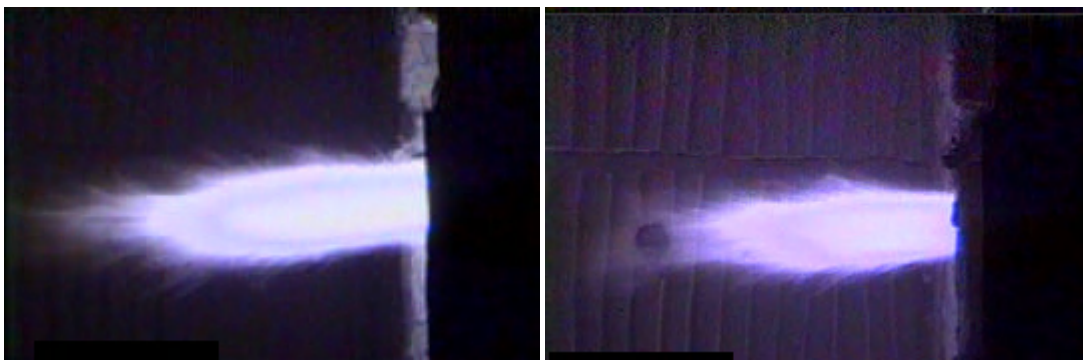
Figure 2.10: Flame Speed for Different Combustible Gases

Flame stability is one of the preliminary requirements for any burner intended for high temperature combustion. Shown in Figure 2.11 are the flame appearances achieved by burning heavy fuel oil purely on primary air at furnace temperatures ranging from 900° C to 1200° C. A stabilized flame is obtained due to high temperature air recovery and does not contain any smoke [57].



Flame at 900°C Furnace Temperature

Flame at 1000°C Furnace Temperature



Flame at 1100°C Furnace Temperature

Flame at 1200°C Furnace Temperature

Figure 2.11: Flame Appearance at Various Furnace Temperatures

2.6.6 Emissions from Fuel Oil Burners

Physical form of fuels and their contaminant contents are the two main factors affecting their pollutant emissions. With proper burner designs and fuel combustion practices WLO can be burned relatively clean to generate CO₂, water vapour and heat energy. This research mainly concentrates on waste lubrication oil burner design that will reduce combustion emissions like CO, unburnt hydrocarbons and at the same time maximizing heat generation.

2.7 Summary of Gaps

Current methods of utilizing WLO generally have negative impacts on the environment. Below is a summary of the shortcomings of current WLO uses and the existing burner designs:

- Most applications of WLO lead to more combustion emissions, contamination of underground water and soil degradation. Again, re-refining WLO in refineries for reuse is quite expensive and therefore not economically viable for small scale applications.
- Very high pressure fuel oil atomization is required with porous burners.
- Relatively high NO_x emission is realized when bunsen burner is used. This is as a result of increased residence time in the high-flame temperature zone. Also, if thermal efficiency of a bunsen burner is increased to improve heat exchange rate, incomplete combustion and soot accumulation in the heat exchanger may occur.
- Employing reburn technique in burners requires proper injection of the reburn gas into the exhaust products which is quite difficult to achieve. Furthermore, the reburn zone in burner reburn technique requires modification to sustain combustion at lower temperatures. Finally, energy produced during reburn can only be captured when a heat recovery system is added in the process which leads to additional cost.
- Longer flames developed by LNB require deeper furnaces to avoid flame impingement on furnace walls facing the burner.
- LNB adjustments due to retrofits affect the system's NO_x reduction capability. LNB retrofits can as well result in changed heat transfer patterns within the furnace, increased corrosion of furnace walls and increased furnace fouling.

Among the conditions required for complete combustion of any fuel is proper mixing of fuel with sufficient air. This is normally difficult to achieve and therefore an excess air is required above stoichiometric air to enhance complete combustion process. The most common emissions from fuel oil burners include: unburnt hydrocarbons, particulate matter, carbon monoxide, oxides of nitrogen and oxides of sulphur.

CHAPTER THREE

3.0 EXPERIMENTAL DESIGN AND METHODOLOGY

3.1 Background

The problem of coming up with proper and reliable waste oil burners to enable safe combustion of WLO for process heat generation as well as offer safe disposal solutions has been in existence for a long time. Due to continued generation of WLO with increasing population, technology and development, there is a need to seek solution to these problems to avoid health and environmental problems associated with WLO handling. In this chapter, design and construction of a waste oil burner is presented. The burner is constructed with provisions for air and waste oil fuel flow regulations to optimize clean combustion. A set up to evaluate burner performance in terms of fuel consumption, emissions and power output is presented thereafter. In this research, design of various components of a WLO burner and their performance assessment were done.

3.2 Design of Waste Lubrication Oil Burner

Burning waste oils in general requires a burner and boiler both designed to handle it as proposed by Arumugam et al [5]. A special oil atomizing nozzle for the burner must also be sought for finer oil atomization. An oil preheater may also be included to facilitate better oil atomization by lowering its viscosity. A WLO burner refers to a heating device in which WLO fuel is mixed with air under controlled conditions to achieve efficient combustion for process heat generation [58]. In a complete combustion process, products of combustion should be heat energy, CO₂ and water vapour. This,

however, is not the case in practice due to poor combustion processes arising from either lean or rich combustion. Even with excess air supply, complete combustion is impossible to achieve but with regulated air and fuel supply, it is possible to optimize performance of WLO burner.

Design parameters included in this burner development were: fuel and air flow rate measurements, atomizing nozzle, fuel pressure monitoring gauge, fuel pumping mechanism, combustion air supply mechanism, and system stand among others. Figures 3.1 and 3.2 show schematic and pictorial views, respectively, of the burner as designed.

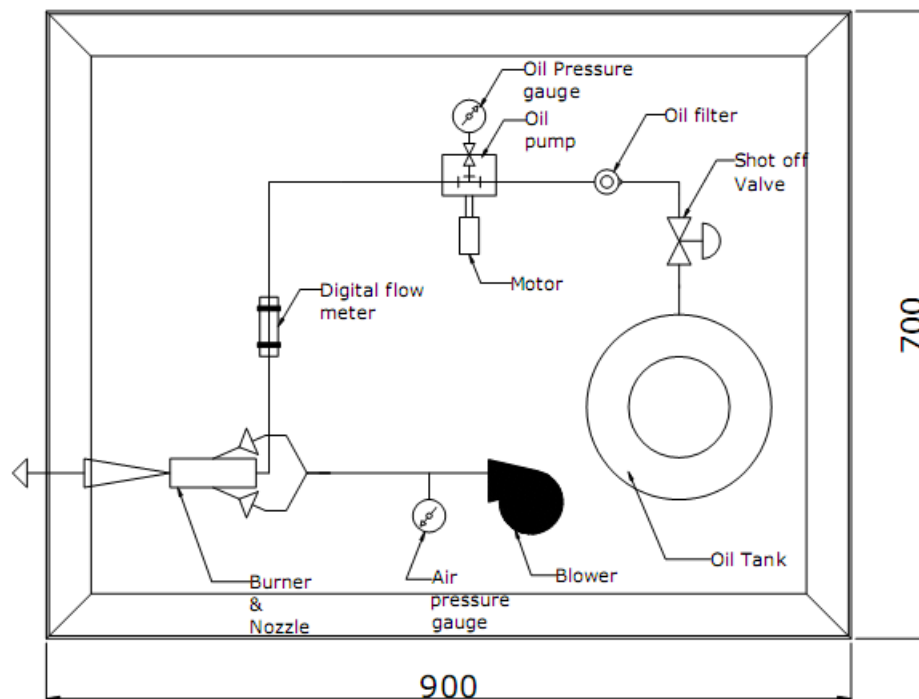


Figure 3.1: Schematic Illustration of the Designed Burner

From the figures, flow regulators (digital flow meter for fuel and variable flow air blower) are notable. There is also an oil pump with flow monitoring pressure gauge mounted on it and an oil filter fitted along the suction side of the pump to ensure only clean oil passes through to protect the pump from clogging. Also notable is the shut off valve

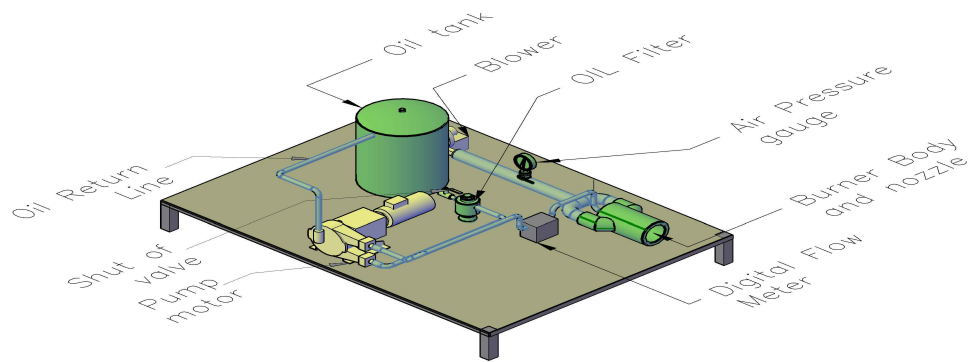


Figure 3.2: Pictorial Illustration of the Designed Burner

and the return line to take back any excess oil to the fuel reservoir. Figure 3.3 shows the whole burner set up after fabrication.

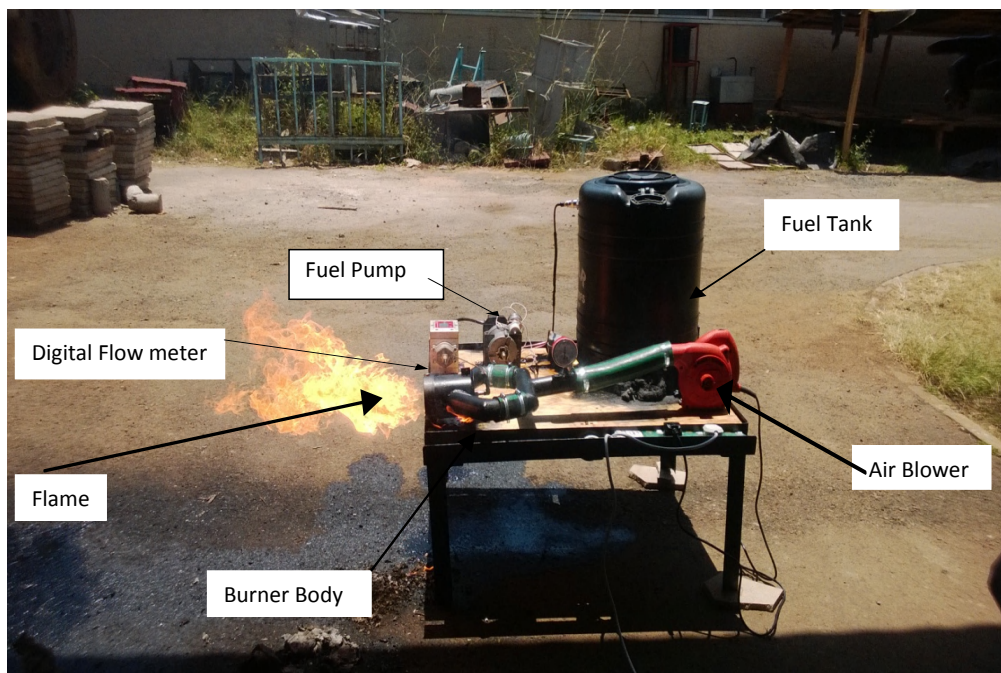


Figure 3.3: Pictorial View of the Assembled Burner

At the top right corner of the set up is an oil tank reservoir with fuel line connected from its bottom to the suction side of the pump and return line to the top of the tank. A digital flow meter is just next to the oil fuel pump and its driving motor. The flow

meter is connected to the burner through a T-joint for an even air distribution. The set up was tested for combustion capability and leakage problems before performance tests were conducted. The flame can be seen clearly at the burner end on the left side of the set up.

Sizing of this burner was based on a typical family size in Kenya since it was intended to heat water for a monogamous family and supply process heat for utilization in restaurants and hotels. A typical family in Kenya is made up of about five members. An assumption was then made that each member uses about 20 L of water to bathe. Water quantity and conventional water heaters capacity (3 kW) were used as the initial basis for sizing the burner.

3.2.1 Combustion Reactions of Waste Lubrication Oil

The burner design began by doing a stoichiometric reaction of WLO using available literature on WLO chemical composition. Excess air of 12%, 20% and 30% were used to calibrate a variable flow air blower with the following specifications: 3.5 m³/min maximum flow rate, 600 W power rating and 50 Hz frequency. The burner capacity or heat release rate (HRR) was determined as shown in Equation 3.1 below:

$$HRR = \frac{\dot{m}LHV}{3.6} \quad (3.1)$$

Where HRR is the heat release rate or burner capacity in kW, \dot{m} is the oil mass flow rate in kg/hr, LHV is the oil lower heating value in MJ/kg. Maximum burner capacity determined from Equation 3.1 in Appendix C at oil flow rate of 6.25 kg/hr and calorific value of 43.39 MJ/kg was 75.33 kW.

Performance parameters of the rig were determined after carrying out reactions between WLO and an oxidizer (oxygen in atmospheric air). A stoichiometric reaction (SR) was developed to help establish burner capacity, total amount of combustion air required to burn a given amount of waste lubrication oil, air and fuel flow rates. Nwachukwu et al [59] carried out tests on WLO to determine properties necessary for its efficient combustion and their findings were as shown in Table 3.1.

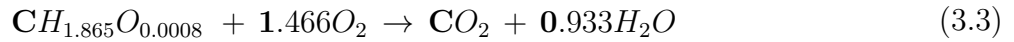
Table 3.1: Typical Properties of Waste Lubrication Oil

Test	Value
Density	895.2 kg/m ³
Relative density	0.8952
Kinematic viscosity at 100 °F	101.48 Centistoke
Flash point	146 °C
Ash content	0.75%
Sulphated ash	0.85%
Moisture content	14%

These values were used to perform stoichiometric reaction for WLO. Equivalence ratio (ϕ) which is the ratio between actual air/fuel mass ratio to the theoretical air/fuel mass ratio is expressed as shown in Equation 3.2 below. An equivalence ratio of 1.0 indicates that both actual and theoretical combustion air masses are equal and as such stoichiometric combustion results.

$$\phi = \frac{A_{act}/F_{act}}{A_{theoret}/F_{theoret}} \quad (3.2)$$

Where A_{act} and $A_{theoret}$ are the actual and theoretical combustion air mass respectively while F_{act} and $F_{theoret}$ refer to the actual and theoretical mass of fuel respectively. The overall combustion reaction equation for waste lubrication oil used in this research was as shown in Equation 3.3 below:



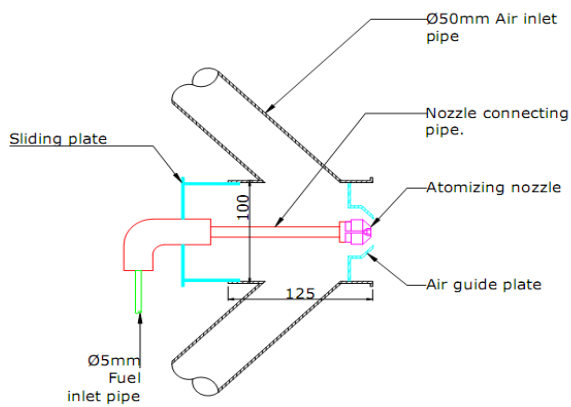
3.3 Waste Lubrication Oil Burner Setup

The burner setup had six main components:- burner body, atomizing nozzle, fuel supply system, fuel reservoir, air supply system and oil filter presented as follows:

3.3.1 Waste Lubrication Oil Burner Body

Schematic and pictorial views of the burner body are shown in Figure 3.4 below. The diameter of the burner was set to 100 mm to allow flame to cover most of the combustion chamber area and its length was 125 mm. The air inlet to the burner was set at two opposite sides of the burner body each 50 mm in diameter to enable uniform turbulent mixing and more air in the burner body. A sliding plate was provided for at the back of the burner to regulate air supply. The burner body was made of mild steel as it is easier to weld, relatively cheap, hard and finally, corrosion does not effect its performance. This material is cost effective and ideal for long term operation of the burner. The burner air inlets and air pipe from air supply blower were joined by a 50 mm diameter flexible pipe to accommodate any misalignment and allow for adjustment of the burner forward or backward.

Air regulation in the combustion chamber was achieved mainly by a variable flow blower. At the center of the burner, an internally threaded small metallic tube was



Burner schematic view



Burner pictorial view

Figure 3.4: Waste Lubrication Oil Burner Body

fitted to accommodate fuel atomizing nozzle.

3.3.2 Nozzle Selection

Waste lubrication oil ignited when atomized to very fine droplets. Droplet size was larger in higher fuel discharge rates than lower discharge rates holding fuel flow pressure and spray angle constant. Again, droplet size was smaller in wider spray angles and required wide combustion chambers to avoid flame impingement on chamber walls. A 45° spray had higher droplets than 80° spray. On the other hand, 80° spray could not sustain wide combustion chambers. An increase in nozzle spray angle caused a decrease in CO emission upto an angle of 60° after which CO emission started increasing [60]. A 3.785 Litres per hour (L/hr), 60° spray angle nozzle was selected after considering the above factors. Nozzle design was a very important determinant of droplet size in a spray. The smallest possible droplet size was not necessarily the most desirable one. Therefore, a good droplet size distribution to produce efficient and quiet fires was determined by the nozzle design [49]. There are basically three types of oil atomizing

nozzles that can be utilized in WLO combustion. These include single point nozzle, multi point nozzle and adjustable spray nozzle [5]. Due to WLO's high viscosity, a 5.6775 L/hr, single point nozzle with 60° spray angle was selected to sustain smooth oil flow through the orifice.

From the nozzle table given in ST 50 Oil Burner Manual [61], a 5.6775 L/hr and 60° spray angle nozzle should give an output power at various fuel flow pressures as shown in Table 3.2. This table is important in that it enables the comparison of burner power output at a given fuel flow rate with the output calculated using firepower equation.

Table 3.2: Oil Atomizing Nozzle Table

Pump pressure (bar)	Oil flow rate (kg/h)	Power output (kW)
8	4.98	53
9	5.29	63
10	5.58	66
11	5.85	69
12	6.11	72
13	6.36	75
14	6.60	78
15	6.83	81

3.3.3 Fuel Pump Selection

WLO fuel was supplied to the atomizing nozzle in the burner body using a Danfoss BFP11 variable pressure heavy fuel oil (HFO) gear pump. A gear pump was chosen because of its capability to develop high flow pressures desired in the research and it does not allow back flow of fuel. It was capable of pumping any liquid fuel with viscosity range of 1.3 - 12.0 mm²/sec. Its pumping pressure ranged between 7 - 15 bar and it was capable of pumping oil of any temperature range between -10° C to 70° C. It had provisions for fuel pressure gauge, venting and varying pressure from 0 to 15.0

bar using a 4 mm allen key. It operated on a single phase electric motor rated 175 W and 1400 rpm. Heavy fuel oil yields good spray droplets for combustion at about 7.0 bar pumping pressure when oil is preheated before pumping. Figure 3.5 shows pictorial diagram of the oil pump used in this research.

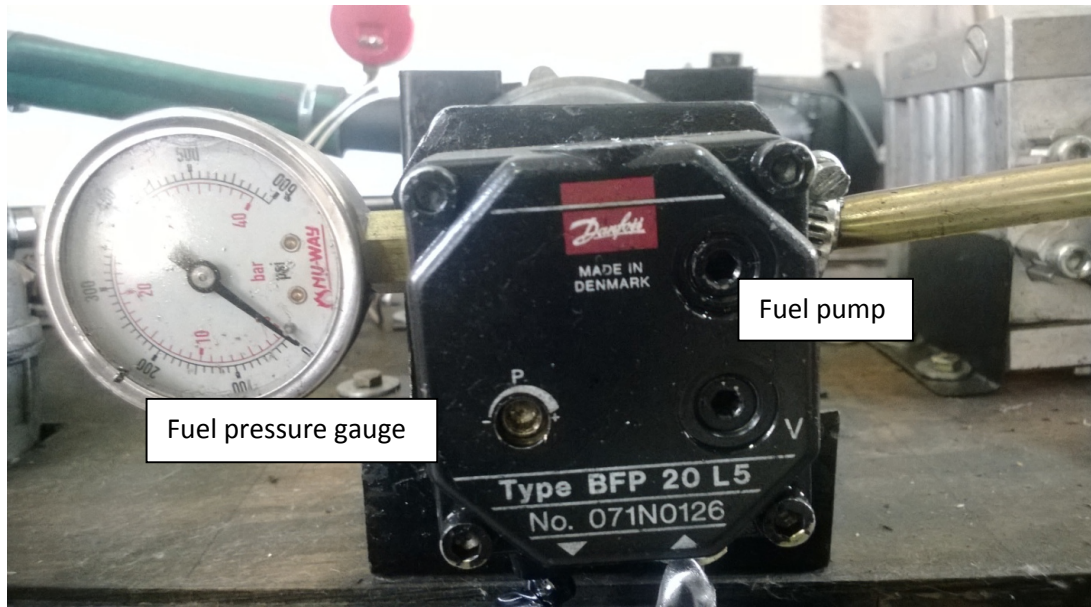


Figure 3.5: The Danfoss BFP11 Oil Pump

Pump operation was as follows: when oil pump was started, WLO was drawn from the oil tank and passed through a filter to the suction port of the gear pump and pumped to the pressure side. Pressure was varied from 0 to 15 bar using a regulating valve. Oil quantity utilized was determined by the set pressure by the regulating valve and recorded on the digital flow meter along the pressure line.

3.3.4 Fuel Reservoir

A 50 L capacity black cylindrical plastic tank was selected as fuel reservoir for the setup. It had three openings, $\phi 12.7$ mm each, to fit fuel pump suction line, return

line and drainage pipe at the bottom. It was a 50 L capacity tank sized based on the combustion duration and refill rate. The highest flow rate (6.25 kg/hr) required an average tank refill every 7 hours. It was also fitted with a filter at the top to facilitate initial filtration of WLO when filling the tank.

3.3.5 WLO Flow Measurement

WLO flow measurement was done using an Oval Gear Digital flow Meter with a provision for resetting readings. Flow was measured in Liters of fuel passing through it in a given time period. It also had an in-built memory to show the immediate previous flow reading. Timing was done using a stopwatch with an accuracy of $\pm 1\%$. Figure 3.6 shows this digital flow meter.



Figure 3.6: The Oval Gear Digital Flow Meter

3.3.6 Air Supply System

Air supply at the back of a burner introduces a phenomenon called draft which is the flow of gases through a heat generating equipment [62]. Once combustion occurs,

the heated gas leaves combustion chamber and passes through heat exchangers to the exhaust stack. Draft can be natural where combustion air flows into the burner freely or forced/mechanical where combustion air is forced into combustion chamber by a fan. Draft mostly relies on a combination of both natural and forced means.

Air supply to the burner system was achieved through a Black & Decker blower. It was a variable flow blower with six levels of flow rates labeled 1 to 6. It had a power rating of 600 W, 50 Hz frequency and a maximum flow rate of 3.5 m³/min. This Blower was calibrated using an Air Flow Bench to establish flow rate at each level. Figure 3.7 shows the air flow bench used to calibrate the blower.

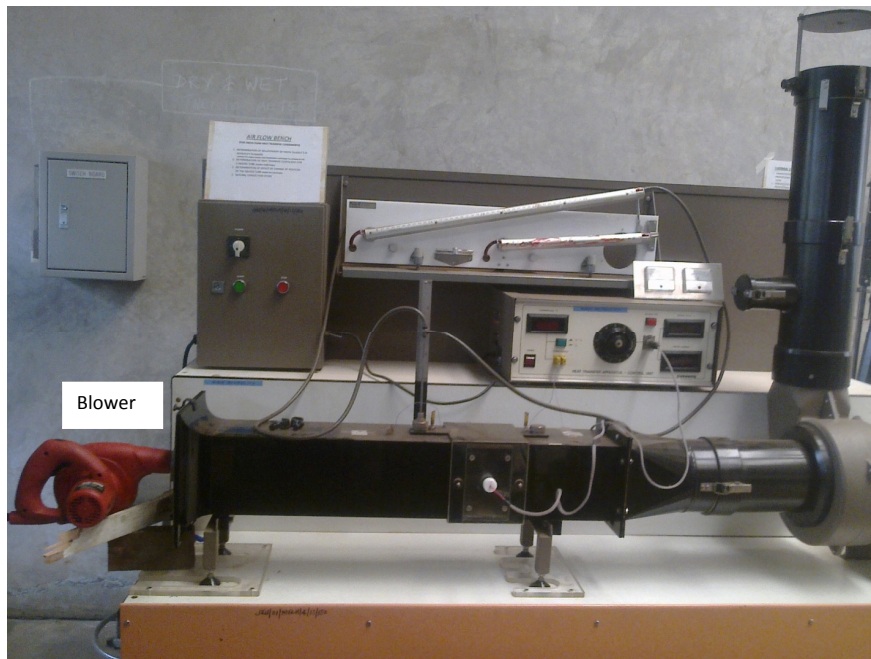


Figure 3.7: The Air Flow Bench Used for Blower Calibration

The air flow bench was operated as follows: Blower was fitted on one end of the bench as shown in the diagram above. A single mercury tube test module, with 12.7 mm diameter tube in position, was fitted into the duct and coupled to the bench control unit. Bench heater was switched on adjusting the output until a temperature change

of about 20° C was recorded. The reading on the mercury tube was then taken at this temperature change. This procedure was repeated for all blower flow levels after which conversion was done based on the readings recorded.

3.4 Safety

Safety is required in any activity that an individual does. In this research, it was ensured that both the user and WLO burner rig components were well protected during combustion process. The most critical components of the rig protected were fuel pump and atomizing nozzle. Clogging of these components destroys them permanently. WLO contains a lot of contaminants including metal parts drawn into lubrication oil due to wear of engine walls during operation. To prevent these particles from damaging pump and nozzle, oil was filtered in two stages. First, was at the entrance of the oil tank and the second filtration was done just before the oil entered suction port of the pump using a fine mesh line filter.

Also conducted was the leaking test. The rig had several joints along the suction and delivery sides of the fuel line. The joints between the suction line and fuel tank, fuel return line and the tank as well as the drain pipe and the tank were fastened together using nuts secured with rubber seals. The other joints connecting oil filter, shut off valve, nozzle and digital flow meter were fastened together using joint nuts with thread tape between the threads to prevent oil leaks.

3.5 Performance Parameters

The fabricated burner performance was determined by measuring flame temperatures at various fuel flow rates (5.05, 5.65 and 6.25 kg/hr) during combustion. Others included CO, CO₂ and HC emissions measurement at these flow rates. This required the knowledge of WLO energy content to enable determination of the burner firepower. Methods used to determine WLO energy content, flame temperatures, firepower and emissions are presented in this section.

3.5.1 Fuel Heating Value

Heating value of a fuel refers to the energy released per unit mass or per unit volume of the fuel when it is completely burnt [63]. This value is also called Calorific value (expressed in MJ/kg) and can be Higher heating value (HHV) or Lower heating value (LHV) depending on the state of water molecules in the final combustion products. HHV is achieved when no energy is used to vaporize the water present in combustion products and as such this water is condensed. HHV therefore, contains both sensible heat energy and latent heat of vaporization. LHV results when all the water in combustion products is vaporized by latent heat of vaporization and thus it contains only the sensible heat energy. Any evaluation involving heating value utilizes LHV.

HHV was determined experimentally using an auto - adiabatic constant volume bomb calorimeter, Gallenkamp type with an accuracy of +5%. It had a pressure-tight combustion chamber where combustion O₂ was charged into the chamber at a pressure of 30 bar. A steel chamber was immersed into another cylindrical container having its weight and water in it adding up to 3.0 kg. HHV was then determined by completely

burning 0.5 grams of WLO in the confined combustion chamber full of O₂ at 30.0 bar as indicated above. A 90.0 mm thread was used in the combustion chamber to initiate ignition of WLO. Combustion products were cooled to ambient conditions to condense any water vapour present in the combustion products. HHV was finally estimated using Equation 3.4 as shown:

$$HHV = \frac{(10.35\Delta T) - 0.126}{m_s} \quad (3.4)$$

where ΔT is the difference between initial and final temperature of burned sample, m_s is the mass of the sample burned, 10.35 is the bomb calorimeter constant and 0.126 is the energy for the 90.0 mm thread. Shown in Figure 3.8 is the photograph of the bomb calorimeter used.



Figure 3.8: Constant Volume Bomb Calorimeter

Moisture content of WLO was then determined by distillation method in the Food Science Chemistry laboratory, JKUAT and also at the Kenya Ministry of Roads (material

testing department) and its value used to calculate latent heat of vaporization of water vapour in WLO. LHV was then calculated by deducting the latent heat of vaporization from the HHV as shown in Equation 3.5 below [63].

$$LHV = HHV(1 - M) - 2.447M \quad (3.5)$$

where M is the wet basis moisture content and 2.447 is the latent heat of vaporization of water in MJ/kg at 25° C. To achieve a more accurate estimate from Equation 3.5, heat released by hydrogen content combustion should also be included.

The moisture content of WLO in Equation 3.5 was determined by Distillation method. 5 grams of WLO sample was heated in a flask with an immiscible solvent for 30 minutes and water vapour continuously distilled with an immiscible solvent. This distilled water was then collected in a receiver, allowed to settle and then its volume measured.

3.5.2 WLO Burner FirePower (FP)

WLO burner firepower refers to the amount of WLO used by the burner per unit time to generate power. It was expressed as the ratio of the product of fuel consumed and its net calorific value to the test duration. For flame temperature measurements, each test was taken every 5 minutes. In this case, WLO burner rig firepower was used to determine power output of the rig during a combustion process. Variations of the rig's output were observed under varying fuel flow rates (5.05, 5.65 and 6.25 kg/hr) and chemical reactions with excess air (EA) of 12%, 20% and 30%. Equation 3.6 below was

used to determine the burner's firepower.

$$FP = \frac{f_m(LHV)}{60t} \quad (3.6)$$

Where f_m is fuel mass consumed (kg), LHV is fuel lower heating value (MJ/kg) and t is the total time (minutes) taken during the test.

3.5.3 Emissions Test

Combustion emissions are directly influenced by the type and composition of the fuel burnt, combustion method and combustion efficiency of the energy recovery unit [5]. A MEXA-544GF emissions analyzer shown in Figure 3.9 was used to monitor emissions. It could measure CO (% volume), CO₂ (% volume) and UHC (ppm) emissions. The analyzer was first connected to power, switched on and left to warm up for about ten minutes after which it was ready for measurement. A push button was pressed to switch it to a measuring mode. Its probe was then inserted into the exhaust port of the combustion equipment to sample emissions and display values on its screen.

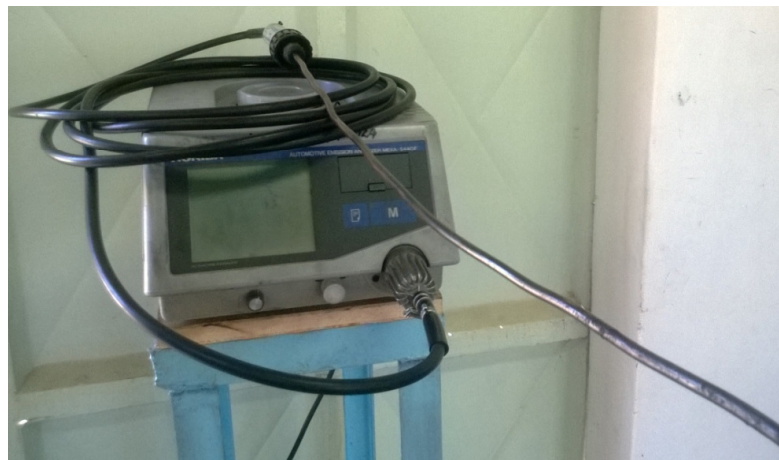


Figure 3.9: The MEXA - 544GF Emissions Analyzer

3.5.4 Temperature Measurement

Burner flame temperature was determined using a 50 mm long probe k-type thermocouples. Probe diameter was 8 mm, had a cable length of 3 m and could operate at temperatures of 100° C to 1250° C. This thermocouple was connected to a TDS-530 automatic, multichannel, scanning data logger to convert its signals to temperature readings in °C. Figure 3.10 shows the TDS-530 data logger used to take temperature readings. Thermocouple probe was placed a distance of 100 mm from the burner end to be approximately at the flame center for maximum temperature recording.



Figure 3.10: TDS - 530 Data Logger

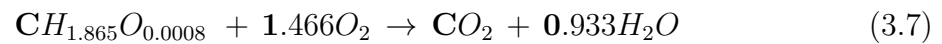
3.6 Determination of Burner Theoretical Emissions

3.6.1 Overview

Solid and liquid fuels are normally analyzed by mass to determine their individual constituent composition. During combustion, atmospheric air (21% oxygen and 79% nitrogen) is used.

3.6.2 Combustion of WLO by Volume

Combustion by volume is guided by two laws: Dalton's Law of partial pressures and Avogadro's Law. Dalton's Law states that 'the total pressure of a mixture of gases equals to the sum of partial pressures of individual gas constituents'. Partial pressure of a gas refers to the pressure that the gas would exert if it occupied the same volume and temperature alone. Avogadro's Law states that '1 m³ of any gas at the same pressure (P) and temperature (T_m) contains the same number of molecules'. Therefore, the volume of a gas at the same pressure and temperature is directly proportional to the number of its molecules. It is therefore concluded that the volume of a kmol of any gas is the same if P and T_m are the same [64]. Combustion reaction of WLO is expressed by Equation 3.7 below.



The volume ratio of the reactants and products from the equation is given as

$$1 : 1.466 \rightarrow 1 : 0.933$$

Stoichiometric air required to fully oxidize WLO in the above reaction Equation was calculated as 6.981 m³.

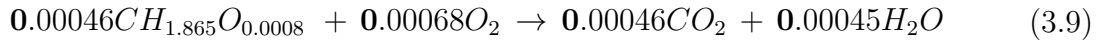
3.6.3 Theoretical CO₂ Emission Determination at 12% Excess Air

Oil density = 875.9 kg/m³, combustion takes 5 minutes.

At fuel flow rate of 5.05 kg/hr, oil burnt in 5 minutes is calculated as:

$$SC_{air} = t.\dot{m}_f \quad (3.8)$$

SC_{air} which is the stoichiometric combustion air amount was calculated as 0.4 kg and volume of oil burnt as 0.00046 m³. From this value, stoichiometric reaction is balanced as in Equation 3.9 below.



Volume ratio of the reactants and products from the equation is

$$0.00046 : 0.00068 \rightarrow 0.00046 : 0.00045$$

From Equation C.14, SC_{air} was evaluated as 0.003 m³ and an excess air 12% EA increased it to 0.00333 m³.

Analysis of Dry Products

Volumetric composition of each product of combustion was determined and tabulated as in Table 3.3.

Table 3.3: Volumetric Analysis of WLO Dry Combustion Products

Product	Calculation	Value
N ₂	79% × 0.00325	0.00254 m ³
CO ₂	-	0.00046 m ³
O ₂	12% × 0.00068	0.000082 m ³
Total	-	0.00308 m ³

Theoretical CO₂ emission was determined as 14.92%. Similar reactions and equations were done for 20% and 30% EA for all fuel flow rates and results tabulated as shown in table D.2 of Appendix D.

3.7 Theoretical CO Emission Determination at 12% Excess Air

Theoretical CO emission was estimated for each excess air used using Equation 3.10. The values determined were tabulated as will be seen hereafter.

$$CO_{th} = CO_{2(th)} - CO_{2(exp)} - UHC_{2(exp)} \quad (3.10)$$

Where CO_{th} is theoretical CO emission, $CO_{2(th)}$ refers to theoretical CO₂ emission, $CO_{2(exp)}$ is experimental CO₂ emission and UHC_{exp} is experimental UHC emission.

Theoretical unburnt hydrocarbon emission was estimated using Equation 3.11.

$$UHC_{th} = CO_{2(th)} - CO_{2(exp)} - CO_{exp} \quad (3.11)$$

Results for all these calculations were presented as shown in Tables D.2, D.3, D.4, D.5, D.6, D.7, D.8 of Appendix D. These values together with their corresponding experimental results were used to plot graphs of the respective emissions for comparison as shown in Figures 4.2, 4.3 and 4.4 of the Results.

3.7.1 Adiabatic Flame Temperature for WLO Fuel

Adiabatic flame temperature refers to the maximum flame temperature theoretically achieved by combustion products in a combustion process assuming no heat losses to the surrounding environment and that all energy released from combustion is used to heat combustion products [65]. This temperature can be calculated using constant pressure or constant volume combustion process methods depending on the one held constant when determining reactants and products specific heat capacities. In this research, combustion was done at constant pressure values and therefore adiabatic flame temperature was estimated using specific heat capacity values at constant pressure. To estimate this temperature, energy conservation balance between the reactants and products was used as shown in Equation 3.12.

$$LHV + H_R = H_P \quad (3.12)$$

Where LHV is the fuel lower heating value in kJ/kg, H_R and H_P are enthalpy for the reactants and products respectively in kJ/kg.

Reactants enthalpy or sensible heat in fuel and air, H_R , is given by Equation 3.13 below.

$$H_R = (t_i - 25) \sum (mC_p)_R \quad (3.13)$$

Where t_i is the initial fuel and air temperatures ($^{\circ}\text{C}$), 25 is the reference temperature at standard conditions ($^{\circ}\text{C}$), m is the mass of each reactant (kg) and C_p is the specific heat capacity of each reactant at constant pressure (kJ/kgK). Initial temperature, t_i , of the reactants was 20.5°C .

Specific heats of fuel, oxygen and nitrogen were evaluated at mean temperature of

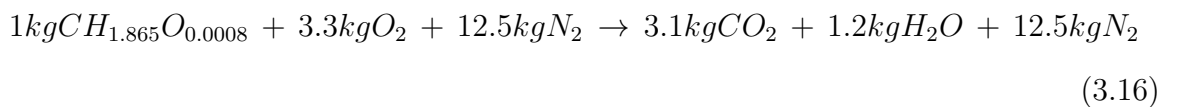
$(t_i + 25)/2$ to determine enthalpy of the reactants, H_R . The enthalpy of combustion products, H_P , is defined using Equation 3.14.

$$H_P = (t_f - 25) \sum (mC_p)_P \quad (3.14)$$

Where t_f is adiabatic flame temperature. Equation 3.12 is therefore expanded to yield Equation 3.15.

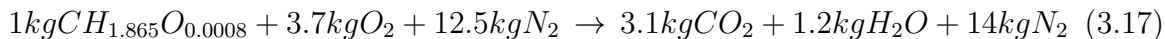
$$LHV + (t_i - 25) \sum (mC_R)_P = (t_f - 25) \sum (mC_p)_P \quad (3.15)$$

Iteration method was used to estimate adiabatic flame temperature using Equation 3.15. In this method, an arbitrary flame temperature, t_f , was chosen and used to determine C_p for the combustion products used in the equation to estimate the new t_f . This new value was then used to estimate the next set of C_p values for t_f estimation again. The whole process was repeated until a constant value of t_f or a variation of within 5° C was achieved. For this to be possible, a reaction equation of 1 kg of fuel was balanced to determine amount in kg of each reactant and product required for the completion of combustion process. Stoichiometric reaction for 1 kg fuel combustion was balanced as shown in Equation 3.16.



This equation was used with various excess air values (12, 20 and 30%) to evaluate specific heat capacities for the reactants and products. Excess air had effects of increasing the mass of O_2 and N_2 used which greatly affected adiabatic flame temperature. Using

12% excess air in Equation 3.16 above changes it to Equation 3.17 shown below.



This equation was modified for the other excess air and C_p values and adiabatic flame temperature estimated. Results of C_p values and adiabatic flame temperature at various excess air were recorded as shown in Tables D.9, D.10, D.11, D.12 and D.13 of Appendix D.

3.8 Uncertainty Analysis

3.8.1 Background

Uncertainty refers to the margin of doubt that exists about the result of any measurement. To quantify an uncertainty, one needs to state the width of the margin or interval and the confidence level as a percentage. Unless stated, confidence level is normally taken as 95%. No physical quantity can be measured with a perfect certainty, there are always errors in any measurement data taken [66]. A series of measurements will always produce a scatter of values distributed around a mean value [67]. The fabricated burner was tested for performance and data collected using equipment like TDS - 530 data logger, MEXA-544GF emissions analyzer, digital liquid flow meter and an oil flow pressure gauge among others. WLO HHV was estimated using constant volume bomb calorimeter. Uncertainty was obtained by carrying out various tests several times and then their mean and standard deviation evaluated. The benefit of taking mean values is that the influences (external factors) causing variations in the measurements tend to be nullified. Standard deviation of the repeated measurements can be worked out and the values determined used to estimate variations of these measurements from the

mean. This is called standard uncertainty of the mean [68]. A statement of uncertainty indicates how large a measurement doubt can be [68]. Bell [69] suggests that a near estimate of the true value of a measurement requires between four and ten readings of the same measurement. International Atomic Energy Agency [68] gives a simple example of understanding uncertainty as shown in Equation 3.18.

$$X = X_m \pm U_m \quad (3.18)$$

where X is true value, X_m is the measured value and U_m is measurement uncertainty. Instrumental and Experimental uncertainties analysis are presented below:

3.8.2 Instrumental Uncertainties

Various instruments with different accuracies were used during data collection in the research. These varied accuracies independently contributed to the overall measurements taken. The instruments include: stop watch, digital flow meter, digital data logger and bomb calorimeter explained in Section 3.4. Bevington and Robinson [70] proposed a technique with a propagation equation to estimate these uncertainties. This technique was applied by Ndiritu [71] and Oketch [72] in obtaining instrumentation random uncertainties in absorption rig for industrial capture of carbon dioxide emission and optimization of performance of Bio-ethanol gel cookstove respectively. This technique has been employed in evaluating instrumental uncertainties in this research.

Performance of the WLO Burner rig involved determination of flame temperature at different fuel and combustion air flow rates, fuel consumption and firepower. Firepower consisted of fuel lower heating value, mass of fuel consumed and time taken to consume

it. The overall uncertainty equation relating these parameters is shown in Equation 3.19.

$$\xi = \sqrt{\left(\frac{\partial FP}{\partial LHV}\xi_{LHV}\right)^2 + \left(\frac{\partial FP}{\partial f_m}\xi_{f_m}\right)^2 + \left(\frac{\partial FP}{\partial t}\xi_t\right)^2} \quad (3.19)$$

where FP is the firepower and ξ_{LHV} , ξ_{f_m} and ξ_t are the uncertainties from the respective measuring instruments (constant volume bomb calorimeter, digital liquid flow meter and stop watch). Resolution of a stopwatch was 1 second. Equation 3.19 was then rewritten as a percentage to yield Equation 3.20 shown.

$$\frac{\xi}{FP} = 100 \times \sqrt{(\beta_{LHV})^2 + (\beta_{f_m})^2 + (\beta_t)^2} \quad (3.20)$$

where $\beta_{LHV} = \frac{\xi_{LHV}}{LHV}$, $\beta_{f_m} = \frac{\xi_{f_m}}{f_m}$ and $\beta_t = \frac{\xi_t}{t}$ respectively.

Determining uncertainty for heating value involved various instruments like constant volume bomb calorimeter, oxygen gas cylinder pressure gauge and weighing machine. Taking any two representative instruments, Equation 3.20 reduces to Equation 3.21 below.

$$\frac{\xi}{FP} = 100 \times \sqrt{(\beta_{f_m})^2 + (\beta_t)^2} \quad (3.21)$$

From Equation 3.21, uncertainty was determined as 0.38%. Based on 95% confidence level the uncertainties calculated should not go beyond 5% and therefore this value was within the range of accuracies of the instruments used.

3.8.3 Experimental Uncertainties

An experimental uncertainty refers to deviation from the mean of the data collected repeatedly under similar conditions. It was necessary that these deviations which bring about experimental uncertainties be determined. This uncertainty is mainly estimated

using Standard Deviation, (σ). Equation 3.22 shows the formula used to calculate standard deviation as suggested by Taylor [73] and Bevington and Robinson [70]. This is the most conventional method for evaluating uncertainty based on the behaviour of the measured data.

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (SFC_i - \overline{SFC})^2} \quad (3.22)$$

Standard deviation was further expressed as a percentage of the mean so as to be consistent with the results from instrumental uncertainties. This resulted in Equation 3.23 as shown.

$$\sigma = 100 \times \frac{\sqrt{\frac{1}{N-1} \sum_{i=1}^N (SFC_i - \overline{SFC})^2}}{\overline{SFC}} \quad (3.23)$$

Where N is the total number of samples, SFC is specific fuel consumption and \overline{SFC} is the average SFC expressed in Equation 3.24 as.

$$\overline{SFC} = \frac{1}{N} \sum_{i=1}^N SFC_i \quad (3.24)$$

One of the parameters used to evaluate experimental uncertainties was the specific fuel consumption. Experimental uncertainties were very significant in establishing capacity of the WLO burner to give uniform results of specific fuel consumption. Four measurements were therefore taken repeatedly at each fuel flow rate for all EA values (12%, 20 % and 30%) and used to evaluate standard deviation. Results in Table 3.4 indicate reproducibility of the data collected using a representative fuel flow rate of 5.65 kg/hr.

Table 3.4: Standard Deviation for Specific Fuel Consumption Values

SR Values	Air Flow (m ³ /min)	Average SFC (g/sec)	Standard deviation (%)
1.12	1.26	1.40167	0.208
1.20	1.35	1.40000	0.104
1.30	1.46	1.40167	0.103

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 Background

Test results and discussions of the WLO burner performance under varying conditions (fuel and air flow rates) are presented in this chapter. Specific fuel consumption and firepower of the burner when repeated measurements under similar conditions were carried out have been presented before. Other determined results are also presented and discussed as below.

4.2 Waste Lubrication Oil Analysis

Performance of a given fuel is influenced greatly by its physical and chemical properties. Therefore, it was very important that physical-chemical property analysis of WLO be done. Properties of WLO (From Compression Ignition (CI) engine) determined during this research were: calorific value (HHV and LHV, done for WLO from both Spark Ignition (SI) and CI engines), moisture content, density, viscosity, insoluble residue, flash point and ash content. Results from the analysis are presented in Table 4.1 below.

Table 4.1: Properties of CI Engine Waste Lubrication Oil

Test	Mean Value	Test	Mean Value
Oil HHV	43.39 MJ/kg	HHV (Mixed SI & CI engines oil)	42.98 MJ/kg
Moisture content	0 %	Density	875.9 kg/m ³
Relative density	0.8759	Kinematic viscosity (25 ⁰ C)	1371.5 Cst
Insoluble residue	0.056 %	Flash point	202 ⁰ C
Ash content	0.765 %		

WLO LHV was determined using the expression in Equation 3.5. CI engine WLO test results from both JKUAT Food Science Department and Ministry of Roads (Material Testing Department) depicted WLO moisture content as zero. This implied that both LHV and HHV were equal. Oil flash point from test results was 202^o C which was quite close to the value available in literature (200^o C) as presented by Isidoro Martinez [74]. The normal way of evaluating LHV is to make an assumption that latent heat of vaporization of water in fuel together with reaction products is not recovered and hence this value is deducted from the HHV. From the test results, it is quite clear that waste lubrication oil contain a lot of untapped energy (LHV) which can boost energy requirements if properly utilized towards energy generation. Oil kinematic viscosity result shows that it is very viscous and therefore its efficient flow and combustion requires preheating. This is also justified by the oil's high flash point.

Soot formation is a common phenomenon in a combustion process. Amount of soot formed during combustion is a function of combustion temperatures, pressure and fuel structure variables. Initial fuel structure, fuel/air equivalence ratio and the maximum flame temperature are the key parameters in controlling the tendency of a premixed flame to soot. Viscosity as fuel structure property influences formation of soot greatly during combustion. As seen from WLO test results, Kinematic viscosity is quite high and therefore will enhance more soot formation on the combustion chamber walls which

will reduce combustion efficiency in the long run. This phenomenon was not accounted for in the current work mainly because there is a challenge of accurately predicting the soot emission in practical combustion configurations.

Nwachukwu et al [59] also did tests on both virgin lubrication oil and WLO properties and their findings show closer relationship to the results for WLO used in this research. Nwachukwu determined the relative density for his waste lube oil as 0.8952, flash point as 146 °C, ash content as 0.75 % and moisture content as 14 %. Waste lubrication oils will contain more moisture than virgin lubrication oils when seals are leaking thereby allowing some of the combustion products to sip down the oil sump. When fuel and oxidizer (oxygen) undergo combustion reaction, products of combustion that result are CO₂, energy and water vapour which then condenses to liquid. If the engine in which combustion occurs has leaking oil sump seals then some water vapour resulting from combustion process will find its way into the lubrication oil sump adding to its water content. However, in this research WLO sample tested in two different places, JKUAT Food Science department (chemistry laboratory) and Kenya Ministry of Roads Material Testing department yielded the same result of 0 % water content. This could imply that the engine from which the research WLO was collected had leak proof sump seals and therefore water resulting from combustion process all vaporized. The knowledge of oil fuel moisture content is very important in estimating the amount of potential localized fog formed by a combustion system in a given period of time [65]. Water vapour in the fuel adds to water formed during combustion and escape to the surrounding environment. The more the fuel moisture content, the more the water released to the atmosphere and the more the localized fog formed. Again, moisture in the oil undergoes chain initiation process to form OH and H radicals which reacts faster with CO in chain branching process to form more CO₂.

4.3 Comparison of Heating Water by Electric Heater and WLO Burner

The costs of heating 100 liters of water for a fixed time duration (15 minutes) using a 3kW electric heater and WLO burner were computed and compared. Units of power used by electric heater and WLO burner were 0.1875 kWh and 0.75 kWh respectively. The total amount of money used in purchasing units (holding other charges constant) for electric heater and burner were Ksh. 2.00 and ksh. 0.50 respectively thereby saving 75% on power. The designed WLO burner performance was evaluated based on its firepower, specific fuel consumption, combustion emissions and flame temperature. The results were as presented below.

4.4 Waste Lubrication Oil Burner Firepower

WLO burner firepower was used to determine its power output during combustion and variations of the output observed under varying flow rates (5.05, 5.65 and 6.25 kg/hr fuel flow and 12%, 20% and 30% air flow for lean combustion). Lean combustion ensures more combustion products (CO₂ and water vapour) and less emission generated. This was the reason rich combustion was never conducted. Figure 4.1 shows variations of the burner's power output with fuel flow rate.

WLO burner firepower was greatly influenced by fuel flow rate as observed in Figure 4.1. There was a marked improvement in firepower between the minimum and maximum flow rates evaluated as 23.53%. Fuel flow rates and heating value were the main factors that influenced firepower. There was a provision for adjusting flow pressures from 0 to 15 bar which in turn influenced fuel flow rate. Equation 3.6 can be used

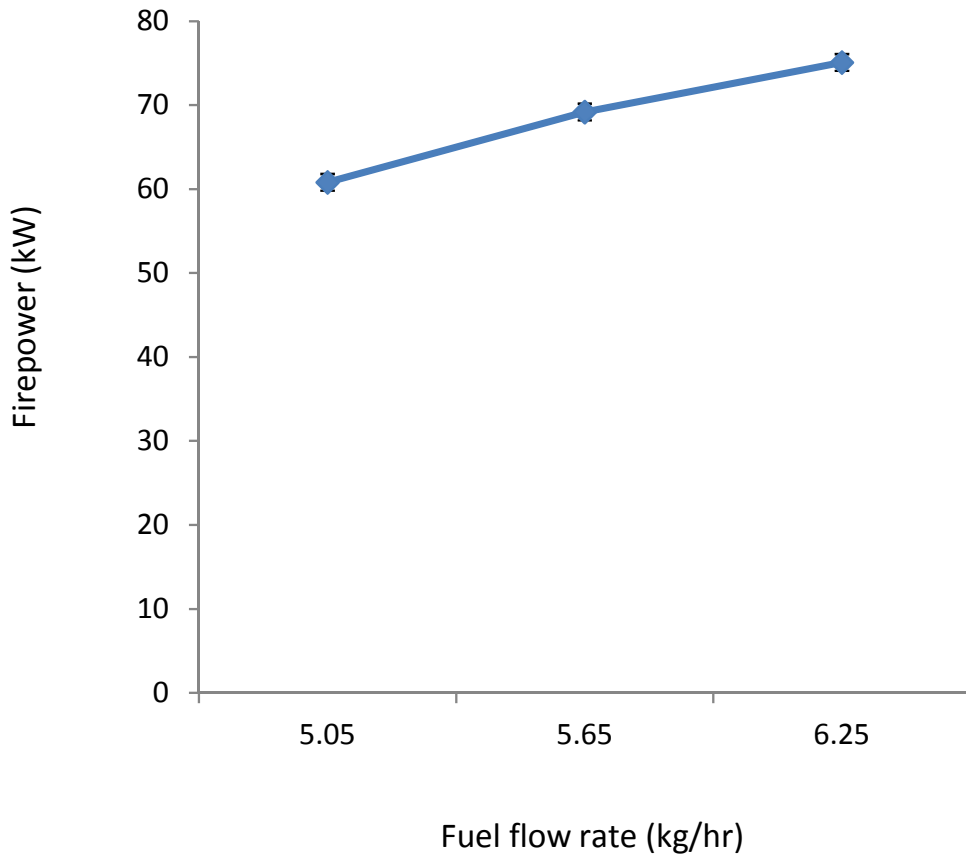


Figure 4.1: Firepower Variations with Fuel Pump Flow Rate

to explain the firepower results. In the tests conducted, both the fuel LHV and test duration were constant leaving fuel mass consumed as the only varying parameter. Therefore, firepower was determined by the mass of fuel burnt in a duration of 300 seconds. Firepower and mass of fuel burnt varied directly and as such an increase in fuel mass burnt meant an increase in firepower as shown in the results. The increase in firepower with increasing fuel flow rate was attributed to finer atomization of fuel with increasing flow rate thereby enhancing proper mixing of reactants and efficient combustion. Values of firepower achieved vary slightly from typical analytical values presented in Table 3.2. Fuel atomization nozzle achieved a minimum fuel atomization required to initiate combustion at 10 bar flow pressure and 5.05 kg/hr flow rate without fuel or air preheating.

4.5 Combustion Emissions

4.5.1 Overview

In combustion systems design, assessment of combustion emissions is very important to ensure they are within acceptable levels. Some combustion emissions are very harmful to human, other animals and the environment. It is therefore highly recommended that emissions from any combustion process be assessed.

Emissions measured from WLO combustion were CO, CO₂ and UHC. This was because they were the most probable emissions that occur during combustion of hydrocarbon fuels alongside oxides of nitrogen (NO_x) and oxides of sulphur (SO_x). NO_x and SO_x could not be included because emissions analyzer used had no provision for measuring them. Concentration of CO₂, CO and UHC emissions for all excess air (EA) values and fuel flow rates are presented below.

4.5.2 Carbon Dioxide

CO₂ is one of the by-products of combustion along side water vapour. It can be used as an indicator of combustion system's performance. Higher CO₂ amount generated implies an efficient combustion process. Figure 4.2 below shows variations in CO₂ emission with fuel flow rate at various EA values.

An excess air of 12% (also expressed as stoichiometric ratio, SR1.12) and fuel flow rate of 5.05 kg/hr resulted in formation of maximum CO₂. This was because there was

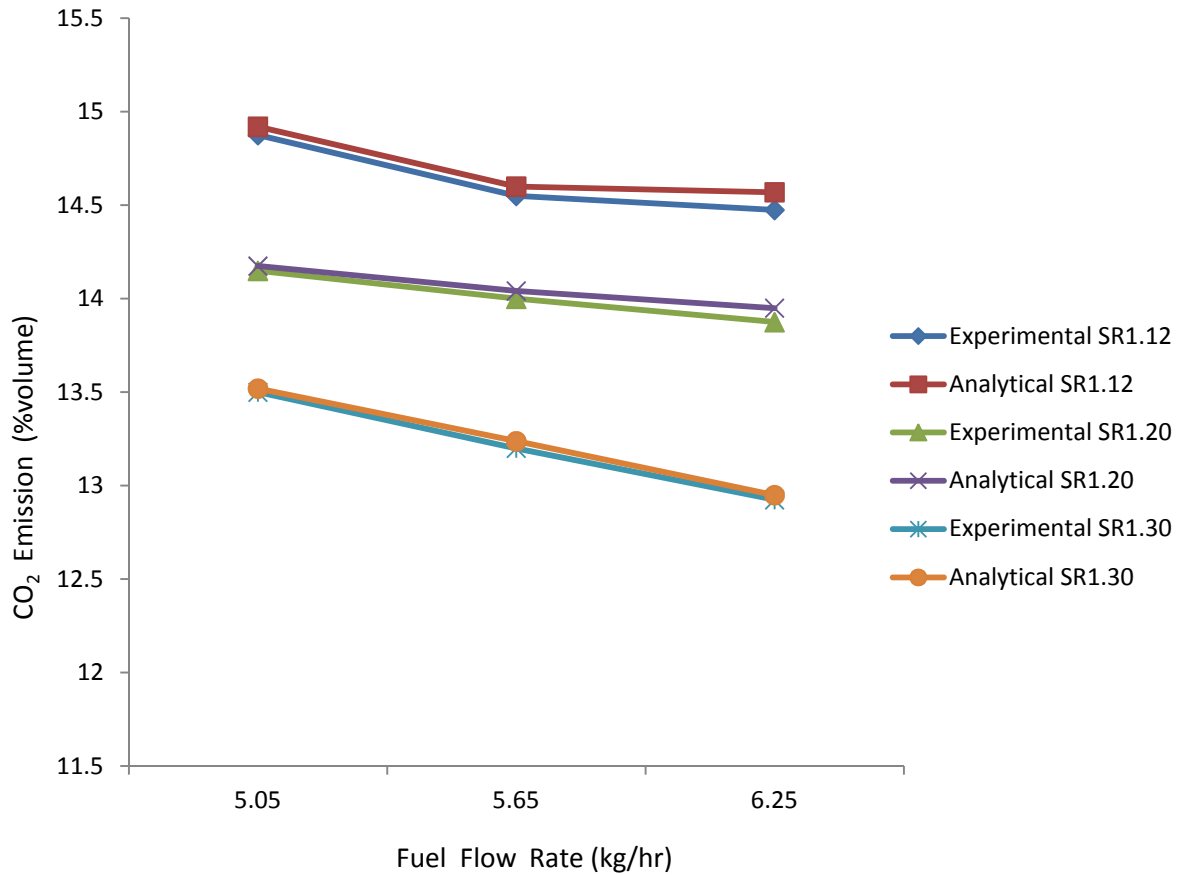


Figure 4.2: CO₂ Emission Variation with Fuel Flow Rates and SR Values

more excess air relative to amount of fuel supplied and a lean combustion resulted. Therefore, more of intermediate species (CO) formed was converted to CO₂ by oxygen radicals generated during chain initiation process. Excess air ensured more fuel was oxidized and a near complete combustion achieved leading to more CO₂ generation. As more excess air was added, reduction in amount of CO₂ generated was realized. This was as a result of the extra air supplied cooling the combustion system by absorbing heat and transporting it out in flue gases. System cooling contributed in reducing combustion temperatures and slowing down reactants reaction thereby reducing amount of combustion byproducts generated. It also stopped further CO conversion to CO₂ as this process required high temperatures of above 1100 K. Excess air also diluted flue gases further and thus contributing to more reduction in CO₂ concentration. A maxi-

imum difference in CO₂ emission was achieved at 6.25 kg/hr fuel flow rate. This was the difference between CO₂ emissions at SR1.30 and SR1.12 which was equal to 11.99%. Excess air mainly aims at converting more CO to CO₂ in an attempt to achieve complete combustion. A lower CO/CO₂ ratio is normally targeted in a combustion process.

This graph also compares CO₂ emission that was experimentally recorded and analytical values determined from WLO chemical reaction calculations done on the basis of 100% fuel carbon being converted to CO₂ for all fuel flow rates and EA values. In all cases, analytical CO₂ values were higher than experimental values. This was expected since theoretically it is assumed that all fuel used in combustion is fully converted to CO₂ and water vapour only. The least percent difference between experimental and analytical values was realized at 5.05 kg/hr fuel flow and 20% EA. This value was 0.12% implying that the burner was performing quite well at 20% excess air.

4.5.3 Carbon Monoxide

Carbon monoxide emission from WLO combustion was recorded for each SR value and fuel flow rate. Graphs of CO emission concentration versus fuel flow rates at various SR values were then plotted as shown in Figure 4.3.

CO emission increased with fuel flow rate but decreased with increase in excess air with 30% EA combustion having the least amount of CO. CO is an intermediate species formed before CO₂ in a hydrocarbon combustion. It is formed once fuel and intermediate hydrocarbon fragments are consumed as shown in Equations 4.1 and 4.2 below. Equation 4.1 illustrates chain initiation process where oxygen molecule is broken

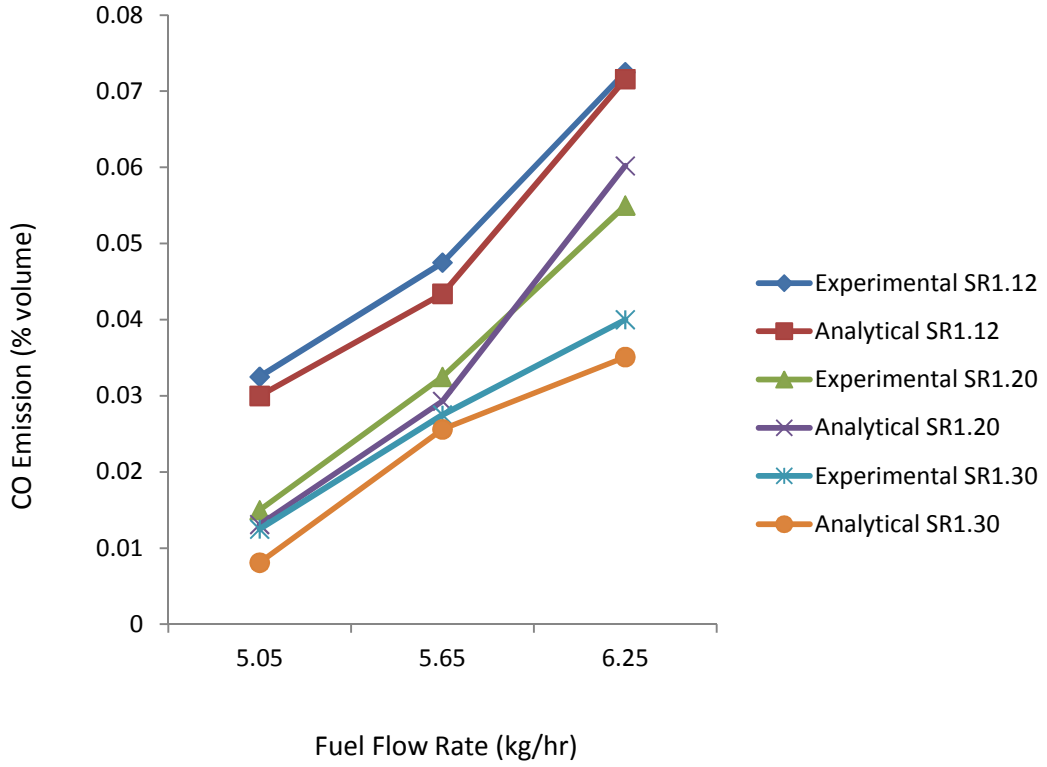
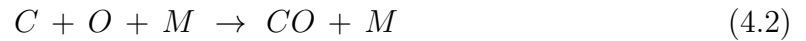


Figure 4.3: CO Emission at Various SR Values and Fuel Flow Rates

into two oxygen atoms with the help of an energetic third body, M.



The second equation demonstrates fuel carbon part combining with oxygen atom from chain initiation process to form CO. For a lean combustion, there will be more oxygen atoms resulting from the first equation and as such CO will react further with oxygen atom to form CO₂ as shown in Equation 4.3 below.



The above reactions require high temperatures (above 1100 K) to complete. Complete conversion of CO to CO₂ therefore depends on oxygen availability and reaction temperatures. In rich mixtures, large amount of CO remains unconverted due to low temperatures and inadequate O₂. Again, in very lean mixtures CO remains unconverted due to low temperatures and long chemical time (total time taken by the reactants to completely react in the combustion chamber).

CO is a toxic gas and therefore large and prolonged exposure to its emission can result in significant toxicity of the central nervous system, heart and eventually death [75]. Its emission reduction is therefore desirable and highly recommended. A reduction of 44.83% CO emission was achieved with WLO burner designed. This verified the fact that excess air is required for a nearly complete combustion to occur. Excess air in combustion ensures that as much fuel carbon as possible is oxidized to CO₂. However, amount of excess air is limited since too much of it lowers combustion temperature by absorbing and carrying some heat away to the exhaust. This is not desired since it affects combustion system's thermal efficiency. Lou et al [76] put it that in a combustion process, CO concentration decreased as flame temperature increased with an excess air of up to 25% used. Excess air can improve fuel oxidation, combustion efficiency as well as lower flue gas temperature. According to experiments done by Lou et al [76] on municipal solid waste combustion, exit flame temperature increased to a maximum of 650 °C with excess air up to 30% after which it started decreasing. Even with much excess air used in combustion, complete combustion is still difficult to achieve and therefore not possible to eliminate CO emission. The two main reasons as to why this is not possible include:

- It is not possible to create enough turbulence to facilitate sufficient fuel and oxidizer mixing.

- The mixing time is usually very short which may not warrant complete and sufficient mixing of fuel and oxidizer.

Also plotted on the graph are CO analytical values determined from chemical reaction equation of WLO fuel and air at all fuel flow rates and SR values. All analytical values were less than their respective equivalent experimental values for all fuel flow rates and SR values. This was because theoretically it was assumed that any fuel carbon part not fully oxidized to CO₂ was partially oxidized to CO. In actual sense, some fuel passed through combustion chamber to the exhaust unburnt to form unburnt hydrocarbon (UHC) thereby reducing amount of CO emission. The least difference between analytical and experimental CO emission values was 1.24% at 6.25 kg/hr fuel flow and 12% excess air. The overall comparison of analytical and experimental data showed very minimal variations in corresponding values as observed from the graph.

The values of CO emissions recorded were very high since combustion was conducted in an open space. This needs to be reviewed to meet minimum allowable CO emission requirements in a combustion process. Conducting combustion in a closed chamber of a boiler with refractory linings would keep most heat in the chamber, enhance more reaction and minimize CO and UHC emissions [77]. Again, there can never be perfect mixing of fuel and combustion air due to insufficiency of both residence time and turbulence. This also contributed to more CO and UHC emissions.

4.5.4 Unburnt Hydrocarbon (UHC)

Complete and efficient combustion is difficult to achieve due to the reasons given in Section 4.5.1. It is therefore expected that part of the fuel will leave combustion cham-

ber unburnt. Unburnt fuel during combustion is referred to as unburnt hydrocarbon. Figure 4.4 shows UHC concentration results for SR1.12, SR1.20 and SR1.30 at various fuel flow rates during combustion.

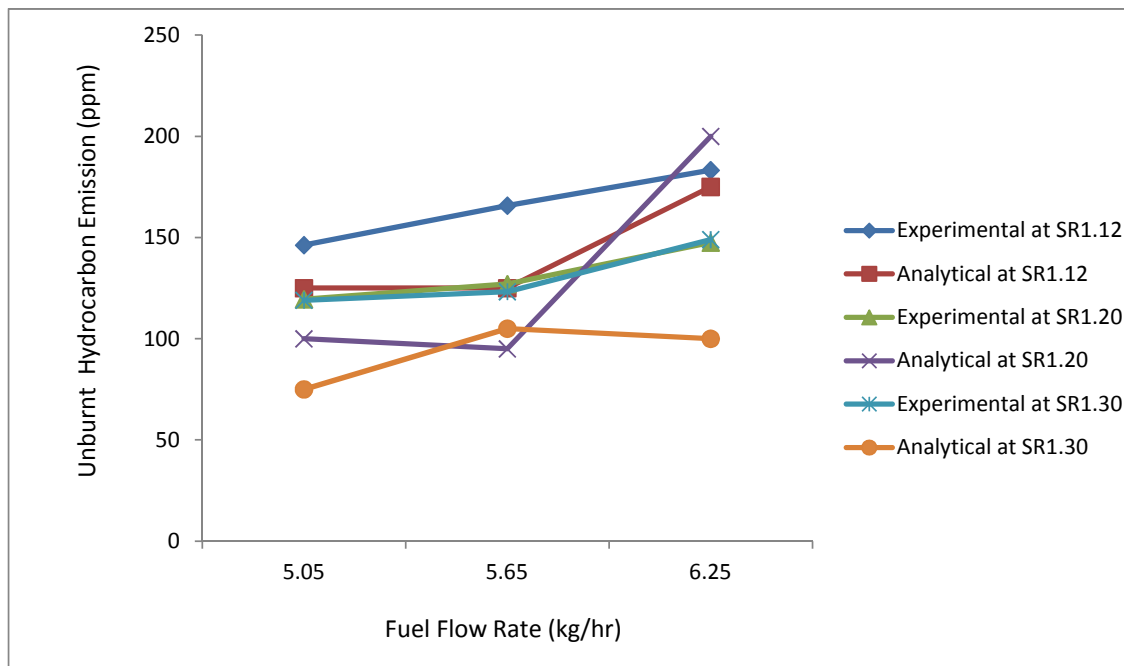


Figure 4.4: UHC Emission Variation with Fuel Flow Rates and SR Values

Maximum UHC was recorded at 6.25 kg/hr fuel flow and 12% EA. This was attributed to the fact that much fuel was pumped to burner atomizing nozzle at minimal excess air which could not sustain conversion of all fuel carbon to CO_2 and H_2O . Therefore, some fuel particles left combustion chamber to the exhaust unburnt. UHC increased with fuel flow rate but decreased with increasing excess air. Increasing excess air at constant fuel flow rate resulted into a leaner combustion with more fuel being converted to CO_2 and H_2O leaving just a small amount of it unburnt.

The graph compares analytical and experimental values of unburnt hydrocarbon (UHC) for all fuel flow rates and SR values as well. Analytical values were lower than experimental values in all cases due to the factors ignored in analytical calculations which

must be considered in actual combustion process. These factors include: combustion temperature, reactants residence time and turbulence referred to as the 3 Ts of combustion. These factors affect combustion and influence greatly both combustion emission and combustion products. A near complete combustion can be achieved by allowing enough residence time for the reactants to fully mix, creating proper turbulence to facilitate rapid mixing and oxidation of fuel and maintaining high combustion temperatures to speed up the reaction. Ignoring these factors in analytical calculations implies that perfect combustion occurs and therefore minimal UHC emission results. This explains why analytical values of UHC are lower than experimental values for each fuel flow rate and SR values. UHC emission has a direct relationship to CO₂ and water vapour (H₂O) generated during combustion. A near complete combustion will yield more combustion products (CO₂ and water vapour) and less UHC and such condition is desired in any combustion process. Comparison graphs for CO and UHC emissions for each SR value are also presented in Figures 4.5, 4.6 and 4.7 below.

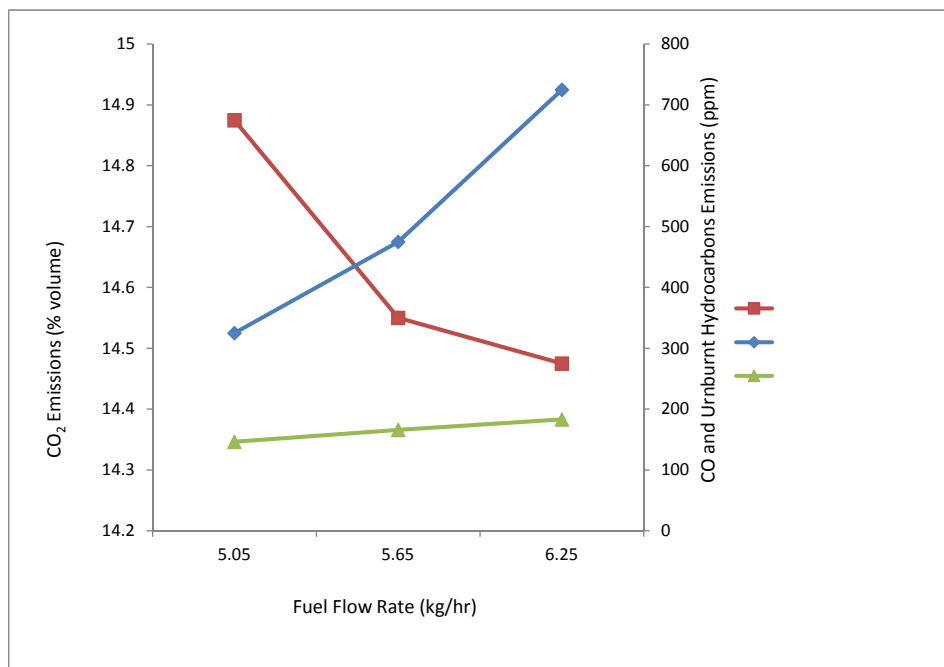


Figure 4.5: Combined Emission Versus Fuel Flow Rate at SR1.12

Emissions (CO₂, CO and UHC) formation were mainly affected by excess air amount in

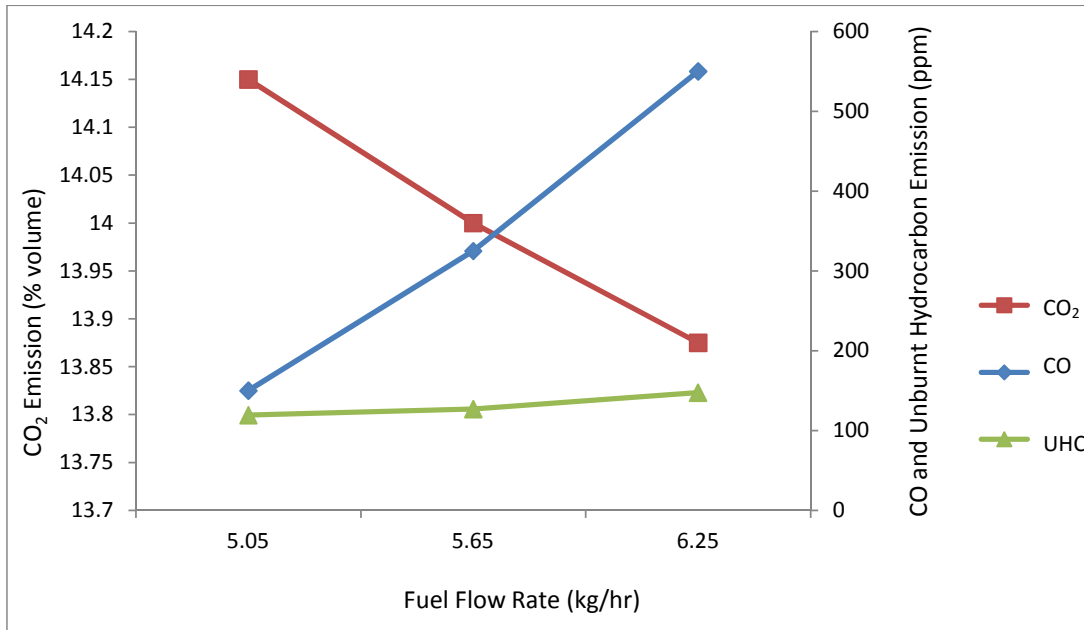


Figure 4.6: Combined Emission Versus Fuel Flow Rate at SR1.20

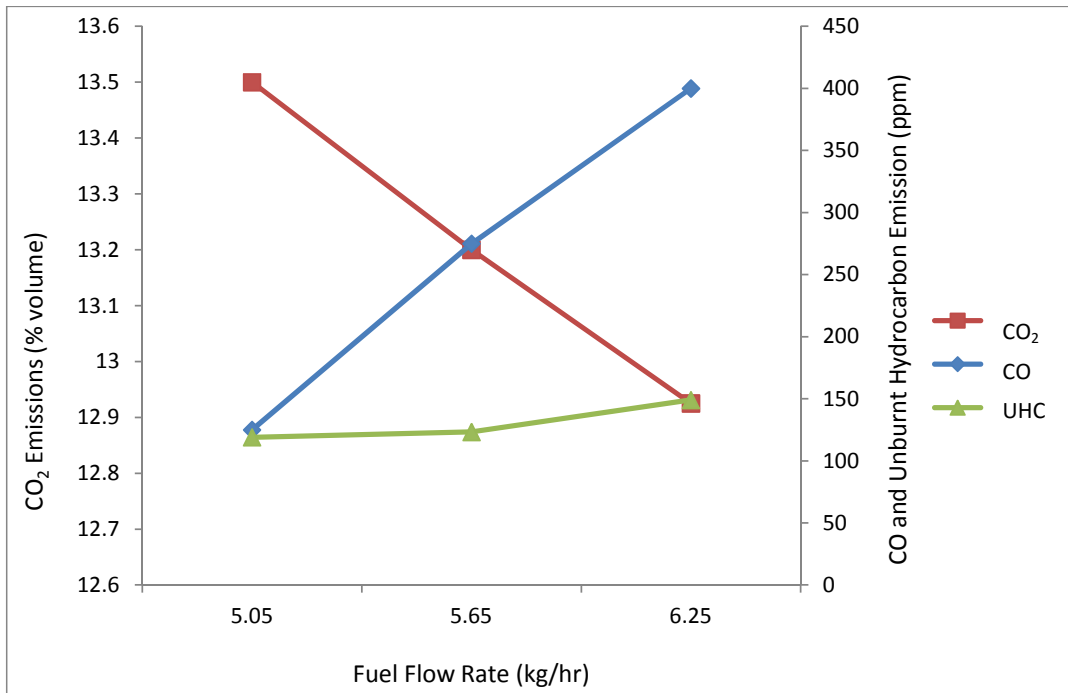


Figure 4.7: Combined Emission Versus Fuel Flow Rate at SR1.30

combustion and combustion process efficiency (level of fuel atomization). An intermediate species, CO, was formed from reaction of fuel carbon with oxygen radical. This

CO reacted further with available oxygen radicals to form CO₂. With more excess air, more radicals were formed and as such more CO₂ generated. Conversion of more CO to CO₂ reduced CO and increased CO₂ amount in exhaust gases. This is the reason why CO₂ and CO graphs have an indirect relation. Both CO and UHC emissions resulted due to incomplete combustion. An increase in CO emission was accompanied by an increase in UHC emission. Again, UHC emission was influenced by flame speed and fuel reaction speed. Higher fuel reaction speed than flame speed meant that more fuel passed through combustion chamber unburnt to form UHC. Higher fuel flow rates at constant excess air value implied a rich fuel combustion and hence more CO and UHC generated. It is therefore concluded that CO₂, CO and UHC emissions generation are dependent on one another.

Flame temperature is a very important parameter to be monitored in any combustion system as it is one of the determinants of the system's thermal efficiency. It was one of the parameters observed under various fuel flow rates during burner testing. Flame temperature variations with fuel flow rates is therefore presented in the following section.

4.6 The Burner Flame Temperature

4.6.1 Actual Flame Temperature

Flame temperature changes were monitored during WLO combustion. Temperatures at different fuel flow rates and SR values were recorded and presented as shown in Figure 4.8. Flame temperature was taken by placing the probe of K-type thermocouple connected to the data logger at the center of the flame 100 mm axial distance from the

burner tip.

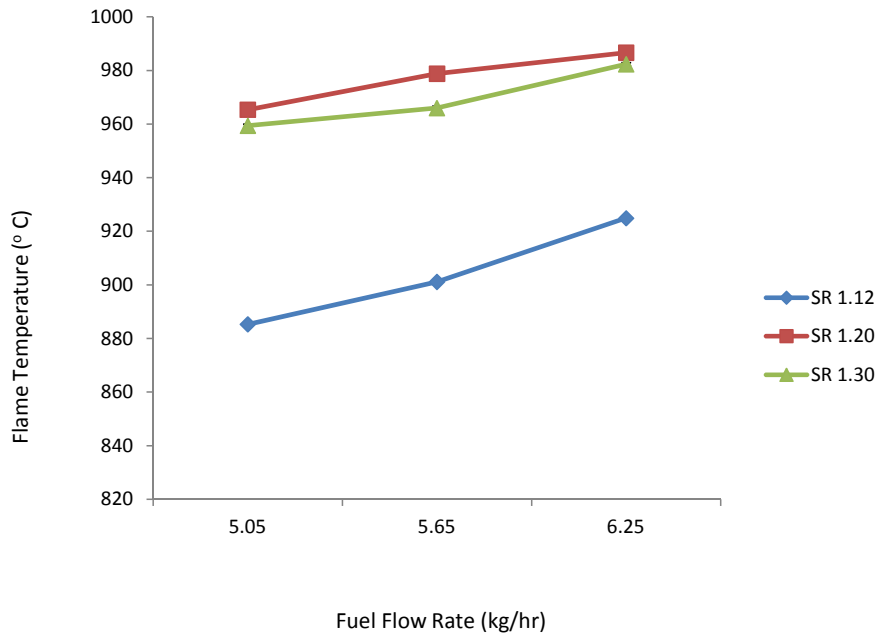


Figure 4.8: Flame Temperature Variation with Fuel Flow Rates and SR

From Figure 4.8, flame temperature increased with fuel flow rate at all SR values. This was due to the fact that at lower fuel flow rates, flow pressures were not sufficient to atomize fuel to very fine sprays for an efficient combustion. As a result, fuel/air mixing was not thorough and therefore combustion was not as efficient as desired. This was also verified by the fact that UHC was highest for the corresponding flow rate and excess air as shown in Figure 4.4. Flame temperatures achieved in combustion depend on fuel type used, amount of excess air as well as the level of atomization and oxidation in the process. Liquid and gaseous fuels are capable of achieving flame temperatures beyond 1200° C. In this research, maximum flame temperature achieved was 986.7° C which was as a result of improved fuel atomization attributed to high pressure fuel flow rates. Better atomization results in better fuel oxidation which in turn leads to a near complete combustion. Flame temperature also increased with excess air supply. An increase in oxygen content of combustion air allows more stable combustion to occur, yields higher combustion and flame temperatures that lead to better heat transfer

and improves combustion thermal efficiency [78]. Based on Figures 4.4 and 4.8, it is concluded that turbulence was more important than both chemical and residence time during combustion.

Flame temperature increased with excess air when fuel flow rate was held constant. This was because more air supply for combustion enhanced more fuel oxidation, high reaction rates and faster conversion rates of reactants to products. Ighodalo et al [79] did tests on flame temperature variations with gaseous fuel flow pressure and achieved maximum temperature of 1275° C at an axial distance of 100 mm from burner tip along the flame axis. This maximum temperature was achieved at 100% fuel flow pressure. An open flame test always yield lower flame temperatures as opposed to tests done in combustion chambers. This is because in an open flame tests there is diluting effect on flame temperature by atmospheric air. Tests in this research were done in open space and this could be one of the reasons why the value for maximum flame temperature above was achieved. It is expected that higher flame temperatures can be achieved when the burner is fired in a combustion chamber.

4.6.2 Adiabatic Flame Temperature (AFT)

Results of adiabatic flame temperature for 1 kg of WLO burnt at various excess air values shown in Table D.13 of Appendix D were used to plot a graph of adiabatic flame temperature versus excess air as shown in Figure 4.9 below.

Adiabatic flame temperature is an ideal temperature of combustion products calculated with many assumptions made. Heating a substance causes simultaneous change in both its volume and pressure. It is quite difficult to determine properties of such a substance when both factors (volume and pressure) are varied. It is therefore desirable

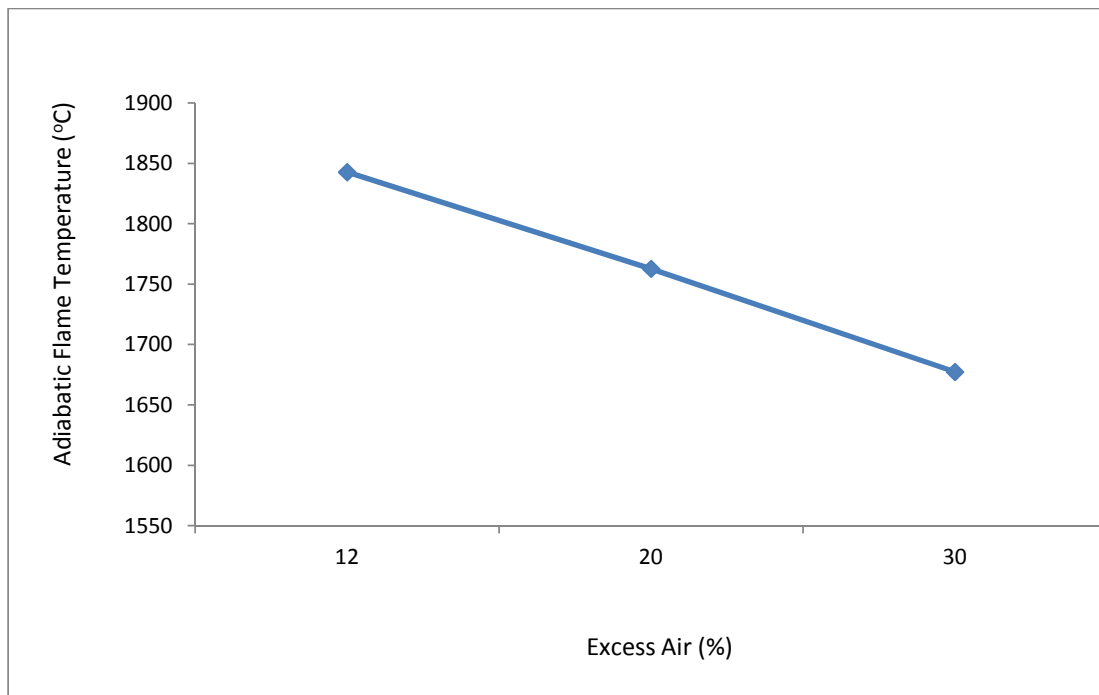


Figure 4.9: WLO Adiabatic Flame Temperature at Various Excess Air Values

to hold one of the factors constant and vary the other. AFT can hence be calculated at constant volume or at constant pressure to yield constant volume AFT and constant pressure AFT respectively. Constant volume AFT is the temperature that results when complete combustion process occurs without any work, heat transfer across the walls of a combustion system or changes in kinetic or potential energy. Constant pressure AFT results from complete combustion process without any heat transfer across the boundaries of a combustion system or changes in kinetic or potential energy. Constant pressure AFT is lower than constant volume AFT because some of the energy is used to change the volume of the system i.e generate work [80].

AFT decreased with increase in excess air due to the fact that excess air increased the amount of N_2 and O_2 in the Products of Combustion (POC) and these two molecules influence very much the value of enthalpy of POC, H_P . There was a big difference between the minimum AFT and maximum actual flame temperature achieved experimentally ($1677.3^\circ C - 986.7^\circ C = 690.6^\circ C$). This difference was brought about by

the assumptions made during AFT calculation that no heat exchange occurred across combustion chamber walls and no changes in both kinetic and potential energy during the process which is not the case in practice. Again, WLO burner combustion tests were conducted in open air which could have contributed to a lot of heat loss to the atmosphere resulting in lower flame temperatures achieved. Atmospheric air also diluted flame temperature in open air combustion lowering further the maximum possible flame temperature reached.

The results for WLO burner safety, firepower, combustion emissions and flame temperature offer information that can be used in sizing and describing WLO burner appropriately. The next chapter presents conclusions deduced from waste lubrication oils combustion and waste oil burners. Recommendations for further work on this research are also presented.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

In this research, WLO burner was designed and fabricated. Physical and chemical properties of WLO were also determined. Thereafter, performance tests of the fabricated burner were conducted and percent change in various parameters were monitored and recorded.

This research aimed at addressing energy problems as well as offering safer disposal solution to waste lubrication oils. From the results, the following conclusions were deduced:

- It is possible to burn WLO for generation of process heat to supplement energy demand in small to medium enterprises. This can reduce costs associated with energy production processes.
- The higher heating value of WLO from compression ignition engine was 43.39 MJ/kg and that from a mixture of spark ignition and compression ignition engines was 42.98 MJ/kg. This confirmed that WLO contain a lot of untapped energy which is disposed off with WLO. Conventional fuels like coal which are mainly used for energy generation have very low heating values compared to WLO. Therefore, WLO should be utilized towards energy generation.
- Combustion emissions and flame temperature are influenced by both fuel flow rate and combustion excess air. Increasing excess air and fuel flow rate improved

combustion. Combustion emissions, CO and UHC, reduced with increasing combustion air supply at fixed fuel flow rates.

- The maximum flame temperature of 986.7° C achieved in open space combustion indicates the capability of WLO burner to supply process heat for steam boilers, hotels, restaurants, small workshops among others.
- Using WLO burner to supply process heat in the above mentioned areas can really save on power and finances compared to when mains electricity is relied on fully. Heating 100 L of bath water using WLO burner can save up to 75% on power as opposed to using 3 kW electric heater.

Waste lubrication oils are very good liquid fuels and with good burner designs and fabrication, they can be a reliable source of supplement energy to our country's energy bank. Taking this path of energy of generation will also enhance achievement of Vision 2030.

5.2 RECOMMENDATIONS

From this research and results discussions, the following recommendations for later study are suggested:

- WLO used was not processed to remove contaminants including metallic particles. Its recycling and purification is quite intensive and should constitute an independent research which was reserved for future work. These contaminants in WLO may have affected the burner performance by influencing oil atomization and burning due to interrupted heat transfer in micro scale. WLO recycling is therefore recommended to investigate its effect on burner performance.
- Waste lubrication oils are usually more viscous than most liquid fuels and this property makes them difficult to atomize to very fine particles. This affects burner performance and contributes to formation of soot and UHC. Preheating WLO before burning is recommended to investigate how it affects combustion.
- Viscous fuels have a tendency of forming soot during combustion due to poor atomization and lack of proper air/fuel mixing. This phenomenon is greatly contributed to by fuel structure, combustion temperature and pressure. A critical study of fuel structure before combustion is recommended to design a desired burner for a specific fuel. Another recommendation is to come up with integrated soot models to predict soot and temperature fields as well as burning rate, radiative emission and soot yield from a growing turbulent fire.
- Finally, the threshold limit value (TLV) of a chemical substance is the level or concentration to which it is believed a worker can be exposed to day after day for a working lifetime without adverse health effects. TLV for CO is generally 50 ppm but according to the Code of Practice for Safety, Health and Welfare

at work, a worker in an 8 hour shift should not be exposed to CO emission of above 20 ppm [81]. The least CO emitted by the burner was approximately 100 ppm. Based on this important Health and Safety issue, a proposal is made that an appropriate chimney be fabricated and installed to enable the hot flue gases dilute CO emission to acceptable levels before it descends to ground level. Fuel preheat mentioned earlier also improves fuel atomization, fuel-oxidizer mixing and combustion reaction leading to more conversion of CO to CO₂. Being a first generation WLO burner for this case, further tests and proper flow regulations are recommended to improve the performance. A future improvement can also include Exhaust Gas Recirculation (EGR), ensuring sufficient reactions residence time and preheating of combustion air.

REFERENCES

- [1] International Energy Agency, “World Energy Outlook 2013 Factsheet,” pp. 1 – 5, 2013.
- [2] M. Z. Jacobson, M. A. Delucchi, “Providing All Global Energy with Wind, Water, and Solar Power, Part I: Technologies, Energy Resources, Quantities and Areas of Infrastructure, and Materials,” *Journal of Energy Policy*, vol. 39, pp. 1154 – 1169, 2011.
- [3] World Energy Council, London, www.worldenergy.org, “2013 World Energy Issues Monitor.”.
- [4] UNEP, “Compendium of Recycling and Destruction Technologies For Waste oils,” 2012.
- [5] K. Arumugam, S. Veeraraja, P. Esakkimuthu, “Combustion of Waste/ Used Oil by Using Specialized Burner,” *International Journal of Applied Engineering Research*, vol. 8, pp. 1839 – 1846, 2013.
- [6] PIRA Energy Group, New York, www.pira.com, “An Assessment of the Diesel Fuel Market,” pp. 1 – 32, 2014.
- [7] A. Benjamin, M. Patrick, “Energy sector liberalization in Kenya: Critical policy issues in petroleum retail market,” *Energy Policy*, vol. 27, pp. 45–56, 1999.
- [8] C. Kajdas, “Major Pathways for Used Oil Disposal and Recycling. Part 1,” *Tri-otest Journal*, vol. 7, Issue 1, pp. 61 – 74, 2000.
- [9] P. Zenon, U. Wieslaw, K. Tadeusz, S. Michal, “Energy conservation through recycling of used oil,” *Ecological Engineering*, vol. 36, pp. 1761 – 1764, 2010.
- [10] Washington State Department of Ecology, “Used Oil Facts,” *Publication 02 - 04 - 006*, Revised, 2005.

- [11] S. Jhanani , J. Kurian, “Used Oil Generation and Management in the Automotive Industries,” *International Journal of Environmental Sciences*, vol. 2, No. 2, 2011.
- [12] A. Edward, E. Pechan, “Emission factor documentation for AP-42 section 1.11 Waste oil combustion,” *Unite States Environmental Protection Agency*, 1993
- [13] <http://www.epa.gov/ttnchie1/ap42/ch01/final/c01s03>, “United States Environmental Protection Agency,” pp. 1 – 7, 1970.
- [14] M. Veronique, L. Eric, “Critical Review of existing studies and life cycle Analysis on the Regeneration and Incineration of Waste Oils,” 2001.
- [15] L. Jelena, O. Aleksandar, S. Michael, J. Jovan, S. Dejan, “Re-refining of Waste mineral insulating oil by extraction with N-methyl-2-pyrrolidone,” *Separation and Purification Technology*, vol. 51, pp. 150 – 156, 2006.
- [16] F. Birol, M. Argiri, “World Energy Prospects to 2020,” *International Energy Agency*, vol. 24, pp. 905 – 918, 1999.
- [17] N. Dianah, M. John, O. Hellen, A. Eric, “Household Energy Demand in Kenya,” *Energy Policy*, vol. 39, pp. 7084 – 7094, 2011.
- [18] International Monetary Fund, “World Economic Outlook,” 2011.
- [19] National Environment Management Authority, “Technical Guidelines on Handling, Management and Disposal of Used oil/ Sludge in Kenya,” pp. 1 – 22, 2014.
- [20] Martin M. Bunyasi, “Vulnerability of Hydro-Electric Energy Resources in Kenya Due to Climate Change Effects: The Case of the Seven Forks Project,” *Journal of Agricultural and Environmental Sciences*, vol. 1, pp. 36 – 49, 2012.

- [21] The Environment Agency for England and Wales, the Scottish Environment Protection Agency and the Environment and Heritage Service in Northern Ireland, "Pollution Prevention Guidelines," 2004.
- [22] J. Conesa, R. Font, A. Fullana, I. Martin-Gullon, I. Aracil, A. Galvez, J. Molto, M. Gomez-Rico, "Comparison between emissions from the pyrolysis and combustion of different wastes," *Journal of Analytical and Applied Pyrolysis*, pp. 1 – 8, 2008.
- [23] M. Bowen, M. Morara, M. Samuel, "Management of Business Challenges Among Small and Micro Enterprises in Nairobi-Kenya," *KCA Journal of Business Management*, vol. 2, issue 1, pp. 17 – 31, 2009.
- [24] Ministry of Energy - Kenya, "National Energy Policy - Third Draft," 2012.
- [25] O. P. Abioye, P. Agamuthu, A. R. Abdul Aziz, "Biodegradation of Used Motor Oil in Soil Using Organic Waste Amendments," *Biotechnology Research International*, vol. 1, pp. 8, 2012.
- [26] G. Javier, F. Pablo, C. Adela, F. Maria, R. Rebeca, B. Elena, L. Gonzalo, "Cancer mortality in towns in the vicinity of incinerators and installations for the recovery or disposal of hazardous waste," *Environment International*, vol. 51, pp. 31 – 44, 2013.
- [27] M. F. Gomez-Rico, I. Martin-Gullon, A. Fullana, J. A. Conesa, R. Font, "Pyrolysis and combustion kinetics and emissions of waste lube oils," *Journal of Analytical and Applied Pyrolysis*, pp. 527 – 546, 2003.
- [28] Energy Conservation Building "Bureau of Energy Efficiency." *Ministry of Power, Government of India*, 2007
- [29] H. A. Durrani , "Energy Management by Recycling of Vehicle Waste Oil in Pakistan," *International Journal of Scientific Engineering and Technology* , vol. No.2, Issue No.9, pp. 928 – 931, 2013.

- [30] I. Macpherson, Richardson, A. Aradi, D. Cleaver, “Additives and Lubricant formulations for improved used oil combustion properties,” pp. 1 – 8, 2008.
- [31] Secretariat of the Basel Convention and the United Nations Environment Programme, “Technical Guidelines on Waste Oils from Petroleum Origins and Sources,” *Waste Oils from Petroleum Origins and Sources (Y8)*, vol. 02, pp. 2, 2002.
- [32] H. Vest, “Reuse and Refining of Waste Engine Oil,” *Technical Information W17e*, pp. 1 – 10, 2000.
- [33] K. Vorapot, K. Worapon, P. Bunyarit, W. Porntip, P. Prasert, “Used lubricating oil management options based on life cycle thinking,” *Resource, Conservation and Recycling*, vol. 53, pp. 294 – 299, 2009.
- [34] F. Giovanna, O. Khlebinkaia, A. Lodolo, S. Miertus, “Compendium of Used Oil Regeneration Technologies,” *International Centre for Science and High Technology*, pp. 14 – 16, 2003.
- [35] A. Orphan, Y. Recep, A. Zeki, “Experimental investigation of the effects of diesel-like fuel obtained from waste lubrication oil on engine performance and exhaust emission,” *Fuel Processing Technology*, vol. 91, pp. 1241 – 1249, 2010.
- [36] B. Pritinika, S. Murugan, “Combustion, Performance and emission parameters of used transformer oil and its diesel blends in a DI diesel engine,” *Fuel*, vol. 104, pp. 147 – 154, 2013.
- [37] L. Shiung, D. Alan, L. Chern, L. Ki, A. Howard, “Production of hydrogen and light hydrocarbons as a potential gaseous fuel from microwave-heated pyrolysis of waste automotive engine oil,” *International Journal of Hydrogen Energy*, vol. 37, pp. 5011 – 5021, 2012.

- [38] A. Naveed, S. A. Syed, A. Zubair, Z. Jabar, J. Abdul, M. Tariq, Syed Sibtain, “Recycling Automotive Lubricating Waste Oil and its Quality Assessment For Environment-Friendly Use,” *Research Journal of Environmental and Earth Sciences*, vol. 4, No. 10, pp. 912 – 916, 2012.
- [39] N. Gabor, S. Laszlo, B. Jenő, H. Jenő, “Possibilities for Processing of used Lubricating Oils - Part 2,” 2010.
- [40] The European Lubricants Industry Magazine, “Used Oil Re-refining,” *Lube Magazine*, vol. 111, pp. 21 – 24, 2012.
- [41] H. Ahmad, E. Al-Zubaidy, E. Muhammad, “Used lubricating Oil Recycling using hydrocarbon Solvents,” *Journal of Environmental Management*, vol. 74, pp. 153 – 159, 2005.
- [42] S. Lee, S. Kum, C. Lee, “An experimental study of a cylindrical multi-hole premixed burner for the development of a condensing gas boiler,” *Energy*, vol. 36, pp. 4150 – 4157, 2011.
- [43] C. E. Baukal, R. Hayes, M. Grant, P. Singh, D. Foote, “Nitrogen Oxides Emissions Reduction Technologies in the Petrochemical and Refining Industries,” *Environmental Progress*, vol. 23, No. 1, pp. 19 – 28, 2004.
- [44] T. V. Mathew, “Fuel Consumption and Emission Studies,” *Transportation Systems Engineering*, pp. 1 – 25, 2014.
- [45] B. Repić, A. Eric, D. Djurović, A. Marinković, G. Živković, “Experimental determination of the swirl burner laboratory models hydraulic resistance,” *Procedia Engineering*, vol. 42, pp. 672 – 682, 2012.
- [46] B. Park, D. Chung, W. Kim, Y. Kim, “A study on the design of recuperative burner,” *International Journal of Energy Research*, vol. 22, pp. 209 – 220, 1998.

- [47] S. Jugjai, C. Pongsai, “Liquid Fuels-Fired Porous Burner,” *Combustion Science and Technology*, vol. 179, No. 9, pp. 1823 – 1840, 2007.
- [48] R. K. Srivastava, W. Neuffer, D. Grano, S. Khan, J. E. Staudt, W. Jozewicz, “Controlling NOx Emission from Industrial Sources,” *Environmental Progress*, vol. 24, No. 2, pp. 181 – 197, 2005.
- [49] E. O. Olson, “Fuel Nozzles for Oil Burners, Technical Aspects of Applications,” pp. 1 – 11, 1999.
- [50] F. J. McGarry, C. J. Gregory, “A Comparison of the size Distribution of Particulates Emitted from Air, Mechanical and Steam Atomized Oil Fired Burners,” *Journal of the Air Pollution Control*, vol. 22:8, pp. 636–639, 2012.
- [51] R. E. Hall, W. M. Cooke, R. L. Barbour, “Comparison of air Pollutant Emissions from Vaporizing and Air atomizing Waste Oil Heaters,” *Journal of the Air Pollutant Control Association*, vol. 33, No. 7, pp. 683–687, 2012.
- [52] T. Laughlin, “Combustion of Number 2 fuel oil, Domestic Pressure Atomizing oil Burners, Pumps and Piping, controls,” pp. 1 – 6, 2009.
- [53] G. Bethold, L. Barozzi, M. Dotti, M. Gilioli, G. Gangale, “Gas Burner Technology and Gas Burner Design for Application,” *Energy Transfortaion Technology*, pp. 1 – 40, 2011.
- [54] M. Lalovic, Z. Radovic, N. Jaukovic, “Flame temperature as a function of the combustion conditions of gaseous fuels,” *Original Scientific Paper*, vol. 40, pp. 89 – 92, 2006.
- [55] S. Alejandro, “Industrial Application of Natural Gas/ www.intechopen.com,” pp. 250 – 256.

- [56] C. A. Srinivasan, C. G. Saravanan, “Emission Reduction in SI Engine Using Ethanol - Gasoline Blends on Thermal Barrier Coated Pistons,” *International Journal of Energy and Environment*, vol. 1, pp. 715 – 726, 2010.
- [57] C. Rey-Chein , C. Wen-Chiang, “Research of High Temperature Air Combustion Fired Heavy Oil,” *Energy and Resources Laboratories, Industrial Technology Research Institute*, pp. 1 – 9.
- [58] Waste Oil Heaters - “<http://www.wasteoilheat.com>”
- [59] M. A. Nwachukwu, J. Alinnor, H. Feng, “Review and assessment of mechanic village potentials for small scale used engine oil recycling business,” *African Journal of Environmental Science and Technology*, vol. 6(12), pp. 464 – 475, 2012
- [60] I. Abrishamchi, Y. khazraii, K. Bashirnezhad, “Effect of Fuel Spray Angle on Pollutants Emission in Turbulent Spray Flames,” *Proceedings of 2010 International Conference on Chemical Engineering and Applications (CCEA 2010)* , pp. 1 – 4, 2010.
- [61] Nu-way Limited, “ST 50 Oil Burner Installation and Maintenance Manual,” vol. 1, No. 1, 2008.
- [62] TSI Incorporated, “Combustion Analysis Basics - An Overview of Measurements, Methods and Calculations Used in Combustion Analysis,” pp. 7 – 14, 2004.
- [63] “Biomass Energy Data Book – <http://cta.ornl.gov/bedb>,” 2011.
- [64] D. J. Dunn - www.freestudy.co.uk, “Heat Transfer and Combustion,” pp. 1 – 20.
- [65] Sara McAllister, Jyh-Yuan Chen, A. Carlos Fernandez-Pello, *Fundamentals of Combustion Processes*. Springer Science+Business Media, LLC, 233 Spring Street, New York, NY 10013, USA), 2011.

- [66] G. A. Carlson, “Experimental Errors and Uncertainty,” pp. 1 – 6, 2002.
- [67] K. Birch, “An Intermediate Guide to Estimating and Reporting Uncertainty of Measurement in Testing ,” pp. 3 – 16, 2003.
- [68] International Atomic Energy Agency, “Measurement Uncertainty - A Practical Guide for Secondary Standards Dosimetry Laboratories,” pp. 12 – 16, 2008.
- [69] S. Bell, “A Beginner’s Guide to Uncertainty of Measurement,” vol. 1, No. 2, pp. 1 – 6, 2001.
- [70] P.R. Bevington, D.H. Robinson, *Data Reduction and Error Analysis for the Physical Sciences*. McGraw Hill, 2003.
- [71] H. M. Ndiritu, “Capture of Industrial Carbon Dioxide Emission by Wet Scrubbing. Ph.D thesis, Jomo Kenyatta University of Agriculture and Technology,” 2012.
- [72] P. O .Oketch, “Optimization of Performance of Bio-Ethanol Gel Cookstove. MSc. thesis, Jomo Kenyatta University of Agriculture and Technology,” 2013.
- [73] J. R. Taylor, *An Introduction to Error Analysis: The Study of Uncertainties in Physics Measurements*. University Science Books, 1997.
- [74] I. Martinez, *Combustion Kinetics*. 2015.
- [75] J. A. Raub, “Health Effects of Exposure to Ambient Carbon monoxide,” *Global Change Science*, vol. 1, pp. 331 – 351, 1998.
- [76] J. Lou, C. Huang, T. Yang, “Effect of Excess Air on Combustion Efficiency and Emissions from Incineration of Municipal Solid Wastes,” *Journal of Chinese Institute of Environmental Engineering*, vol. 9, pp. 219 – 227, 1999.

- [77] Sina Moloodi, “Experimental Investigation of The Effects of Fuel Properties on Combustion Performance and Emissions of Biomass Fast Pyrolysis Liquid-Ethanol Blends in a Swirl Burner,” Master’s thesis, University of Toronto, 2011.
- [78] M. Lalovi, . Radovi, M. Mirjana Lalovi, N. Tadi, “The Effect of Oxygen Enrichment of Combustion Air on The amount and Chemical composition of Combustion Products,” pp. 87 – 95, 2011.
- [79] O. A. Ighodalo, C. I. Ajuwa, B. R. Iredje, “Development and performance of a high velocity burner for furnace operations,” *American Journal of Science and Industrial Research*, vol. 2(1), pp. 49 – 53, 2011.
- [80] S. A. George, N. Constantin, “Algorithms Applied in Flame Temperature Calculation,” *Annals Computer Science Series*, vol. 11, pp. 124 – 128, 2013.
- [81] Health and Safety Authority, “Code of Practice for Safety, Health and Welfare at Work (Chemical Agents) Regulations 2001,” pp. 1– 60, 2011.

APPENDIX A

RESULTS DATA

Data collected and the respective graphs in this research were presented as shown in the below Tables and Figures respectively.

A.1 Waste Lubrication Oil Burner Firepower

Table A.1: Burner Firepower Data

Fuel flow rate (kg/hr)	5.05	5.65	6.25
Firepower (kW)	60.81	69.19	75.09

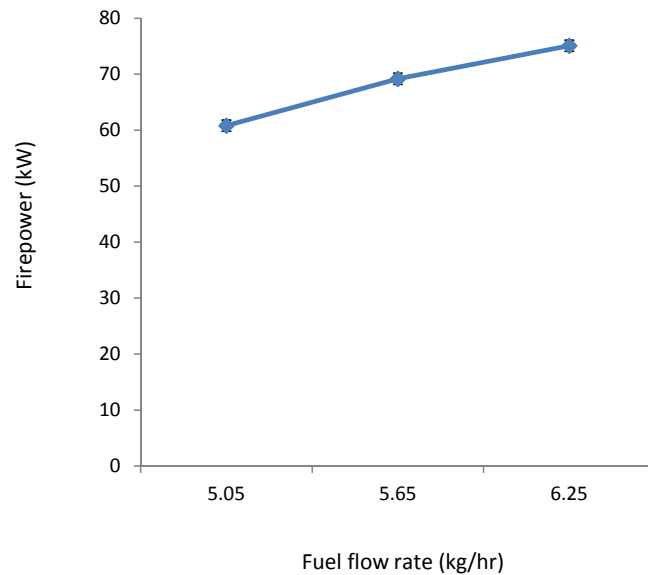


Figure A.1: Firepower Variations with Fuel Pump Flow Rate

A.2 Effect of Fuel Flow Rate on Combustion Emissions

Table A.2: CO₂ Experimental and Analytical Emission Results

Fuel Flow Rate (kg/hr)	Result	SR1.12	SR1.20	SR1.30
5.05	Experimental	14.875	14.150	14.500
5.05	Analytical	14.920	14.175	13.520
5.65	Experimental	14.540	14.000	13.200
5.65	Analytical	14.600	14.042	13.238
6.25	Experimental	14.475	13.875	12.900
6.25	Analytical	14.570	13.950	12.950

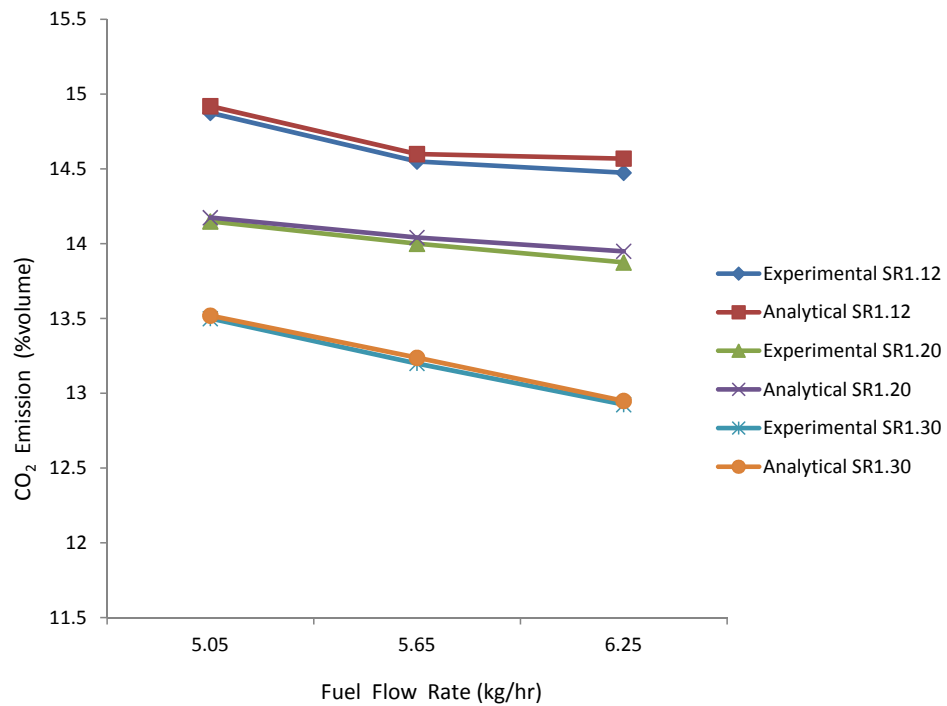


Figure A.2: CO₂ Emission at Various Fuel Flow Rates and SR Values

Table A.3: CO Experimental and Analytical Emission Results

Fuel Flow Rate (kg/hr)	Result	SR1.12	SR1.20	SR1.30
5.05	Experimental	0.0325	0.015	0.0125
5.05	Analytical	0.030	0.0131	0.0081
5.65	Experimental	0.0475	0.0325	0.0275
5.65	Analytical	0.0434	0.0293	0.0256
6.25	Experimental	0.0725	0.055	0.04
6.25	Analytical	0.0716	0.0602	0.0351

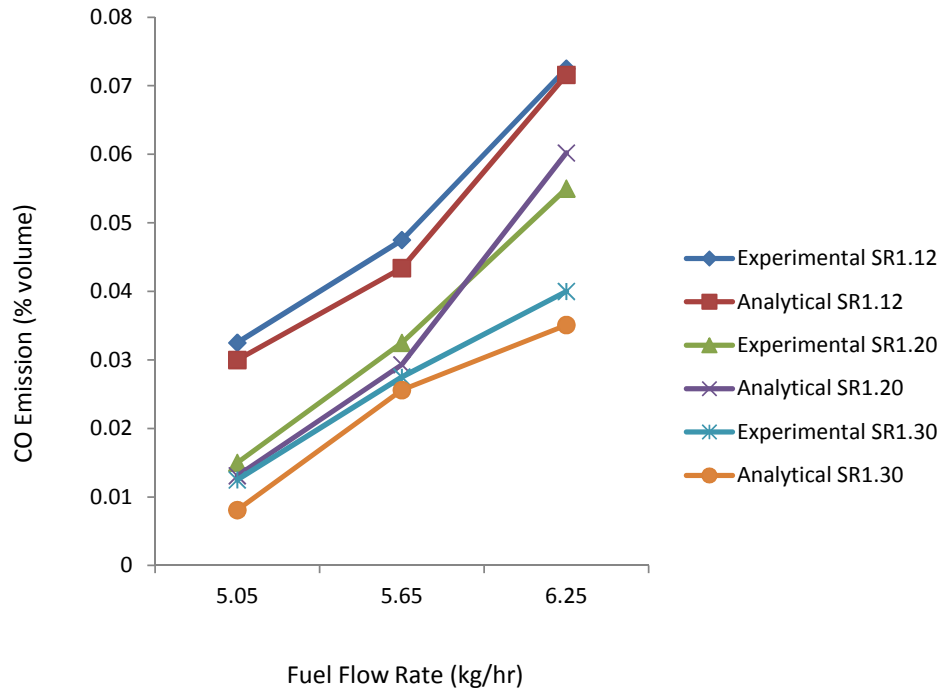


Figure A.3: CO Emission at Various SR Values and Fuel Flow Rates

Table A.4: UHC Experimental and Analytical Emission Results

Fuel Flow Rate (kg/hr)	Result	SR1.12	SR1.20	SR1.30
5.05	Experimental	146.25	119.50	119.00
5.05	Analytical	125.00	100.00	75.00
5.65	Experimental	165.75	127.00	123.25
5.65	Analytical	125.00	95.00	105.00
6.25	Experimental	183.25	147.50	149.00
6.25	Analytical	14.570	13.950	12.950

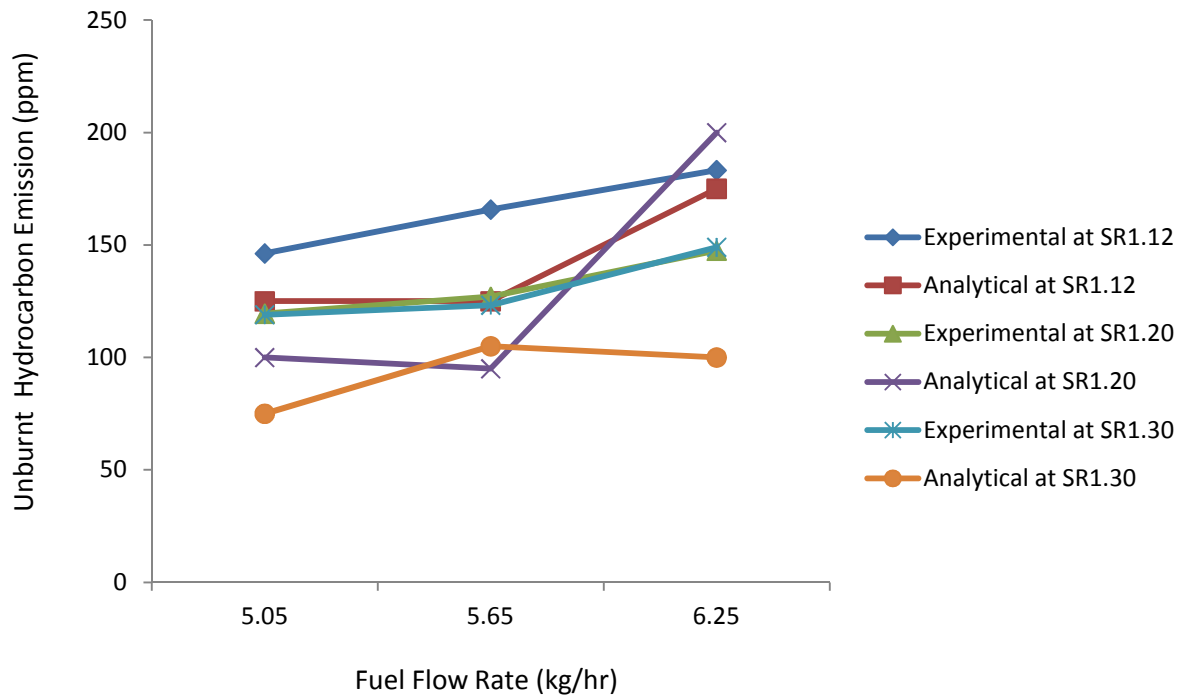


Figure A.4: UHC Emission at Various Fuel Flow Rates and SR Values

A.3 Effect of Fuel Flow Rate on Flame Temperature

Table A.5: Flame Temperature Results

Fuel flow rate (kg/hr)	SR1.12	SR1.20	SR1.30
5.05	885.300	965.375	959.375
5.65	901.150	978.825	965.975
6.25	924.875	986.675	982.325

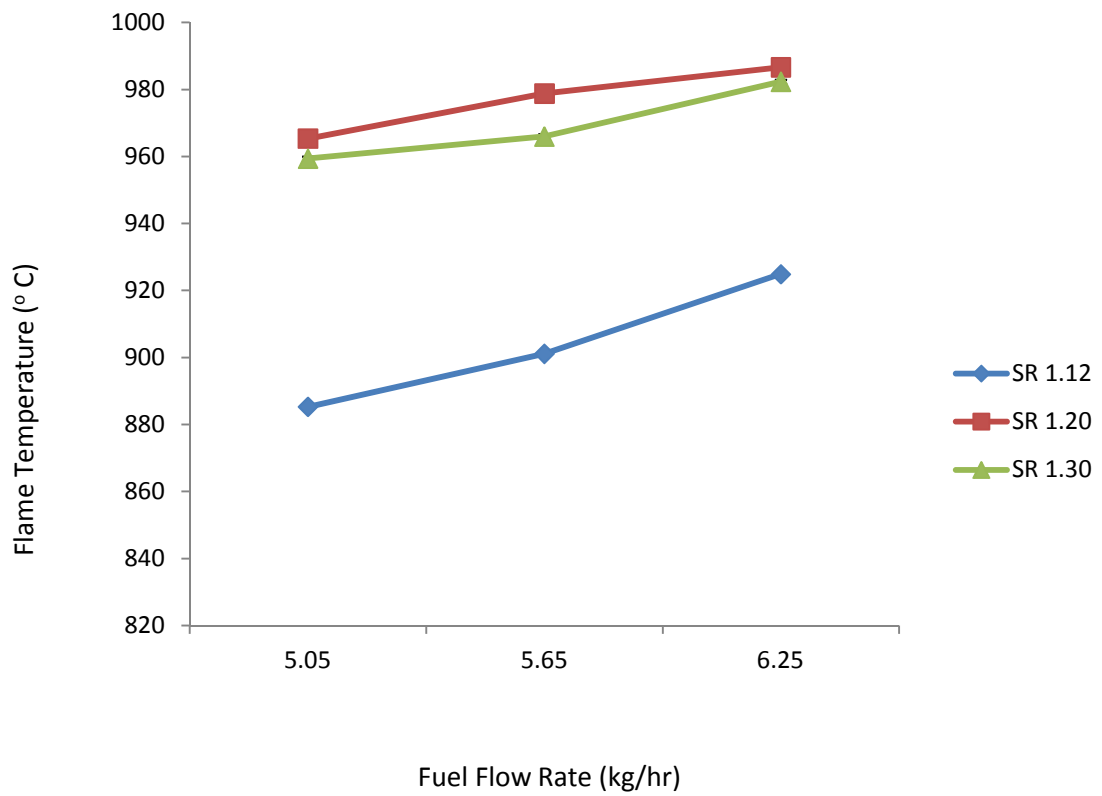


Figure A.5: Flame Temperature at Various Fuel Flow Rates and SR Values

APPENDIX B

PRELIMINARY WORK

B.1 Properties of Waste Lubrication Oils

Preliminary study was carried out at the beginning of this research to find out the requirements for safe environmental waste oil handling and utilization. Information from the National Environment Management Authority (NEMA) stipulated clearly the rules and regulations to be followed when handling, disposing off waste oil and even when using it to generate power through combustion. Tests were carried out on waste lubrication oil to determine its ability and feasibility of using it as fuel for energy generation. These tests included:- energy content (heating values), viscosity, density, moisture content, flash point and undissolved residue and they were done in Jomo Kenyatta University of Agriculture and Technology, Kenyatta University (chemistry department) and Kenya Ministry of Roads (material testing department). Test results from ministry of roads are shown in Table B.1 below.

Table B.1: Test Results for WLO from Compression Ignition Engine

WLO Property	Average Value
Density	875.9 kg/m ³
Relative Density	0.8759
Kinematic Viscosity (25° C)	1371.5 Cst
Moisture Content	0
Insoluble Residue	0.056%
Ash Content	0.765%
Flash Point	202° C

B.2 Combustion Air Blower Calibration

Combustion air was supplied to the burner using a Black & Decker blower with variable flow rates. This blower had flow variation from level 1 to 6. However, these flow levels could not be quantified in m^3/min since only level 6 corresponded to the maximum flow rate of $3.5 \text{ m}^3/\text{min}$. Therefore, calibration was required to determine flow rate at each level of flow. This was done on an air flow bench as discussed in Section 3.3.6 of the Experimental Design and Methodology. Blower calibration results were as presented in Table B.2.

From the table, the blower could be utilized to a near level 2 flow rate. The maximum flow rate that could sustain combustion effectively was $1.45 \text{ m}^3/\text{min}$ which corresponded to blower flow level of 1.5, any flow above this value created noisier and violent turbulent that ended up blowing out flame.

Table B.2: Air Supply Blower Calibration Results

Flow Level	Excess Air (%)	Flow Rate (m^3/min)
1.00	5	1.17
1.10	12	1.23
1.13	15	1.28
1.18	20	1.34
1.23	25	1.39
1.50	30	1.45

APPENDIX C

BURNER DESIGN CALCULATIONS

C.1 Calculations Used in WLO Burner Design

WLO combustion equivalence ratio, ϕ , was calculated using atmospheric air as:

$$\phi = \frac{A_{act}/F_{act}}{A_{theoret}/F_{theoret}} \quad (C.1)$$

Where A_{act} and $A_{theoret}$ are the actual and theoretical combustion air mass respectively while F_{act} and $F_{theoret}$ are actual and theoretical fuel mass respectively.

Both actual and theoretical fuel used are equal but actual and theoretical air different.

Therefore, Equation C.1 reduces to Equation C.2 below:

$$\phi = \frac{A_{act}}{A_{theoret}} \quad (C.2)$$

The actual and theoretical air are equal at SR1.0 and therefore combustion at this stage is said to be stoichiometric.

Ultimate Analysis of WLO

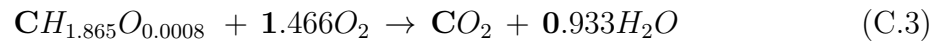
The chemical composition of WLO from Literature is presented in Table C.1 below.

Table C.1: Ultimate Analysis of Waste Lubrication oil

Constituents	% weight (kg)	Atomic wt (kg/kmol)
Carbon	85.25	12
Hydrogen	13.25	2
Oxygen	0.09	32
Nitrogen	0.9	28
Sulphur	0.46	32
H ₂ O	-	18
Ash	0.05	-
CO ₂	-	44
SO ₂	-	64

Lower heating value (LHV) for this WLO was 48.17 MJ/kg. Moles of each fuel constituent were determined and used to develop chemical formula of WLO as C_{7.104}H_{13.25}O_{0.006} which reduced to CH_{1.865}O_{0.0008} on normalization.

A balanced Stoichiometric Reaction (at SR1.0) between WLO and air was given by Equation C.3 below.



Minimum and maximum fuel flow rates were 5.05 kg/hr and 6.25 kg/hr respectively. An intermediary flow rate (5.65 kg/hr) was chosen to be able to work with three flow values during combustion at stoichiometric ratios of SR1.12, SR1.20 and SR1.30. Flow rate for each carbon fuel and oxygen were determined using equations below. Carbon mass flow rate $\dot{m}_{fuel(C)}$ is determined using Equation C.4 below.

$$\dot{m}_{fuel(C)} = w_C \dot{m}_{fuel} \quad (C.4)$$

Where $\dot{m}_{fuel(C)}$ is carbon mass flow rate (g/sec), w_C is the percent weight of carbon element in fuel and \dot{m}_{fuel} is fuel mass flow rate.

Fuel carbon molar flow rate $\dot{n}_{fuel(C)}$ in moles/sec is computed as

$$\dot{n}_{fuel(C)} = \frac{\dot{m}_{fuel(C)}}{mw_C} \quad (C.5)$$

Where mw_C is carbon molar weight. Oxygen molar flow rate is determined using Equation C.8 shown below

$$\dot{n}_{fuel(O_2)} = \dot{n}_{fuel(C)} SC_{O_2} \quad (C.6)$$

Where SC_{O_2} is the amount of oxygen required for stoichiometric combustion. Oxygen volume flow rate at room temperature and pressure (RTP), $\dot{V}_{O_2@RTP}$ is given as

$$\dot{V}_{O_2@RTP} = 24\dot{n}_{fuel(O_2)} \quad (C.7)$$

Constant 24 in the above equation is the capacity of atmospheric air at standard conditions in L/mole. Atmospheric air volume flow rate at RTP, $\dot{V}_{air@RTP}$, is therefore estimated as shown in Equation C.8 below

$$\dot{V}_{air@RTP} = \frac{\dot{V}_{air@RP}}{0.21} \quad (C.8)$$

Similar equations were used to determine carbon and oxygen values for 5.65 kg/hr and 6.25 kg/hr flows and results presented as shown in Table C.2.

Table C.2: Fuel Carbon and Oxygen Flow Rates

Fuel Flow (kg/hr)	Element	\dot{m} (g/sec)	\dot{n} (moles/sec)	\dot{v} (m ³ /min)
5.05	Carbon	1.196	0.1	-
5.05	Oxygen	-	0.147	0.211
5.05	Air	-	-	1.006
5.65	Carbon	1.338	0.111	-
5.65	Oxygen	-	0.164	0.236
5.65	Air	-	-	1.121
6.25	Carbon	1.48	0.123	-
6.25	Oxygen	-	0.181	0.261
6.25	Air	-	-	1.241

C.2 Combustion Air Flow Rates at All Fuel Flow Rates and SR Values

Atmospheric air flow rates determined and recorded in Table C.2 above were used to evaluate air flow rates at various excess air values and fuel flow rates. The results were as shown in Table C.3.

Table C.3: Combustion Air Flow Rates

Fuel Flow (kg/hr)	SR1.12 (m ³ /min)	SR1.20 (m ³ /min)	SR1.30 (m ³ /min)
5.05	1.13	1.21	1.31
5.65	1.26	1.35	1.46
6.25	1.39	1.49	1.61

C.3 WLO Burner Power Consumption and Power Output

Air blower rating = 600 W

Electric motor rating = 150 W, 1400 rpm

Total power consumed by the burner = 750 W

Burner capacity which is also referred to burner output power is estimated using the

formula shown in Equation C.9 below

$$HRR = \frac{\dot{m}LHV}{3.6} \quad (C.9)$$

Where HRR is burner heat release rate in kW, \dot{m} is oil mass flow rate in kg/hr and LHV is oil lower heating value in MJ/kg.

WLO calorific value = 43.39 MJ/kg; minimum fuel flow rate = 5.05 kg/hr; maximum fuel flow rate = 6.25 kg/hr; water to heat = 100 L; water temperature at standard conditions = 25 °C; temperature difference = 35 °C; burner low power was calculated as 60.87 kW.

Another expression used to estimate burner capacity is:

$$B_{cap} = \frac{V_w \Delta T}{790 H_t} \quad (C.10)$$

Where B_{cap} is burner capacity (kW), V_w is volume of water to heat (L), H_t is heat up time (hrs) and ΔT is temperature rise (°C).

Data from Kenya Power and Lighting Company (KPLC) revealed that 29.5 units of power cost Ksh. 73.53 exclusive of fixed charges and other charges like the total tax, fuel index charge, and Forex charge among others. Therefore 1 unit of power \simeq Ksh. 2.50.

Amount spent in running the burner for 15 minutes was Ksh 0.50. A 3kW electric heater heating same amount of water for the same duration of time consumed 0.75 kWh units which required Ksh. 2.00 to purchase holding other charges constant. Total

power saving when using WLO burner was Ksh. 1.50 which was equivalent to 75%.

$$\text{Amount spent on units} = 0.1875 \text{ units} \times 2.50 \text{ Ksh/unit} = \text{Ksh.}0.47 \simeq \text{Ksh.}0.50 \quad (\text{C.11})$$

Heating Water using a 3kW Electric Heater and WLO Burner

$$\text{Power units}(kWh) = 3 \text{ kW} \times 0.25 \text{ hrs} = 0.75 \text{ kWh} \quad (\text{C.12})$$

The total amount of money used in units, holding the other charges constant as was done with WLO burner, is:

$$\text{Amount spent on units} = 0.75 \text{ units} \times 2.50 \text{ Ksh/unit} = \text{Ksh.}1.88 \simeq \text{Ksh.}2.00 \quad (\text{C.13})$$

$$\text{Amount saved} = 2.00 - 0.50 = \text{Ksh.} 1.50$$

Savings on power purchase can now be calculated as shown in the figure below:

$$\% \text{ saving on power} = \frac{2.00 - 0.50}{2.00} = 75\% \quad (\text{C.14})$$

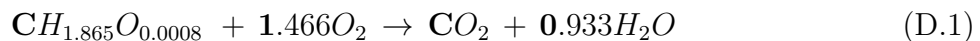
APPENDIX D

WLO BURNER THEORETICAL EMISSIONS AND ADIABATIC FLAME TEMPERATURE DETERMINATION

Solid and liquid fuels are normally analyzed by mass to determine contents of their individual constituent composition. During combustion, volumetric composition of atmospheric air used is, oxygen - 21% and nitrogen - 79%.

D.1 Combustion of WLO by Volume

Combustion by volume is guided by two laws: Dalton's Law of partial pressures and Avogadro's Law. Dalton's Law states that 'the total pressure of a mixture of gases equals to the sum of partial pressures of individual gas constituent'. Partial pressure of a gas refers to the pressure that gas would exert if it occupied the same volume and temperature alone. Avogadro's Law states that 1 m³ of any gas at the same pressure (P) and temperature (T) contains the same number of molecules. Therefore, the volume of a gas at the same pressure and temperature is directly proportional to the number of its molecules. From this it is concluded that the volume of a kmol of any gas is the same if P and T are the same [64]. Combustion reaction of WLO is as shown in Equation D.1



The volume ratio of reactants and products from the equation is

$$1 : 1.466 \rightarrow 1 : 0.933$$

Stoichiometric air required to fully oxidize WLO in the above reaction Equation is

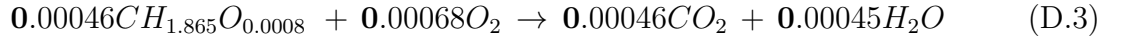
calculated as 6.981 m³.

D.2 Theoretical CO₂ Emission Determination at 12% Excess Air

Oil density = 875.9 kg/m³, combustion takes five minutes. At fuel flow rate of 5.05 kg/hr, oil burnt in five minutes is calculated as

$$SC_{air} = t.\dot{m}_f \quad (D.2)$$

Where SC_{air} is stoichiometric combustion air (kg), t is combustion duration (hrs) and \dot{m}_f is fuel mass flow rate (kg/hr). Volume of oil burnt = 0.00046 m³. From this value, stoichiometric reaction is balanced as in Equation D.3 below.



The volume ratio of reactants and products from the equation is

$$0.00046 : 0.00068 \rightarrow 0.00046 : 0.00045$$

From this, SC_{air} is 0.003 m³ and 12% EA increases it to 0.00333 m³.

Analysis of Dry Products

Volumetric composition of each product of combustion were determined and tabulated as in Table D.1.

Theoretical CO₂ emission by percent volume was determined as 14.92%. Similar reactions and equations were done for 20% and 30% EA for 5.05 kg/hr, 5.65 kg/hr and 6.25 kg/hr flows and the results tabulated as shown in table D.2

Table D.1: WLO Dry Combustion Products Volumetric Analysis

Product	Calculation	Value
N ₂	79% × 0.00325	0.00254 m ³
CO ₂	-	0.00046 m ³
O ₂	12% × 0.00068	0.000082 m ³
Total	-	0.00308 m ³

Table D.2: Analytical CO₂ Emission (% Volume) for 12, 20 and 30% EA

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	14.92	14.175	13.52
5.65	14.60	14.042	13.238
6.25	14.57	13.95	12.95

D.3 Analytical CO Emission Determination at 12% Excess Air

Analytical CO emission from WLO combustion was estimated for each excess air using Equation D.4 below. The values determined were recorded in a table as will be seen hereafter.

$$CO_{th} = CO_{2(th)} - CO_{2(exp)} - UHC_{2(exp)} \quad (D.4)$$

Where CO_{th} is theoretical CO emission, $CO_{2(th)}$ refers to theoretical CO₂ emission, $CO_{2(exp)}$ is the experimental CO₂ emission and UHC_{exp} is the experimental UHC emission. Theoretical UHC was estimated using Equation D.5 below and the results recorded in table form.

$$UHC_{th} = CO_{2(th)} - CO_{2(exp)} - CO_{exp} \quad (D.5)$$

Experimental results for CO₂, CO and UHC emissions recorded were presented as shown in Tables D.3, D.4 and D.5 respectively.

The corresponding theoretical emissions for CO₂, CO and UHC are presented in Tables

Table D.3: Experimental CO₂ (% volume) Emission Data

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	14.875	14.150	13.500
5.65	14.540	14.000	13.200
6.25	14.475	13.875	12.900

Table D.4: Experimental CO (% volume) Emission Data

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	0.0325	0.0150	0.1250
5.65	0.0475	0.0325	0.0275
6.25	0.0725	0.0550	0.0400

D.6, D.7 and D.8 respectively.

D.4 Adiabatic Flame Temperature for WLO Fuel

Adiabatic flame temperature was estimated using specific heat capacity values at constant pressure. An energy conservation balance between the reactants and products shown in Equation D.6 was used to develop equation to estimate this temperature.

$$LHV + H_R = H_P \quad (\text{D.6})$$

Where LHV is fuel lower heating value in kJ/kg, H_R and H_P are enthalpy of the reactants and products respectively in kJ/kg. The sensible heat in fuel and air, H_R , is given as in Equation D.7 below.

$$H_R = (t_i - 25) \sum (mC_p)_R \quad (\text{D.7})$$

Where t_i is the initial fuel and air temperatures in ($^{\circ}\text{C}$), 25 is the reference temperature at standard conditions in ($^{\circ}\text{C}$), m is the mass of each reactant (kg) and C_p is the specific

Table D.5: Experimental UHC (ppm) Emission Data

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	146.25	119.50	119.00
5.65	165.75	127.00	123.25
6.25	183.25	147.50	149.00

Table D.6: Theoretical CO₂ (% volume) Emission Data

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	14.920	14.175	13.520
5.65	14.600	14.042	13.238
6.25	14.570	13.950	12.950

Table D.7: Theoretical CO (% volume) Emission Data

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	0.0300	0.0131	0.0081
5.65	0.0434	0.0293	0.0256
6.25	0.0716	0.0602	0.0351

Table D.8: Theoretical Unburnt HC (ppm) Emission Data

Flow Rate (kg/hr)	12% EA	20% EA	30% EA
5.05	125.00	100.00	75.00
5.65	125.00	95.00	105.00
6.25	175.00	200.00	100.00

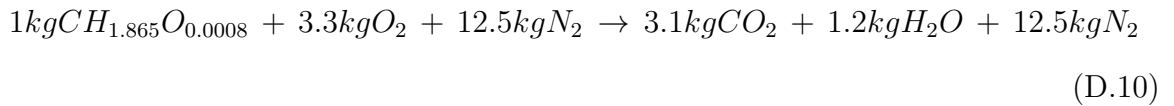
heat capacity of each reactant at constant pressure (kJ/kgK). Enthalpy of combustion products, H_P , is given in Equation D.8.

$$H_P = (t_f - 25) \sum (mC_p)_P \quad (D.8)$$

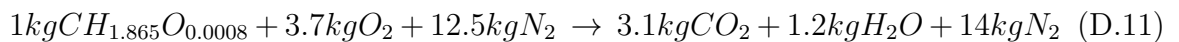
Where t_f is adiabatic flame temperature. Equation D.6 is therefore expanded to Equation D.9.

$$LHV + (t_i - 25) \sum (mC_R)_P = (t_f - 25) \sum (mC_p)_P \quad (D.9)$$

Iteration method was used to estimate adiabatic flame temperature using Equation 3.15. In this method, an arbitrary flame temperature, t_f , was chosen and used to determine C_p for combustion products to be used in the equation to estimate the new t_f . This new value was then used to estimate the next set of C_p values for t_f estimation again. The whole process was repeated until a constant value of t_f or a variation of within 5 °C was achieved. For this to be possible, a reaction equation of 1 kg of fuel was balanced to determine amount, in kg, of each reactant and product required for completion of combustion. Stoichiometric reaction for 1 kg fuel combustion was balanced as shown in Equation D.10



Using 12% excess air in Equation D.10 above changes it to Equation D.11 shown below.



This equation was modified for the other excess air values and C_p values and adiabatic flame temperature estimated. Results of C_p values and adiabatic flame temperature at

various excess air combustion were recorded as shown in Tables D.9, D.10, D.11, D.12 and D.13.

Table D.9: Reactants and Products Masses for WLO Combustion

Reactants	Mass (kg)	Products	Mass (kg)
WLO Fuel	1	CO ₂	3.1
O ₂	3.3	H ₂ O	1.2
N ₂	12.5	N ₂	12.5

This values were determined from a balanced stoichiometric reaction of WLO and air. Various values of excess air on changed O₂ and N₂ mass used. 12%, 20% and 30% excess air used changed O₂ and N₂ values to 3.7 kg and 14.0 kg, 4.0 kg and 15.1 kg and 4.3 kg and 16.1 kg respectively.

Table D.10: Combustion Products C_p Values for 12% EA

Product	1st(kJ/kgK)	2nd(kJ/kgK)	3rd(kJ/kgK)	4th(kJ/kgK)
CO ₂	1.25	1.285	1.28	1.28
H ₂ O	2.33	2.44	2.43	2.43
N ₂	1.18	1.208	1.204	1.204

Table D.11: Combustion Products C_p Values for 20% EA

Product	1st(kJ/kgK)	2nd(kJ/kgK)	3rd(kJ/kgK)	4th(kJ/kgK)
CO ₂	1.25	1.28	1.272	1.274
H ₂ O	2.33	2.43	2.40	2.41
N ₂	1.18	1.21	1.197	1.20

Table D.12: Combustion Products C_p Values for 30% EA

Product	1st(kJ/kgK)	2nd(kJ/kgK)	3rd(kJ/kgK)	4th(kJ/kgK)
CO ₂	1.25	1.266	1.263	1.263
H ₂ O	2.33	2.378	2.372	2.372
N ₂	1.18	1.192	1.191	1.191

Table D.13: Adiabatic Flame Temperature for WLO Fuel

Product	12% EA	20% EA	30% EA
1kg fuel	1842.8° C	1762.7° C	1677.3° C