UNIVERSITY OF NAIROBI

Department of Mechanical & Manufacturing Engineering

A STUDY OF WASTE PLASTIC OIL AS AN ALTERNATIVE FUEL TO DIESEL IN COMPRESSION IGNITION ENGINES

By

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DECLARATION

I hereby declare that this thesis is my original work and has not been presented for a degree in any other university.

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

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DEDICATION

This work is dedicated to my family for their unwavering support, love and encouragement in the course of my study.

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LIST OF ABBREVIATIONS AND ACRONYMS

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
CI	Compression ignition
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DF1	Grade No.1 Diesel Fuel
DF2	Grade No.2 Diesel Fuel
DI	Diesel Index
EN	European Standard
GC	Gas Chromatography
GCV	Gross Calorific Value
HC	Hydro Carbons
HDPE	High Density Polyethylene
IC	Internal Combustion
ISO	International Organization for Standardization
KEBS	Kenya Bureau of Standards
KIRDI	Kenya Industrial Research and Development Institute
KNBS	Kenya National Bureau of Statistics
kW	kiloWatt
kWh	kiloWatt-hour
LDPE	Low Density Polyethylene
LPG	Liquefied Petroleum Gas
NIR	Near Infrared
NO	Nitrogen Monoxide
NO_2	Nitrogen Dioxide

NO_x	Nitrogen Oxides
O_2	Oxygen
PE	Polyethylene
PMCC	Pensky-Martens Closed Cup
PP	Propylene
ppm	Parts per Million
PS	Polystyrene
rpm	revolutions per minute
Sox	Sulphur Oxides
TDC	Top Dead Centre
TGA	Thermogravimetric Analysis
WPO	Waste Plastic Oil

ABSTRACT

Liquid hydrocarbons or fossil fuels are widely adopted as sources of energy for prime movers, including internal combustion engines, because they are easy to handle and have a high energy density. Diesel engines are efficient prime movers, and usually find application in a wide array of areas, including industrial, agricultural and transport sectors. Consequently, conventional hydrocarbon fuels such as petroleum and diesel have remained unchallenged as the preferred sources of energy for engine prime movers. However, the demand for diesel and other petroleum-based fuels across the globe, especially in developing nations such as Kenya, has been rising steadily leading to concerns for long-term energy security. Kenya continues to import vast amounts of petroleum from the Gulf region leading to high energy costs. In addition, the increased use of hydrocarbon fuels use leads to air pollution, both at local and regional levels, ultimately leading to climate change. Due to a combination of these factors, various research initiatives aimed at developing suitable alternative sources of energy continue to be undertaken. This work is one of such initiatives.

This study investigated the suitability of the use of waste plastic oil as an alternative fuel for compression ignition engines. The fuel properties and characteristics of waste plastic oil and its blends with diesel were determined and compared to those of diesel. Comparative engine performance and emission tests were carried out on a 4-stroke, 1-cyliner Kirloskar diesel engine rated 3.5 kW at 3500 rpm. This study investigated the effect of blending waste plastic oil with diesel on fuel properties, engine performance, engine emissions and economic costs.

The fuel properties and characteristics of waste plastic oil were found to be similar to those of diesel while blending diesel with waste plastic oil was found to improve its fuel properties and characteristics to within the minimum and maximum accepted standards, except for density and flash point. The brake thermal efficiency of waste plastic oil was found to be 14% higher than that of diesel. The study revealed the energy consumption cost per power output for waste plastic oil to be 40% lower than that of diesel.

CHAPTER ONE

INTRODUCTION

1.1 Background

Diesel engines are the most popular prime movers, and regularly find application in a wide array of areas, including manufacturing, agricultural and transport sectors, among others. As a result, diesel and other petroleum-based fuels demand across the globe, particularly in developing nations such as Kenya, has been rising steadily leading to concerns for long-term energy security (KNBS, 2015). Kenya, like other non-petroleum producing countries, continues to import vast amounts of petroleum from the Gulf region leading to high energy costs, which in turn lead to high production costs and ultimately high cost of living.

Liquid hydrocarbons are well adapted as sources of energy for internal combustion engines, because they are easy to handle and have a high energy density. As a result, conventional hydrocarbon fuels such as petroleum have remained unchallenged since the advent of the automotive industry. However, the source of these fuels is finite and their reserves are not uniformly distributed. In addition, the increased use of hydrocarbon fuels use leads to emission greenhouse gases, both at local and regional levels, eventually contributing towards climate change (Faiz et al., 1996).

Therefore, Kenya’s quest for alternative fuels to conventional diesel and petrol is a natural choice.

1.2 Alternative Fuels

An alternative fuel should be available readily at low cost, be friendly to the environment, and fulfil energy security needs without compromising an engine’s operational performance (Ampaitepin & Tetsuo, 2010).

Some of the alternative fuels that can be used in an internal combustion engine include alcohol, biodiesel, used engine oil, used vegetable oil, and liquid fuel from waste plastics and tyres. In addition, the utilization of biomass as a substitute fuel for diesel engines holds abundant potential in developing countries although their use is currently low (Guibet, 1997).

1.2.1 Waste Plastic Oil

There have been concerted efforts to develop alternative fuels in order to counter the rising demand for oil. For instance, the use of biodiesel fuels derived from the seeds of plants, such as Jatropha and Canola is yet to become mainstream and thus unable to alleviate the demand for petroleum products in the country. Therefore, there is a need to investigate other sources of alternative fuels that are not only cheap but are also readily available and have minimum impact on the environment. The use of waste-to-fuel conversion technology presents an opportunity to develop substitute fuels. One such type of fuel is Waste Plastic Oil (WPO) obtained from the pyrolysis of plastic waste.

Plastics have become an important part of our life because of their light weight, durability, design flexibility energy and fast rate of production. Plastics are used in industrial, retail and domestic sectors across the globe, and are now increasingly being used in the construction sector in Kenya. However, the use of plastics has led to a very serious environmental challenge due to their huge quantities and problems of disposal. Plastics are non-biodegradable. Instead of biodegrading, plastics undergo a process known as photo-degradation, which changes plastics into plastic dust that enter the food chain and result in complex health problems (Mani et. al, 2011).

Therefore, it is essential to investigate a sustainable approach of disposing plastic waste. Yoshida & Yoshikawa (2015) affirm that a liquid fuel can be derived through thermal treatment of plastic waste. One such thermal treatment process that can be used to derive waste plastic oil from plastics is pyrolysis. Pyrolysis of waste plastics is a sustainable disposal process because it reduces the volumes of plastic that is disposed into the environment, thereby significantly reducing environmental health risks (Mani et. al, 2011).

Successful development of Waste Plastic Oil (WPO) as a substitute fuel will reduce imported petroleum and petroleum-based products demand because Waste Plastic Oil (WPO) will become more useful in various applications, especially as a fuel in the power generation and transport sectors. Waste Plastic Oil (WPO) presents an exciting prospect as a substitute fuel in big, slow-moving diesel engines. Furthermore, converting waste plastics into Waste Plastic Oil (WPO) is a perfect example of turning waste into cheaper and readily available energy while diminishing adverse impact on the environment.

1.3 Properties of Fuels for Internal Combustion (IC) Engines

Fuel properties play an important role in determining the performance of internal combustion engines. As such, it is important to study the properties of a fuel in order to understand how a fuel will behave when used in an internal combustion engine. Some of the important fuel properties that influence the performance of an engine include density, viscosity, heating value and the cetane number. Tests for determining such properties are carried out under standardized procedures usually developed by local and international standards organizations. It is important to investigate the density, viscosity, heating value, cetane number and other properties of waste plastic oil and their influence on the performance of an internal combustion engine.

1.4 Performance of Internal Combustion (IC) Engines

According to the Institution of Mechanical Engineers (1997), internal combustion engines are produced in tens of millions per year as the preferred power unit in transport and other sectors. This is because the IC engine continues to satisfy both requirements and challenges of increased demand, especially in the automotive industry, through continual advancement in technology and innovation from the latest research. It is therefore important to produce efficient and economical engines that not only operate optimally when using conventional fuels, but also when using alternative fuels. There are many parameters that are used to evaluate the performance of an internal combustion engine. Some of the more important parameters include the brake power, brake specific fuel consumption and brake thermal efficiency. It will be important to know the performance of an internal combustion engine when running on waste plastic oil (WPO).

1.5 Environmental Impact of Fuels

Fuels used in internal combustion engines are often associated with air pollution due to the presence of hydrocarbons, nitrogen and sulphur. Incomplete combustion of carbon in the engine is associated with the release of carbon monoxide, which is a poisonous gas. In addition, incomplete combustion of carbon is also associated with smoke, which combines with sulphur dioxide to form smog. On the other hand, high temperatures lead to decomposition of nitrogen and sulphur compounds in a fuel leading to the formation of oxides of Nitrogen (NO_x) and oxides of Sulphur (SO_x), which are often associated with global warming (Demirbas, 2009). Although the levels of Carbon Monoxide, Sulphur and

Nitrogen dioxides emitted by an engine when operating on diesel are known, it is not known to what extent these pollutants are produced when using WPO.

1.6 Economic Impact of Fuels

Fossil fuels as used in internal combustion engines are often associated with high engine operating costs due to the volatility of prices in the global market. It is important to know the economic impact of an engine running on waste plastic oil.

1.7 Objectives

1.7.1 Broad Objective

The main objective of this study was to investigate the suitability of Waste Plastic Oil (WPO) as an alternative fuel to diesel fuel in Compression Ignition (CI) engines. The study aimed at obtaining baseline information regarding the application of WPO in CI engines.

1.7.2 Specific Objectives

1. To analyse the properties and characteristics of Waste Plastic Oil (WPO) i.e. density, viscosity, heating value and ignition quality.
2. To run engine performance trials with 100% diesel and its blends with Waste Plastic Oil (WPO)
3. To perform engine combustion exhaust gases analysis for 100% diesel and its blends with Waste Plastic Oil (WPO)
4. To determine and compare the energy costs/savings of operating a diesel engine fuelled with waste plastic oil/diesel blended fuels

CHAPTER TWO

LITERATURE REVIEW

This chapter will review the properties of diesel fuel as a conventional fuel for IC engines, as well as biodiesel and waste plastic oil (WPO) as alternative fuels for internal combustion engines.

2.1 Fuels for Internal Combustion Engines

An overwhelming majority (99%) of internal combustion engines employ liquid fuels that are fossil-based (Taylor, 1985). Products arising from petroleum refinement are often classified according to their use and their volatility and specific gravity, as determined by distillation at sea level atmospheric pressure. The main products obtained through this process include natural gas, kerosene, gasoline, fuel oils, diesel oils and lubricating oils (Guibert, 1997). This study will compare diesel fuels obtained from crude oil against waste plastic oil.

2.1.1 Diesel Fuels

Diesel fuels refer to the liquid petroleum fuels that are usually employed in compression, or diesel, engines. The American Society of Testing Materials (ASTM) standard D 75 characterizes diesel fuel in the United States, and currently identifies five grades of diesel fuels.

Grade No.1-D (DF1) and Low Sulphur 1-D:

This is a light distillation fuel for applications that require a high volatility fuel for erratic speeds and loads as in light buses and trucks. The specifications of this type of diesel fuel overlap with those of jet fuel and kerosene, and all three fuels are often obtained from the same stock. One of the major uses of No. 1-D diesel is blending with No. 2-D to offer enhanced low temperature properties during winter. In addition, No. 1-D diesel is necessary for highway use due to its low sulphur content of less than 0.05%.

Grade No. 2-D (DF2) and Low Sulphur 2-D

This type refers to a middle distillation fuel for uses that do not need a high volatility fuel. Typical uses include high-speed engines that operate at high loads for sustained periods. Low Sulphur No. 2-D fuel is essential for use on highway due its low sulphur content of less than 0.05%. The standard properties of the different grades of diesel fuels are characterized by

ASTM D 975, and appear in Appendix A. Kenya uses grade No. 2-D fuel for road transport, whose specifications and requirements, as set by the Kenya Bureau of Standards (KEBS, appear in Appendix B. This study will therefore compare the fuel properties of grade no. 2 D against the fuel properties of WPO.

Grade No. 4-D

This grade refers to a heavy distillation fuel that is viscous and may need fuel heating to achieve proper atomization. This grade of fuel finds uses in engines of low speeds.

2.1.2 Biodiesel Fuels

Conventional sources of biodiesel oils such as cottonseed, sunflower, castor, palm and linseed have become leading candidates for alternative sources of fuel for use in diesel engines. According to Munavu and Odhiambo (1984), several indigenous and non-edible vegetable oil sources can also be used as alternative fuel sources in Kenya. Their physical and chemical properties are analogous to those of conventional vegetable oils. One such source for nonconventional vegetable oils is Jatropha curcas.

Pramanik (2002) studied the properties and use of unmodified Jatropha oil and diesel-blended fuels in compression ignition found that between 40 and 50% of unchanged Jatropha oil can be substituted for diesel without the need for preheating of fuel blends and engine modification. Kumar et. al. (2001) assert that diesel engines can use original Jatropha oil without major decline in engine performance. However, the studies established that while the performance of the Jatropha methyl ester was better than that of original Jatropha oil, its performance was still inferior to that of pure diesel. Therefore, it is important to investigate the properties of pyrolysis oils, particularly WPO, in order to determine if they are better alternatives than biodiesel.

Table 2.1: Physical and Chemical Properties of Jatropha biodiesel

Properties	Liang et al, 2006	Liang et al, 2006	Sangha et al, 2004
Density (g/cc), 300C	0.9180	0.93292	0.9135
Kinematic viscosity (cSt), 30^0C		52.76	26.22 @ 25^0C
Cetane number	51	38.00	
Flash point, ^{0}C	240	210.00	
Calorific value, MJ/kg	39.62	38.20	
Saponification value		198.00	185.2
Iodine number		94.00	92.1
Acid value			3.52

2.1.3 Pyrolysis Oils

Pyrolysis refers to the chemical degradation of organic substances by the use of heat in the absence of oxygen (Yoshida & Yoshikawa, 2015). Usually, pyrolysis is the first chemical reaction that occurs in the burning of various organic fuels in solid form, including wood, cloth, paper, tyres and some types of plastic. An anhydrous pyrolysis process can be employed to make liquid fuels from waste plastics with similar characteristics to those of diesel.

The pyrolysis of tyres aims to convert waste tyres into potentially recyclable materials such as pyrolysis oil, flammable gas and carbon black. Tyre pyrolysis oil is associated with a high gross calorific value (GCV) of between 41 and 44 MJ/kg (Lee & Shin, 2007). Various plants for producing tyre pyrolysis oil exist around the world with many producing pyrolysis oil as a substitute for heavy fuel oil used for heating purposes in industrial applications. Usually, waste tyre needs to be shredded before the pyrolysis process can begin. The maximum yield of tyre pyrolysis oil occurs at 350^0C and decomposes rapidly above 400^0C. In addition, desulphurization becomes a necessity during the pyrolysis process in order to eliminate sulphur. Often, the products of tyre pyrolysis, on a weight basis, consist of 35% tyre pyrolysis oil, 56% residue and 9% gases (Miller et. al, 2005). The pyrolysis process is also used to produce WPO from plastic waste.

High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Propylene (PP) and Polystyrene (PS) are all hydrocarbons that entirely consist of hydrogen and carbon, which are similar to hydrocarbon fuels such as gasoline, diesel, and liquefied petroleum gas (LPG). Indeed, plastics are derived from petroleum and the range of their calorific values is similar to that of diesel, petrol and LPG as shown in Table 2.2

Table 2.2: Comparison of the Energy Density of Plastics and other Hydrocarbon Fuels

Material	Calorific Value (MJ/kg)
Polyethylene	46.3
Polypropylene	46.4
Polystyrene	41.4
Polyvinyl chloride	18.0
Coal	24.3
Liquefied petroleum gas	46.1
Petrol	44.0
Kerosene	43.4
Diesel	43.0
Light fuel oil	41.9
Heavy fuel oil	41.1

Source: Baines (1993)

The production process usually involves collection and segregation of waste plastics. The segregated waste plastics are then washed, dried and stored. The waste plastics are then shredded and fed into the hopper of a pyrolysis reactor where they flow into the heating chamber in the presence of a catalyst. The plastic waste is decomposed into liquid vapour which flows into a condenser and liquid and tarry waste which is tapped and collected in containers. The condensed liquid vapour is then tapped and collected as the waste plastic oil (WPO). Fig 2.1 illustrates the pyrolysis process of used plastics that is often employed in small plants.

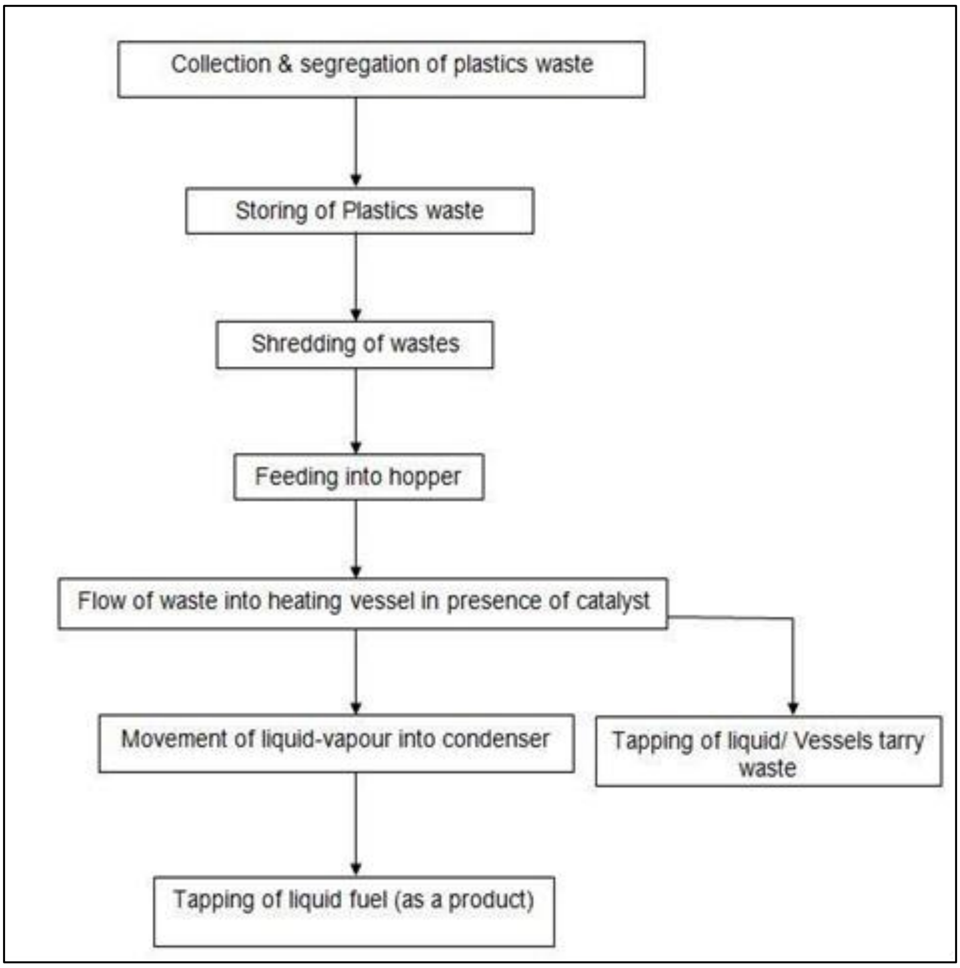


Figure 2.1: Production process of waste plastic oil

The products of the pyrolysis process are directly related to the chemical structure and composition of the plastics to be pyrolyzed. Furthermore, the chemical composition of the feedstock also influences the pyrolysis process. However, in reality, waste plastics undergo contamination before or during recycling which could also have an impact on the pyrolysis process and products. As discussed earlier in this chapter, PE, PP and PS are the most commonly used polymeric hydrocarbons. Polythylene is formed from ethylene through chain polymerization as shown in Equation 2.1 (McMurry, 2005).

$$\underset{\text{Ethylene}}{n\,\mathrm{CH_2{=}CH_2}} \xrightarrow{\text{polymerization}} \underset{\text{Polyethylene}}{\left[\!-\mathrm{CH_2}-\mathrm{CH_2}-\!\right]_n} \qquad (2.1)$$

Plastics can be grouped according to the structural shape of polymer molecules, linear, branched, or cross-linked as shown in Figure 2.2. In a linear polymer, the units are joined only to two others, one to each ends. In a branched polymer, branches extend randomly beyond the main chain polymer. According to McMurry (2005), a significant relationship exists between the branching intensity of polymers and their density. PE with high branching intensity is associated with a relatively lower density. The branched polyethylene is also referred to as Low Density Polyethylene (LDPE), which is dissimilar to the linear polyethylene referred to as high density polyethylene (HDPE).

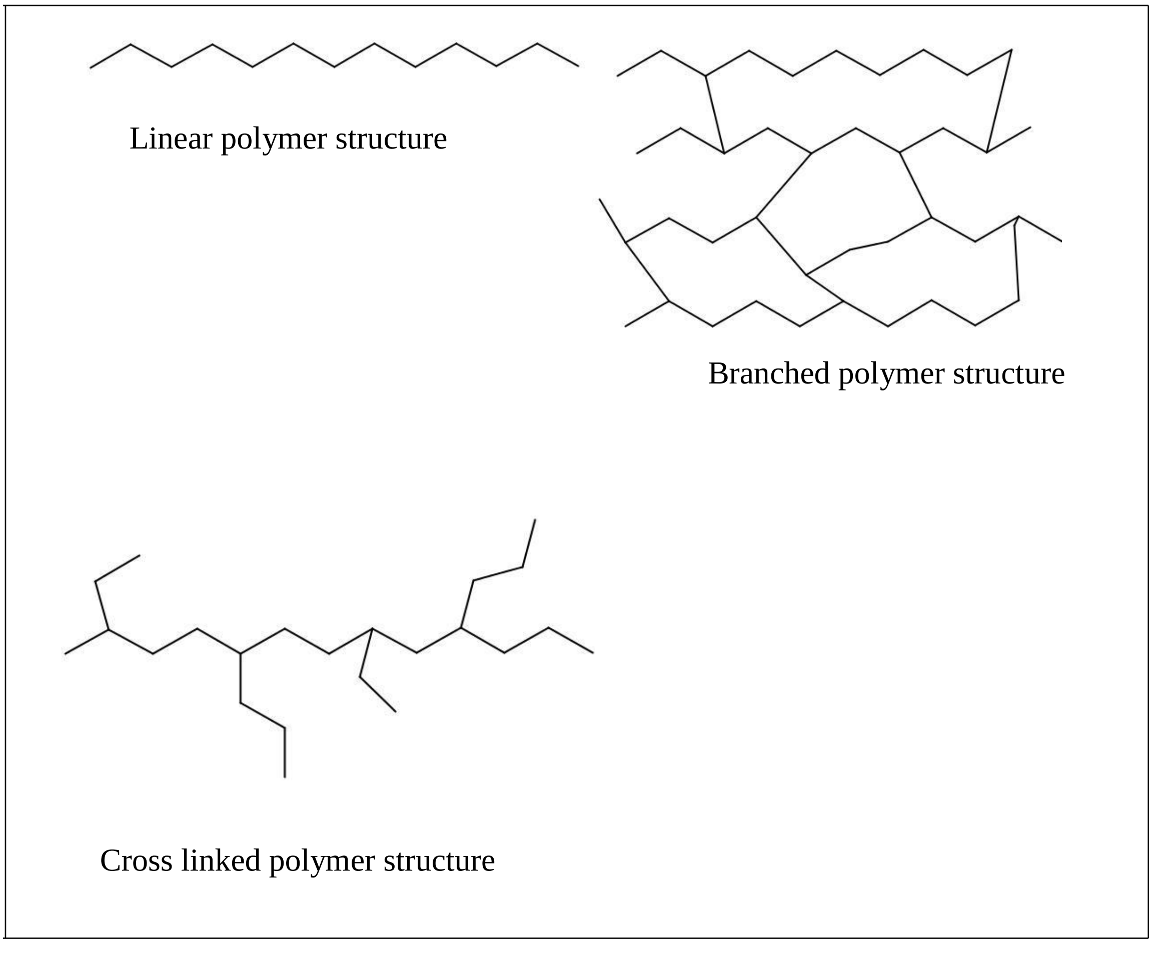


Figure 2.2: Polymer structure; linear, branched & cross-linked (Gao, 2010).

A cross-linked polymer is associated with an interconnected branched polymer where all polymer chains are linked to constitute a large molecule. Hypothetically, a cross-linked polymer's molecular weight can be infinite. In practice, however, the molecular weight of a cross-linked polymer can be restricted owing to the breaking down of molecular interlinkage during processing. The study utilized waste plastics from high density polyethylene (HDPE) because of their high calorific value and ease of decomposition.

The main factors that influence the pyrolysis of plastics and the molecular distribution of products of pyrolysis include feedstock composition, heating rate and cracking temperature, residence time, reactor type, operation pressure and use of catalyst. These factors are discussed in the following paragraphs:

i. Temperature

Temperature is a key factor of pyrolysis process since temperature influences the reaction of polymer materials during cracking. Increasing the temperature does not guarantee the success of cracking in view of some polymer materials. Van der Waals force, which is the force between molecules, attracts molecules together thus preventing their collapse. When molecules of a polymer material are subjected to intense vibration, the molecules will evaporate from an object's surface. Yet, the carbon chain will only break if the energy induced by the Van der Waals forces along the polymer chain exceeds the enthalpy of the C-C bond in the chain. This phenomenon explains why a polymer with high molecular weight decomposes rather than boils when it undergoes heating (Patra & Yethiraj, 2000).

Karaduman et al. (2001) studied the temperature profile along an externally heated tube. The study revealed large temperature variation between the centre and the ends of the tube. Figure 2.3 shows significant heat loss at both ends of the tube reactor.

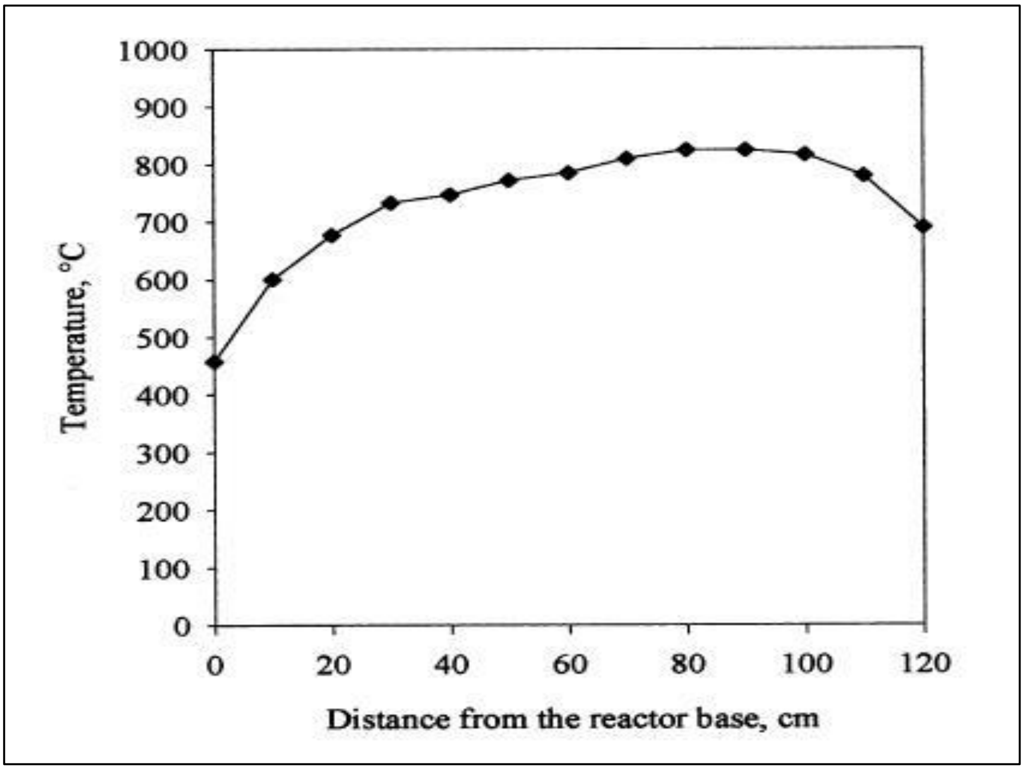


Figure 2.3: Temperature profile along the tube reactor (Karaduman, A., et al., 2001).

Miller et al (2005) pyrolyzed a mixture of post-consumed plastics of PS, PP and PE in a fixed-bed batch reactor at various temperatures for one hour. The study established that higher reaction temperature favoured the production of gas and products associated with heavy molecular weight. Figure 2.4 shows the results of gas chromatography (GC) analysis of the liquid products with respect to the cracking temperature. From the results, liquids formed at higher cracking temperatures had lower flash-off percentage at the same GC temperature during the analysis, which is an indication of a high proportion of heavy molecular weight components in the liquid.

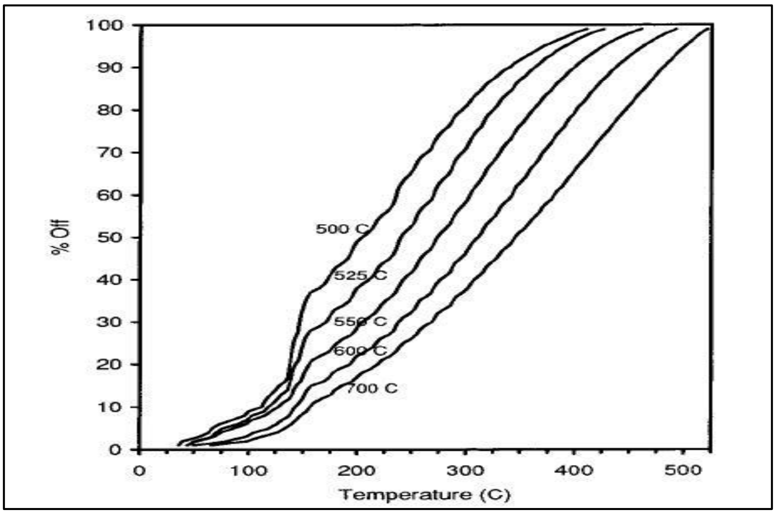


Figure 2.4: GC analysis results of plastic pyrolysis liquid (Karaduman et al., 2001).

However, the proportion of gas product increased with increasing cracking temperature up to 730^{0}C whereas the proportion of liquid product decreased with the cracking temperature in the full range of temperature applied as seen in Figure 2.5

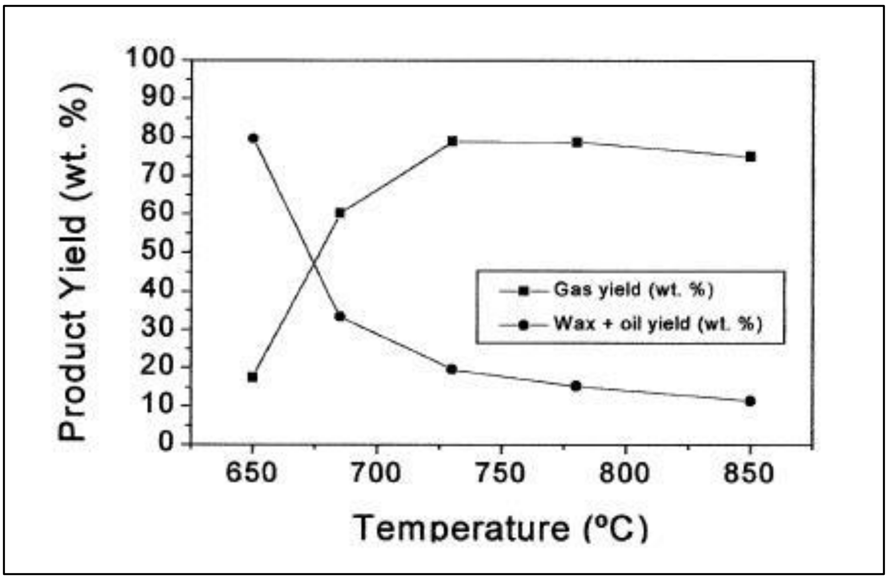


Figure 2.5: Influence of temperature on product distribution (Karaduman et al., 2001).

ii. Heating Rate

The impact of heating rate on product distribution and the plastic pyrolysis process as a whole differs in various studies because of the differences in operating conditions (pressure and temperature), temperature measurement location and design of the pyrolysis reactor. Usually, the heating rate, in fast or flash pyrolysis, refers to the change of temperature of the plastic once it drops on the hot surface until it decomposes and vaporizes. This process is very fast and the high values of heating rate are difficult to determine accurately. Therefore, the surface temperature is used as the reaction temperature indicator instead of the heating rate. However, in the batch process, waste plastic is heated from room temperature to the cracking temperature in several minutes and is thus a slow pyrolysis process.

Once the plastic feedstock attains cracking temperature, the temperature remains reasonably stable until all the feedstock is pyrolyzed. Consequently, the heating rate serves as a good reaction temperature indicator instead of surface temperature. Williams & Slanley (2007) established that the heating rate often varied from 10 to 100^{0}C/minute for slow pyrolysis processes. Saha and Ghoshal (2005) investigated the effect of heating rate on the reaction rate using thermo gravimetric analysis (TGA) as shown Figure 2.6. From the graph, it is established that high heating rates enhance the rate of pyrolysis reactions.

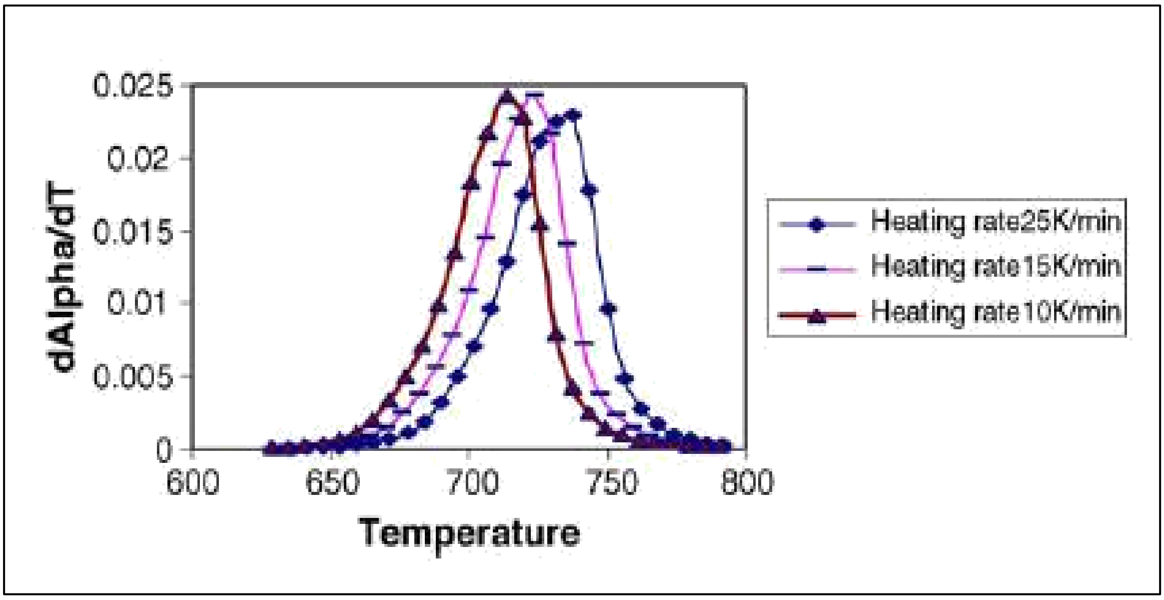


Figure 2.6: Reaction rate as a function of temperature and heating rate in pyrolysis of Coca Cola soft drink PET bottle (Karaduman et al., 2001).

iii. Reactor type

The ttype of reactor used during the pyrolysis process has a significant influence on the mixing of plastics with products of pyrolysis, rate of heat transfer, reflux level of the primary products and residence time.

Depending on the feeding and product removal process, pyrolysis reactors are categorized into batch, semi-batch and continuous reactors. In a batch reactor, plastics to be pyrolyzed are fed into the reactor in batches, either at the beginning of the pyrolysis process or after the processing of the fed materials. In a continuous reactor, plastics are fed into the reactor from one part of the reactor while products exit through another part of the reactor. In a semi-batch reactor, pyrolysis products are continuously removed but the feedstock is added initially before the onset of the pyrolysis process. Some semi-batch reactors apply inert gases to assist in the removal of pyrolysis products. According to Williams & Williams (1997), batch and semi-batch reactors are mainly used for research purposes while the continuous reactor finds usefulness in industrial production. The study employed a batch reactor as it is the easiest type of reactor to fabricate and operate among the three types.

iv. Residence Time

Residence time in continuous pyrolysis processes or fast pyrolysis refers to the time of contact of the plastic on the hot surface of all through the reactor. However, in batch process or slow pyrolysis, residence time refers to the duration when plastic feedstock start to be heated to the time when the products are removed. A longer residence time encourages further conversion of the primary products thereby yielding more stable products such as non-condensable petroleum gases and light molecular weight hydrocarbons (Hernandez et al., 2006). Long residence time in a slow pyrolysis process promotes the carbonization process thus producing more tar and char in the products. With the exception of the batch pyrolysis reactor, it is difficult to control the residence time directly. However, residence time can be adjusted by varying other operation parameters such as carrier gas flow rate, feeding rate and product discharge rate. Table 2.3 illustrates the residence time, target products and pyrolysis conditions. The process employed in the study can be categorised as a slow pyrolysis as it was characterised by a long residence time of about 120 minutes and a low heating rate of about 100K/min.

Table 2.3: Pyrolysis Processes and Target Products

Process	Heating rate	Residence time	Temperature (^{0}C)	Target Products
Slow carbonization	Very low	Days	450-600	Charcoal
Slow pyrolysis	10-100K/min	10-60 min	450-600	Gas, oil, char
Fast pyrolysis	Up to 1000K/s	0.5-5 s	550-650	Gas, oil, (char)
Flash pyrolysis	Up to 10000K/s	<1 s	450-900	Gas, oil, (char)

Source: Hernandez, et al. (2006)

v. Pressure

Operating pressure has a major influence on both the process of pyrolysis and the products of pyrolysis. Higher operating pressure increases the boiling points of pyrolysis products hence further pyrolyzing heavy hydrocarbons, instead of vaporized, at a given operation temperature (Miranda et al., 2001).

Figure 2.7 illustrates the influence of pressure on hydrocarbon number and their fractions in the pyrolysis products of PE. In effect, more energy is needed for further cracking of hydrocarbons in an under pressurised pyrolysis process.

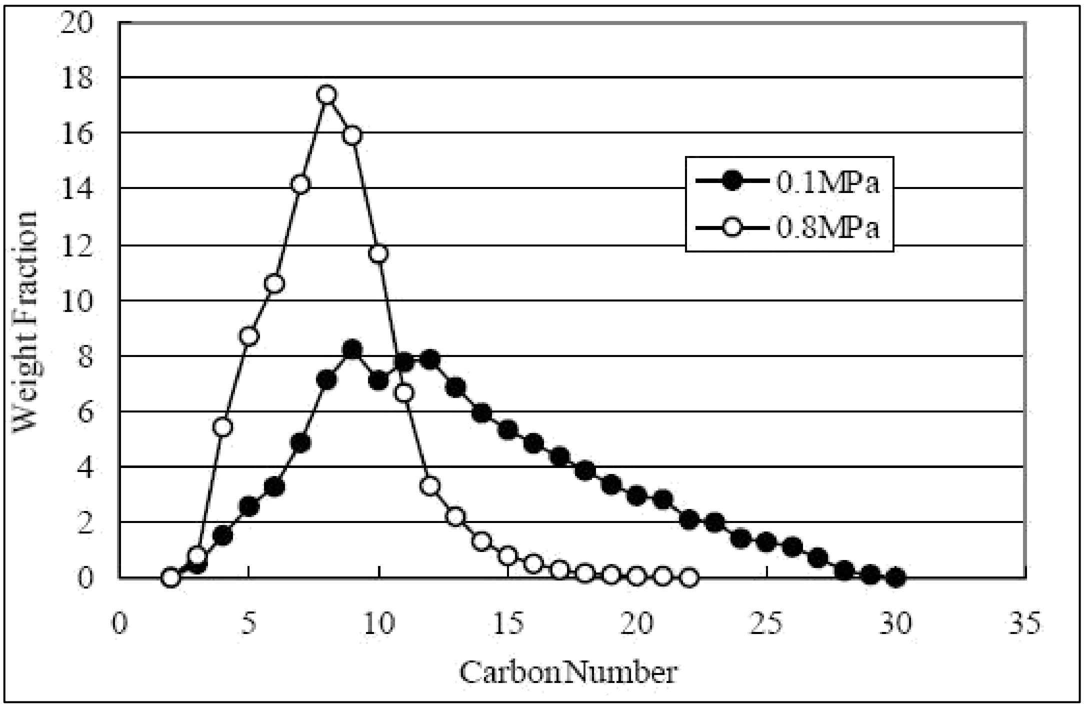


Figure 2.7: Effect of pressure on the distribution of PE pyrolysis products (Murata et al., 2001).

Murata et al., (2001) established that high pressure enhances the yield of non-condensable gases while decreasing the yield of liquid products (Figure 2.8). An increase in pressure leads to a decrease in the average molecular weight of gas products.

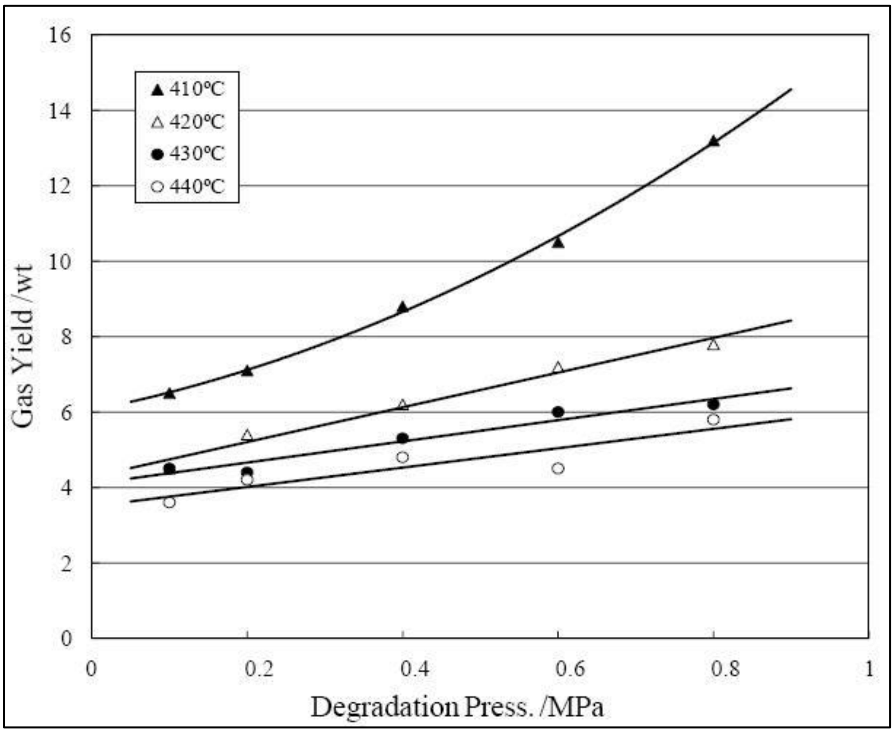


Figure 2.8: Effect of pressure on the yield of gas at different temperature (Murata et al., 2001).

vi. Catalysts

Catalysts are widely used in industrial and research pyrolysis processes in order to optimize plastic pyrolysis reactions and vary the distribution of pyrolysis products. Petroleum fuels such as petrol, kerosene, diesel and LPG are hydrocarbons from C_1 to C_{24} whereas pyrolysis products of PE are majorly straight hydrocarbons from C_1 to C_{80}, which consist of heavier molecular weight components. One of the key objectives of using catalysts is to shorten the length of carbon chain of the pyrolysis products thus decreasing the boiling point of the products. Catalysts are mainly used in PE pyrolysis processes since the primary product from other plastics, such as PS and PP, are mainly light hydrocarbons, with comparable carbon-chain length to the range of commercial fuels. Products from non-catalytic pyrolysis of PE contain high amounts of 1-alkenes and dialkenes (Blazso, 2006). Various catalysts are specifically used to decrease unsaturated hydrocarbons and enhance the yield of naphthenes and aromatics, which can considerably amplify the stability and cetane number of the oil products. NKC-3A zeolite is an example of a catalyst that is widely used in the petroleum industry. It mainly consists of alkali metals and silica aluminate (Gao, 2010).

Other factors that influence the pyrolysis process considerably include reactive additives such as air, hydrogen or oxygen which are sometimes present during reactions for different purposes thus interfering with the reactions and affecting the quality of the products. Therefore, it is important that the pyrolysis process takes place in the absence of the additives.

2.4 Properties of Diesel, Biodiesel, WPO and Blends

The requirements of diesel regulations in most countries can be characterized into four groups namely flowing properties, performance properties, thermodynamic properties and component distribution. One of the most significant thermodynamic properties in the regulation of commercial diesels is the cetane number, which is an indicator of the auto-ignition conditions of a fuel (Gerpen, 1999). The cetane number is calculated from the density and distillation range of a fuel. Another key thermodynamic property is the calorific value of a fuel, which indicates the energy content of a fuel and is determined by use of a bomb calorimeter. .

Flow properties including viscosity, pour point, cloud point and cold filter plugging point are also important. However, the significance of these properties depends on the extent of known information of thermodynamic properties mentioned above, such as distillation range and density.

Miscellaneous properties mirror the influence of minorities in diesel fuels, including water content, sulphur content, ash content, carbon residues and polycyclic aromatic hydrocarbon content. Carbon residue refers to fine solid particles in a fuel that may cause deposits in the combustion chamber. Sulphur content exceeding a certain level denatures catalysts and leads to corrosion and wear of the engine. Water content can promote corrosion of tanks and fuel injection lines and equipment. Ash content refers to the solid residue formed after complete burning of the fuel. The polycyclic aromatic hydrocarbon content is aplied to enhance the cetane number due to their high density and low boiling point.

Performance properties include colour, lubricity, particulate, filter blocking tendency, copper corrosion and oxidation stability. These properties are a result of one or more effects of miscellaneous and fundamental properties. For instance, copper corrosion is an indicator essentially resulting from the sulphur content in the diesel.

2.4.1 Viscosity

The viscosity of a diesel fuel is an important property as it impacts the shape of a fuel spray and therefore the combustion process. High viscosities lead to increased pumping losses in both the injectors and the injector pump, thereby reducing the injection pressure. This scenario causes low atomization, often associated with large-sized droplets, and high penetration of the spray jet leading to incomplete combustion. A highly thick diesel fuel in a cold engine may release a near solid stream into the combustion chamber thus leading to difficulty in starting the engine and a smoky exhaust.

Conversely, low viscosity diesel fuels lead to high leakages past the piston in the injection pump. Although the leakage by itself is not significant, it prevents precise metering of the diesel fuel. There is a reduction of the actual volume of fuel received by the injectors resulting in needle lift delay, leading to late injection and ultimately incomplete combustion. In addition, low viscosity fuels are associated with reduced lubricating qualities (Obert, 1973). ASTM D 975 stipulates a kinematic viscosity range of a minimum of 1.9 to a maximum of 4.1 mm^2/s at 40^{0}C for Grade No.2 diesel fuel.

The viscosity of WPO is expected to be lower than that of diesel. This is because pyrolysis involves the breakdown of large molecules into smaller and lighter molecules of ethane, kerosene and gasoline. Consequently, the viscosities of WPO and its blends with diesel are expected to be lower than those of both diesel and biodiesel.

Vegetable oils viscosity is 15-20 times higher than that of diesel fuel, which results in fuel flow problems during their application as engine fuels (Guibet, 1997). Viscosity in vegetable oils has a direct relationship with the iodine value; the higher the viscosity, the higher the iodine value.

2.4.2 Specific Gravity

Specific and API gravities are very significant properties as the injection system is configured to convey a predetermined volume of oil, while the air-fuel mass ratio is the key parameter in the combustion chamber. A high API gravity is associated with high cetane number and is desirable because it indicates complete combustion due to lack of ignition delay (Guibet, 1997).

The specific gravity of most biodiesels and their methyl esters is higher than that of diesel fuel because of the big molecular mass and nature chemical structures of vegetable oils (Pramanik, 2002). This phenomenon compensates for their low heating value with regard to brake specific fuel consumption. The specific gravity of WPO is lower than that of diesel since WPO consists of the lightest fractions, including kerosene, gasoline and ethane, with a density range of 776-780 kg/m^3 at 20^{0}C. This is because pyrolysis involves the breakdown of large molecules into smaller molecules of ethane, kerosene and gasoline. Consequently, the specific gravities of WPO and its blends with diesel are expected to be lower than that of both diesel and biodiesel.

2.4.3 Cetane Number

The Cetane Number is used to express the ignition quality of a fuel. The Cetane Number (CN) is the benchmark measure of the ignition quality of a diesel fuel. It is based on a special engine which uses a reference fuel mixture of high ignitability fuel, Cetane ($C_{16}H_{34}$) and a low ignitability fuel, alpha-methyl-naphthalene, $C_{11}H_{10}$. The reference fuel mixture is constituted by volume and the ignitability of the test fuel is expressed as the percentage of Cetane in the reference mixture with equivalent ignitability (Taylor, 1985).

Both too low and too high Cetane Number can result in engine problems during operation. Too high a Cetane Number can cause premature ignition leading to increased compression work and ultimately power reduction. On the other hand, too low Cetane Number can cause diesel knock resulting from a rapid rise in pressure because of rapid combustion of mixture that develops during a long ignition delay during which a large fraction of the charge enters the cylinder. The scenario results in a rough engine run. Incomplete combustion, lower engine warm up and higher exhaust gas temperatures are common characteristics of low Cetane Number.

Table 2.4 shows recommended Cetane ratings of fuels for engine speeds running at optimal performance. Engines running at high rpms require fuels with high Cetane Numbers to avoid incomplete combustion and high exhaust temperatures.

Table 2.4: Variation of Cetane Number with Speed

Engine Speed (RPM)	Cetane Number (CN)
0-100	15-30
100-200	15-40
200-400	30-45
400-800	35-50
800-1500	45-55
1500-3000	50-60

Source: Wright and Purday (1950)

The bigger the molecule, the higher the CN within the series (Taylor, 1985). The Cetane number of a biodiesel fuel depends on the fatty acid composition of such a fuel, as well as contaminants such as hydrogen peroxides and unsaponifiable matter in the fuel. According to Gerpen (1999), a longer fatty acid carbon chain signifies highly saturated molecules and consequently a higher Cetane number. He further asserts that the unsaponifiable matter has no influence on the Cetane number of a fuel while hydroperoxides lead to a high Cetane number. According to Krisnangkura (1986), the Cetane number for biodiesel fuels increases with an increase in oil saturation. Studies by Pachter & Hohl (1991) show that biodiesel fuels often have higher Cetane numbers than diesel fuels.

WPO is characterized by the breakdown of large hydrocarbon molecules into smaller molecules of ethane, kerosene and gasoline. Therefore, the cetane numbers of WPO and its blends with diesel are expected to be lower than those of both diesel and biodiesel.

2.4.4 Sulphur Content

Sulphur is present in nearly all petroleum-derived fuels and products, such as lubricants. It exists either in free form or more commonly in chemical compounds such as Sulphides, disulphides, Hydrogen Sulphide, and sulphide ring compounds (Guibert, 1997). There are several reasons why the presence of Sulphur and its compounds in a fuel is undesirable. Firstly, in some forms, especially free sulphur and hydrogen sulphide, the sulphur represents the caustic element of the fuel that can corrode carburettors, injection pumps and fuel lines

(Kimilu, 2008). Secondly, Sulphur reacts with Oxygen to form Sulphur Dioxide, which in turn, at low temperatures, reacts with water to form sulphuric acid. Thirdly, it is likely for Sulphur Dioxide to react with other substances to form products that could lead to wear of the engine, even at high temperatures. In addition, the emission of sulphur dioxide into the atmosphere can lead to acid rain and trapping of heat within the earth's atmosphere thus leading to global warming. Further, Sulphur has a low ignition temperature and thus its occurrence in a fuel can decrease the self-ignition temperature, hence enhancing knock in spark ignition engines while decreasing knock in combustion ignition engines (Kimilu, 2008).

Despite the low sulphur content in petrol, usually less than 0.1%, sulphur content in fuel oils is often much higher and can result in increased engine wear as well as deposits of carbon on pistons and piston rings, and a deterioration in the quality of lubricating oil (Blanc, 1997). The wear and fouling because of sulphur in the diesel fuel is caused by the formation of sulphur trioxide during the combustion of diesel in the presence of large amounts of excess air. The Sulphur trioxide attacks the lubricating oil on the walls of the cylinder to form a resinous amalgam that hardens into varnish and carbon (Blackwood & Cloud, 2003). Sulphur contents beyond 1% are considered damaging whereas contents of up to 0.5% are considered acceptable. The content of sulphur in a fuel is determined by measuring the quantity of sulphur dioxide resulting from combustion and translating the amount into an equivalent mass of free sulphur.

Sulphur and other carryover elements such as phosphorous can be carried over from vegetable oils, for instance, from phospholipids present in all vegetable oils or glucosinolates in rapeseed-based biodiesel (Knothe, 2006). Most biodiesel fuels inherently contain little or no sulfur, except for the possibility in rapeseed oil as just mentioned. The ASTM Biodiesel standard D 6751 specifies the maximum allowable content of sulphur at 0.05 ppm and 0.015 ppm for Grade S 500 and Grade S 15 biodiesel respectively. The specification is important to show that biodiesel will not negatively affect automotive catalyst systems, as well as the operation of an internal combustion engine.

According to Knothe (2006), the sulphur content of waste plastic oil is expected to be higher than that of both diesel and biodiesel because of the presence of aromatics and contamination arising from improper sorting. As such, the sulphur content of waste plastic oil and its blends with diesel is expected to rise with increase in fraction of waste plastic oil in the blend. The high amount of sulphur content in waste plastic oil can however be reduced through the use of affordable desulphurization techniques. The desulphurization methods involve the oxidation of the sulphur compounds present in the fuels with hydrogen peroxide to more polar sulphur compounds such as sulphoxides and sulphones, which can later be eliminated by silica gel adsorption or methanol extraction (Ampaitepin & Tetsuo, 2010).

2.4.5 Heating Value

The heating value, also known as the heat of combustion, is determined using ASTM D 240, which involves burning a fuel with oxygen in a bomb calorimeter and noting the rise in temperature of the cooling bath. The quantity of heat transferred to the cooling bath depends partly on whether all or part of the water vapour from combustion is condensed. A high heating value is obtained if all of the water vapour is condensed. The heating value is an important property as it is a measure of the amount of chemical energy available in a diesel fuel. Further, the property is useful in determining the thermal efficiency of a diesel engine, among other prime movers. Heat of combustion is expressed on a mass basis and while the American Society for Testing and Materials does not specify the heating value, the typical heating value of No. 2 diesel fuel is 44.60 MJ/kg (SAE, 1987).

According to Graboski and McCormic (1998), the heating values of biodiesel fuels are somewhat lower than that of conventional diesel fuels and vary with the composition of fatty acids. The heat of combustion of biodiesel can be determined using a straightforward component-mixing rule based on the quantity of constituent fatty acids.

Plastics have a very high heating value, often exceeding 40 MJ/kg (Ampaitepin & Tetsuo, 2010). It results from a high content of carbon and hydrogen, and low ash content. Depending on the pyrolysis process and the type of plastics, the heating value of plastics can be marginally higher or lower than that of diesel. The high heating values of plastics indicate plastic wastes can partially substitute fossil fuels Therefore, the heating values of WPO and its blends with diesel would be expected to vary with the heating value of the obtained waste plastic oil.

2.4.6 Flash Point

The flash point refers to the lowest temperature to which fuel needs to be heated for the resulting vapour to form a combustible air-fuel mixture at atmospheric pressure. The standard method of measurement is by the Pensky-Martens Closed Cup (PMCC) tester as outlined in

ASTM D 93. The flash point of a diesel fuel is not directly linked to the performance of an engine. However, it is an essential property and is a legal requirement for safety measures during the handling and storage of fuel. A fuel vapour will ignite when its temperature is at or above the flash point causing an easily detectable flash. The flash does not need to translate into a continued flame. For No. 2 diesel fuel, the flash point is a minimum of 52^0C (Gerpen, 2004).

The flash point specification aids in limiting the amount of alcohol in a biodiesel fuel. The prescribed methods, both of which use a closed-cup flash point tester, are ASTM D 93 in ASTM D 6751 and EN 14214 and limit methanol to a maximum of about 0.1% in a biodiesel fuel. The ASTM D 6751 and EN 14214 limit the flash point of a biodiesel to a minimum temperature of 130^0C and 120^0C respectively.

The flash point of WPO is determined according to the ASTM D 93-62 method. The flash points of both diesel and biodiesel are higher than that of waste plastic oil, which indicates they are easier to handle. The low flash point of waste plastic oil is attributed to the presence of lighter and more volatile compounds, such as naphtha (Masuda &Tago, 2006). Therefore, the flash point of waste plastic oil and its blends with diesel is expected to increase with increase in the quantity of diesel.

2.4.7 Carbon Residue

The carbon residue test is designed to indicate the coking tendency of a fuel. The amount of carbon residue formed after evaporation and pyrolysis of the weighed sample is determined by the method Ramsbottom Carbon Residue of Petroleum Products, ASTM 524 (Kimilu, 2008).

When the combustion of a fuel takes place in the presence of a limited amount of oxygen, the resulting residue known as carbon residue. The carbon residue is a representation of the heavier fractions of the liquid fuel, including gum content, that will likely escape complete combustion thus yielding carbon in the engine. High carbon residues cause deposits around the nozzle tips and in the combustion chamber, consequently interfering with the fuel’s spray shape. The maximum carbon residue limit for No.2 diesel is 0.15% (m/m) while the maximum carbon residue limit for biodiesel is 0.05 % (m/m) as outlined by carbon residue test (ASTM D 4504 in ASTM D 6751; ISO 10370 in EN 14214).

Khan et al. (2016) determined the level of carbon residue in waste plastic oil to be comparatively lower than that of both diesel and gasoline and higher than that of biodiesel. The carbon residue in waste plastic oil and its blends with diesel would be expected to increase with increase in the quantity of diesel in the blend.

2.4.8 Ash Content

Ash content is a gauge of the abrasiveness of combustion products that could result in engine wear. The upper limit for DF2 is 0.01% (m/m) and is determined using ASTM D 482, Ash from Petroleum Products. The ASTM D 874 in ASTM D 6751 limits sulphated ash to a maximum of 0.20 % (m/m) for biodiesel fuels.

Khan et al. (2016) determined the level of ash content in waste plastic oil to be comparatively higher than that of both diesel and biodiesel. Therefore, the ash content in waste plastic oil and its blends with diesel would be expected to decrease with increase in the quantity of diesel added to the blend.

2.4.9 Cold Temperature Characteristics

The characteristics of a diesel fuel in cold temperatures have a greater impact on its use specifically during cold weather than on its performance during combustion. A diesel fuel can lose its fluidity and clarity at low temperatures, unlike other petroleum fuels such as kerosene and gasoline. This is attributed to the formation of wax crystals in the fuel, which can cause diverse problems such as plugging of the filter. The behaviour of diesel fuel at cold temperatures can be determined by several standard procedures, including low temperature flow test, pour point, cloud point and cold filter plugging point.

The cloud point of a fuel is determined visually by inspecting for a haze in the normally clear fuel (Paramins, 1994). Cloud point is an important low temperature characteristic as it denotes the formation of wax crystals in the fuel, which can cause diverse problems such as plugging of the filter.

Biodiesels and their esters have poorer cold temperature characteristics than diesel fuels. They have high pour point and cloud point due to various compounds that are present in the fuels. For instance, unsaturated fatty compounds have significantly lower melting points than saturated fatty compounds and as result, they often crystallize at lower temperatures than the saturated fatty compounds. Because of this phenomenon, biodiesel fuels are often improved by blending with diesel fuels (Kimilu, 2008).

Diesel has better cold temperature characteristics than waste plastic oil. WPO is characterized by high cloud point due to various aromatic compounds and other contaminants present in the fuel. Aromatic compounds present in waste plastic oil often crystallize at higher temperatures than naphtha. Consequently, waste plastic oil is often blended with diesel to improve its cloud point.

Pour point is an important property especially when an engine has to function in low ambient temperatures like those experienced in during winter. The pour point is determined by means of the method described by ASTM D 97. Biodiesel fuels tend to have a higher point than diesel fuel due to various compounds that are present in these fuels. Similarly, WPO is characterized by a high pour point due to various aromatic compounds and contaminants present in the fuel. Therefore, waste plastic oil is blended with diesel to improve its pour point.

2.4.10 Water and Sediment

The purity of a diesel fuel is one of the most properties. According to Obert (1973), more engines have been destroyed by water and dirt present in a fuel than by any other deviation from the other properties. Water and dirt in diesel fuels does not settle out of the fuels as rapidly they do in gasoline. Salt water in a diesel fuel causes corrosion of engine and the fuel system. Water may exist as either suspended droplets or dissolved.

According to Gerpen et al. (2004), biodiesel can contain up to 1500 ppm of dissolved water although the maximum allowable limit is 500 ppm. Meanwhile, suspended water is problematic in the fuel injection system as it is associated with the corrosion of the fuel system. In addition, suspended water has been linked to microbial growth in the fuel.

Sediment in a fuel may consist of dirt particles and suspended rust, or may originate from fuel-insoluble compounds that are formed during the oxidation of fuel. The presence of such sediment may lead to filter plugging.

2.4.11 Acid Value

The acid number symbolizes the level of content of carboxylic groups that are present in a chemical compound, including a fatty acids. Under a normal procedure, a sample of diesel fuel of known amount is dissolved in an organic solvent and titrated with a potassium hydroxide solution of known concentration, with the use of phenolphthalein as a colour indicator. Therefore, the acid value is used to symbolize the amount of acid present in a biodiesel sample.

The preferred acid values of biodiesel fuels is lower than 3. There are benchmark methods for determining the acid value of biodiesel and mineral oils, such as ASTM D 974.

2.4.12 Storage Stability

Storage stability refers to a fuel's ability to resist chemical changes during long-term storage, usually six months or longer (Gerpen, 2004). Generally, such chemical changes involve oxidation because of contact with oxygen from the atmosphere. Oils that consist of high poly-unsaturated fatty acids, Linolenic and Linoleic, are more susceptible to these chemical changes. The presence of some metals (in storage containers) may catalyse changes, while the presence of water may cause hydrolysis. Oxidation generates hydro peroxides, which may consequently cause ketones and aldehydes. Under suitable conditions, hydro peroxides may also polymerize. An increase of viscosity and acid number of the fuel signifies oxidation. The darkening of biodiesel from yellow to brown and the development of 'paint' smell accompany the chemical changes. Gerpen et al. (2004) assert that for both diesel and biodiesel fuels to be stored for more than six months, they should be treated with anti-oxidant additives

2.5 Engine Performance

An engine is selected to suit a particular application through consideration of key performance characteristics such as brake power, brake specific fuel consumption and brake thermal efficiency. Other important factors include initial capital cost and running cost. A certain performance criteria need to be defined in order to compare the performance of an engine running on different types of fuels. These are obtained through measurement of the quantities concerned during bench tests, and calculation is by standard procedures. The results are plotted graphically in the form of performance curves. This study will compare the performance of a compression ignition engine running on diesel versus the performance of the same engine while running on diesel blended with WPO.

2.6 Energy Cost Analysis

The society has several reasons for changing its patterns of energy use; to reduce dependence on imported petroleum, to reduce greenhouse emissions, to promote sustainable economic development, or to mitigate environmental pollution. A primary strategy for achieving these goals is increasing the efficiency of a compression ignition engine through the use of alternative fuels. This is because the performance of an engine often varies depending on the type of fuel. Therefore, the cost of fuel used by an engine in order to produce 1 kWh is an important measure of a fuel's efficiency. The study will compare the cost of energy consumption per unit power of an engine running on diesel versus the cost of energy consumption per unit power of an engine running on diesel blended with WPO.

2.7 Engine Emission Analysis

The diesel industry is under increasing pressure worldwide to find methods to reduce particulate matter, NO_x, smoke, HC and CO emissions. The use of legislation to regulate these emissions has given rise to a new term called emission control. As a result, various approaches have been explored, including engine modifications, after exhaust treatment and use of alternative fuels.

The number of official tests and procedures often stipulated in such legislation is high and the cover is comprehensive including the measurements of HC, CO, CO_2, NO_x and smoke (for CI engines). Emissions vary with the engine parameters and tests can be carried out on research engines with the facilities of variable parameters to investigate the characteristics of emissions. This study will investigate the emission characteristics of a CI engine running on diesel and its blends with waste plastic oil.

CHAPTER THREE

METHODOLOGY

This chapter describes how the study was conducted. It gives a short description of the waste plastic oil production process, including the collection and type of plastics used and the location of the production site. It also describes methods of determining various properties of waste plastic oil as a fuel. In addition, the chapter describes the procedure for carrying out engine tests. It specifically outlines the engine instrumentation of the study, as well as the procedures of conducting engine performance, emission determination and economic analysis.

3.1 Sample Collection of Waste Plastics

Waste plastics were collected from the workshop of a waste recycler based at Kariobangi South, approximately 13 kilometres east of Nairobi city centre. The waste plastics were then sorted and segregated into various types of plastics. For the purpose of this study, segregated HDPE plastics were collected and transported to a pyrolysis plant at Kariobangi South. The plastics were then cleaned in a warm water bath and left to dry overnight. The plastics were then shredded into small particles of about 10mm in diameter. The shredded plastics were then stored in plastic bags ready to begin the pyrolysis process.

3.2 Waste Plastic Oil Production

The shredded waste plastics were introduced into a pyrolysis reactor through a hopper. The pyrolysis reactor was the fixed-batch type and the source of heat was firewood or charcoal briquettes. The reactor also used cogeneration as some of the excess gases from the pyrolysis process were introduced into the combustion chamber to provide heat on the reactor’s bed. The reactor had a waste plastic oil production capacity of 800 litres per day.

The shredded plastics were treated in a cylindrical reactor in a slow pyrolysis process of between 300^0C and 350^0C in the absence of oxygen for about 4 hours. The plastic waste was gently cracked by adding a catalyst and the gases were condensed into a series of condensers to achieve gases, char and a low sulphur content distillate, which was the main interest of the study. Feedstock was added into the reactor in batches until 50 litres of waste plastic oil was achieved. The waste plastic oil produced was then stored ready for analysis.

3.3 Fuel Properties & Characteristics of Diesel, WPO and Blends

3.3.1 Density

The specific gravity method was used to determine the density of the WPO and diesel blended samples. A single glass bottle was utilised for the test. The empty bottle was washed, dried, categorized and weighed with an analytical balance in the laboratory.

The bottle was filled with 50 cm^3 of diesel and then immersed into a water bath maintained at 15^0C in accordance with the EN14214 standard. The level of diesel in the bottle was adjusted by the removal or addition of diesel using a pipette. The bottle remained in the bath for 15 to 20 minutes with rare shaking until a uniform temperature of 15^0C was achieved. The bottle was then removed and dried of any water on the surface before being weighed again, from which the mass of the diesel sample was determined. The above steps were then repeated for the sample in ranges of 5^0C up to the final test temperature of 60^0C. The procedure was wholly repeated for all the samples of WPO and diesel blended fuels.

Equation 3.1 was used to determine the densities of the fuel samples at different test temperatures (KIRDI, 2012).

$$\rho = M / V \tag{3.1}$$

Where $\rho = density$

M = mass

V= volume

3.3.2 Viscosity

A Cannon-Fenske viscometer was used to determine the viscosity of the fuel samples in accordance with ASTM D 445. A chromic acid solution was used to clean the viscometer thoroughly to remove any possible traces of organic deposits while distilled water was used to rinse the viscometer. A stream of clean filtered air was used to dry the viscometer.

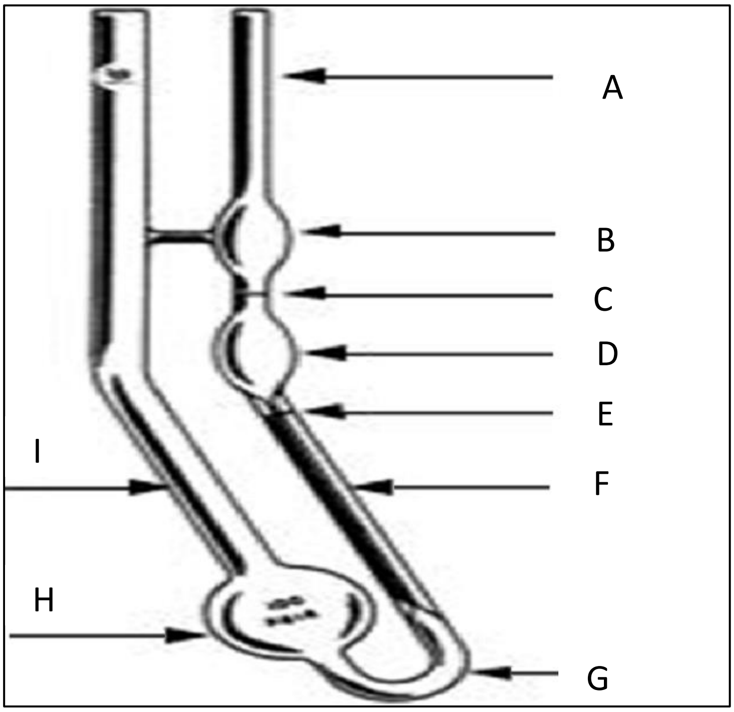


Figure 3.1: A Cannon-Fenske viscometer

The fuel sample was introduced into the viscometer by inserting the viscometer and immersing tube “A” into the fuel and applying suction to “I” thereby causing the sample to rise to etched line “E”. The viscometer was then turned to normal position and tube “A” wiped clean with a cloth. The viscometer was then inserted into a holder and placed in a constant temperature bath of 15^0C. Time was allowed for the viscometer and the water to achieve equilibrium. Suction was then applied to tube “A” and the sample brought into bulb “B” a short distance beyond mark “C”. The efflux time was determined by allowing the free flow of the sample through mark “C” and measuring the time it took for the meniscus to pass from “C” to “E”. The above steps were repeated for different fuel samples.

The kinematic viscosity was calculated by multiplying the efflux time by the viscometer constant as shown in Equation 3.2 (KIRDI, 2012).

$$Dynamic\ viscosity = \ kinematic\ viscosity \times Density \qquad (3.2)$$

3.3.3 Calorific Value

The Bomb calorimeter method was used to determine the calorific values of diesel and its blends with WPO. An analytical balance was used to determine the mass of an empty crucible of the calorimeter. An empty pod was then put inside the crucible after which the crucible was reweighed and the mass of the pod determined. The empty pod, after being removed from the crucible, was filled with the fuel sample and a short cotton thread attached and inserted into the crucible and weighed again. The fuel sample's mass was then calculated. The crucible containing the pod was then put into the firing apparatus of the calorimeter and water introduced into the calorimeter's cooling jacket after which the bomb was carefully assembled, charged with oxygen and the stirrer switched on. A thermometer was used to measure temperatures at breaks of one minute for five minutes, before the bomb was fired. Temperatures were recorded at intervals of 0.5 minutes during the entire period of temperature rise, and at one-minute intervals for five minutes after temperatures started dropping.

The energy absorbed by the cooling was calculated using equation 3.3 (Kimilu, 2008).

$$Energy\left[\frac{cal}{g}\right] = \frac{2335x\Delta T}{massofcapsuleandoil} \tag{3.3}$$

Where: $\Delta = (maximum\ temperature\ attained) - \ (temperature\ at\ firing)$

Energy contributed by the burning pod was determined using Equation 3.4 (Kimilu, 2008).

$$Capsule\ energy\ \left(\frac{cal}{g}\right) = capsule\ mass(g)x\ 4906 \tag{3.4}$$

The net energy contributed by the combustion of the fuel sample was determined by subtracting the capsule energy from the energy absorbed by the cooling water. The value obtained was then converted from cal/g to MJ/kg using a conversion factor of 1 calorie = 4.184 joules.

3.3.5 Cetane Number

The Cetane Numbers of the fuel samples were determined using Near-Infrared (NIR) spectroscopy in accordance with ASTM E1655. The NIR spectra of two variants of diesel, whose Cetane numbers are already known, were measured between 1000 and 1600 using an NIR spectrophotometer. The spectra and the concentration data were then fed into the built-in software of the spectrophotometer and used to develop a calibration model using regression methodology. The model was then used to predict the Cetane Numbers of samples of diesel and its blends with WPO using an in-situ probe inserted in the containers.

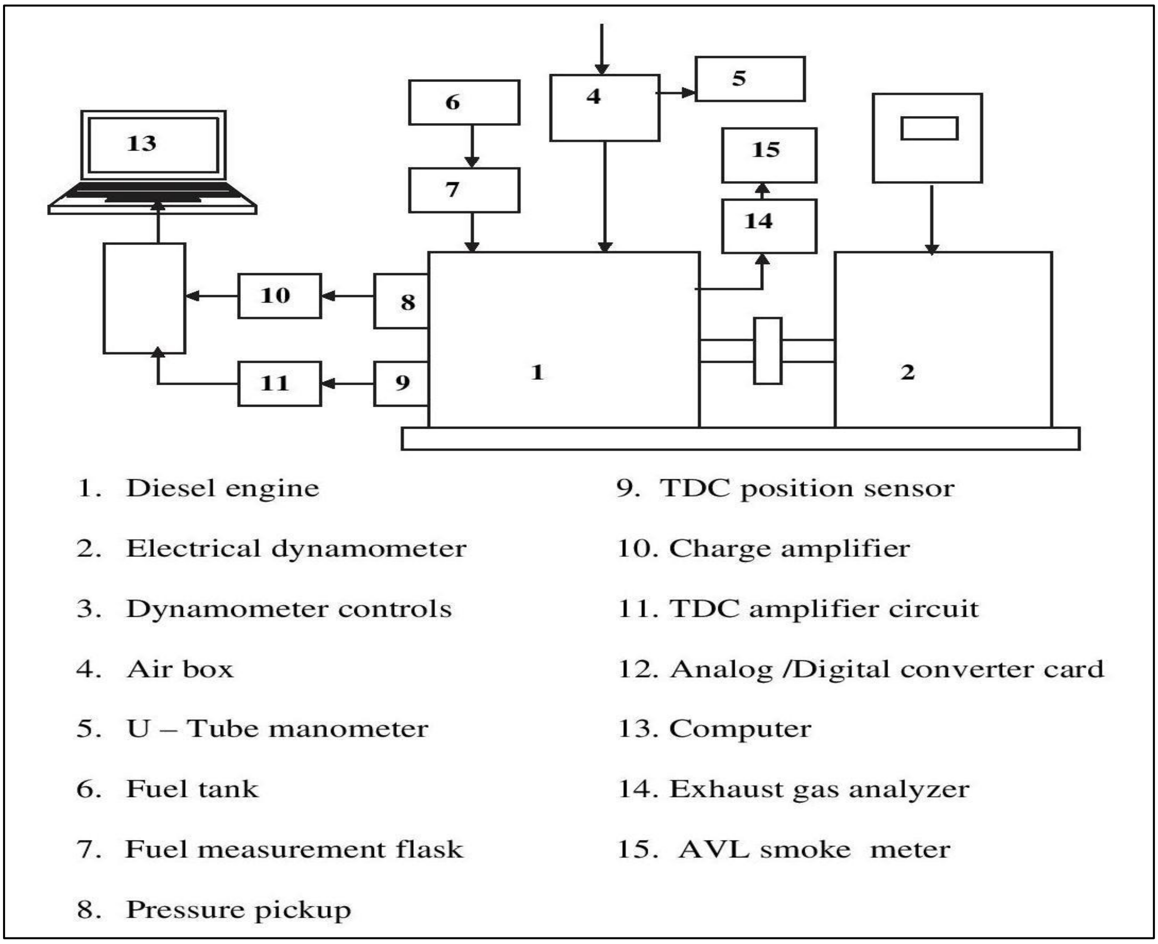
3.3.6 Flash and Cloud Points

The test fuels' flash point was determined through ASTM D 93, which involves the Pensky-Martens Closed Cup (PMCC) while the cloud point was determined using the ASTM D 2500 method.

3.4 Engine Performance Tests

3.4.1 Engine Set Up

The engine used for this study is a research-specific engine made in India by Kilorskar. It is a four-stroke, one-cylinder, reciprocating diesel engine. The engine was rated 3.5kW at 1500 rpm. The parameters of the test engine are shown in detail in the Tables 3.1, 3.2 and 3.3.



1. Diesel engine
2. Electrical dynamometer
3. Dynamometer controls
4. Air box
5. U – Tube manometer
6. Fuel tank
7. Fuel measurement flask
8. Pressure pickup
9. TDC position sensor
10. Charge amplifier
11. TDC amplifier circuit
12. Analog /Digital converter card
13. Computer
14. Exhaust gas analyzer
15. AVL smoke meter

Figure 3.2: A schematic diagram of the experimental set up

Table 3.1: Test Engine specifications

Name	Kirloskar
Type	Diesel 4-stroke, 1 cylinder
Rated Power	3.5 kW
Rated rpm	@ 1500 rpm
Compression Ratio	18:1
Combustion	Direct Injection
Bore, mm	87.5
Stroke, mm	110
Cubic capacity, cm^3	661.45
Connecting rod length, mm	234

Table 3.2: Combustion Parameters

Name	
Specific Gas Constant (kJ/kgK)	1.00
Air Density (kg/m3)	1.17
Adiabatic Index	1.41
Polytrophic Index	1.28
Number of cycles	10
Cylinder Pressure Reference	4
Smoothing	2
TDC reference	0

Table 3.3: Performance parameters

Name	
Orifice diameter (mm)	20
Orifice coefficient of discharge	0.60
Fuel pipe diameter (mm)	12.40
Ambient Temperature (^0C)	27.0
Pulses per revolution	360
Fuel type	Diesel, B20, B40, B60, B80 & WPO
Fuel density (kg/m^3)	As measured in the lab
Calorific value of fuel (kJ/kg)	As measured in the lab

The test engine was coupled to an eddy current dynamometer in order to determine the output of the engine over the entire range of operation during the study. The specifications of the test dynamometer are shown Table 3.4.

Table 3.4: Test dynamometer specifications

Name	
Type	Eddy current
Arm length, r (mm)	185
Fuel pipe diameter, mm	12.4
Orifice diameter, mm	20

Application of loads on the dynamometer was through turning a calibrated dial manually in order to control the amount of current entering the eddy current dynamometer. The loading on the dynamometer was in incremental loads of 2 kilogrammes. Several of the significant features of the engine set up are described below with the help of schematic diagrams.

3.4.2 Fuel System

The fuel system comprised of a fuel tank, filters, fuel lines and a prime pump, and an injector. Figure 3.3 shows the schematic diagram of the fuel system as used in the experimental set up. The fuel tank was raised to improve the flow of fuel by gravity. The primary and secondary filters prevented suspended particles in the fuel from reaching the injector pump thereby ensuring that the injector’s nozzle did not get blocked. The rate of flow of fuel was determined electronically using a built-in software in the computer that was connected to a pipette.

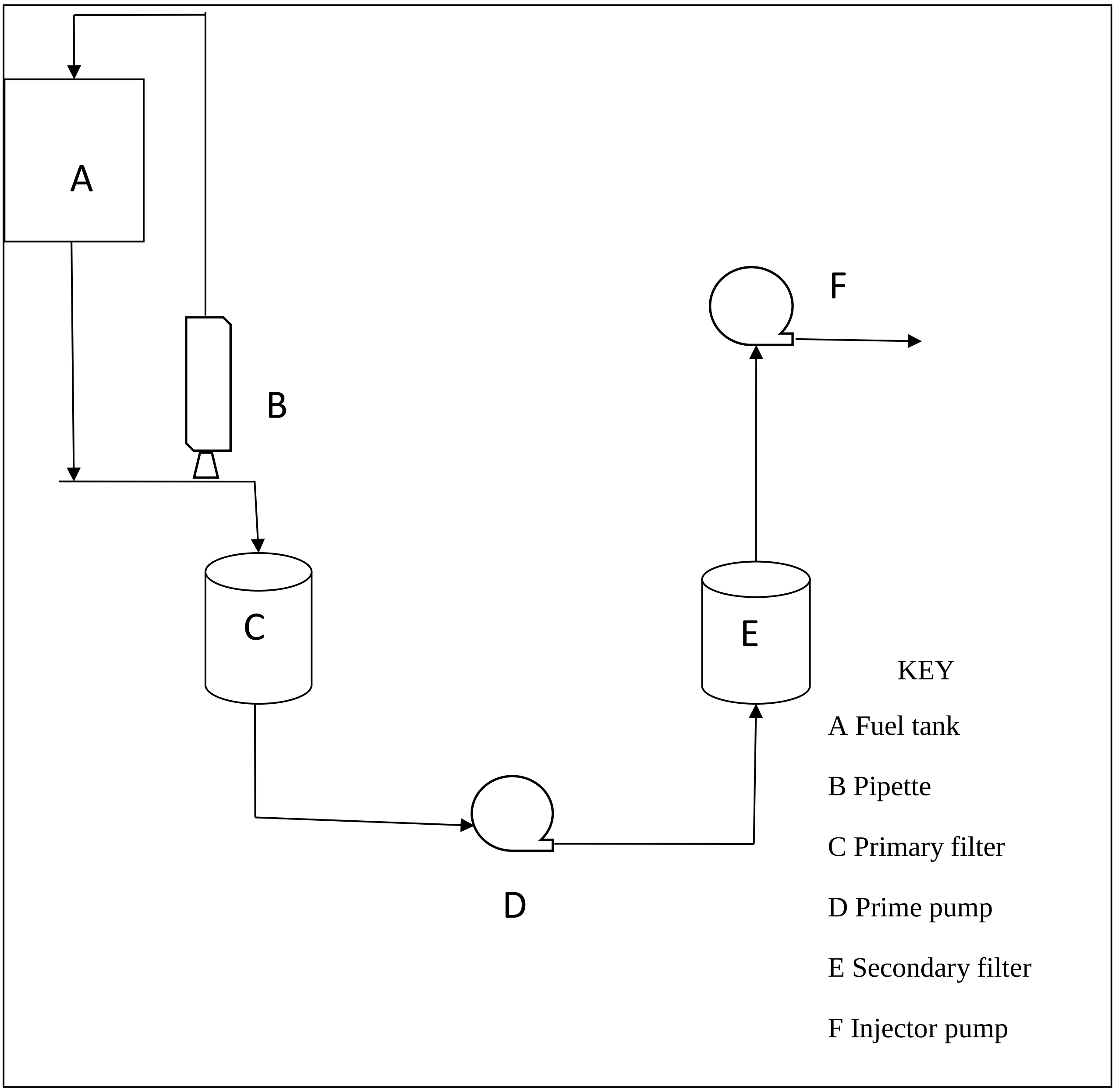


Figure 3.2: A Schematic diagram of the fuel system

3.4.3 Cooling System

The engine used cold water for cooling and an external water pump delivered the water at a constant flow from the supply. The external water circuit consisted of water tap and an external water pump. Thermocouples installed at the inlet and outlet of the engine relayed the inlet and outlet temperatures to a computer that then displayed the results in a tabulated form.

3.4.4 Exhaust Gas Temperature

The exhaust gas temperatures were measured by a thermocouple at the exhaust manifold of the engine. The result was then relayed to a computer electronically, which then displayed the information in a tabulated manner. The exhaust temperature was measured every time the load was increased for every fuel blend and compared to that of engine operation using pure diesel.

3.4.5 Engine Emissions

Engine emissions were measured using a heavy-duty ECON J2KN gas analyser. The setup of the engine, dynamometer, gas analyser and computer were as shown in Figure 3.2.

3.5 Engine Trials

The engine used for the study was accessed at the Thermodynamics Laboratory of the Mechanical Engineering Department of the Jomo Kenyatta University of Agriculture & Technology. It was a one cylinder, 4-stroke diesel-powered engine and was rated 3.5 kW at 1500 rpm. Preliminary engine tests, using pure diesel, for familiarization indicated that normal engine runs were achievable for the rated speed. In addition, full load tests carried out at varying speeds indicated good repeatability at 1500 rpm. Consequently, this study was carried out at 1500 rpm.

3.5.1 Pre-test Procedure

Prior to carrying out the tests, the engine was warmed for approximately seven minutes to the suggested operational temperature of cooling water. The warming up was achieved by running the engine on pure diesel at idle speed for approximately seven minutes.

The engine was operated at a constant speed of 1500 rpm while the loading was adjusted with increments of 2 kg beginning with an initial load of 0.2 kg. Incremental loading of the engine continued until the running of the engine became irregular and the speed started being inconsistent. The rate of fuel consumption and temperatures of the exhaust gases were recorded for each load. The above steps were repeated for all the blended fuel samples under investigation and the data acquired used to determine the engine's torque, brake power (BP), brake specific fuel consumption (BSFC) and brake thermal efficiency (η_{th}).

3.5.2 Engine Rotational Speed

The engine speed in rpm was displayed in a digital dial on the control panel. In addition, a computer that tabulated the speed in rpm to the corresponding load also recorded the speed. The procedure was repeated for the entire range of pure diesel and WPO blended fuels under study.

3.5.3 Fuel Consumption

Although fuel consumption could be determined manually by timing the flow of fuel through a calibrated pipette, it was done electronically. The computer, using a specialised software, calculated the flow rate of fuel through the pipette in cm^3/min for every corresponding load. The procedure was repeated for the entire range of pure diesel and WPO blended fuels.

3.5.4 Brake Torque

Torque was calculated from the moment of engine arm connected to weight scale as shown in Equation 3.5 (Taylor, 1985).

$$T = fxd \tag{3.5}$$

Where:

T is brake torque in Nm

F is force of engine arm applied to the load in N

d is the distance of engine arm from the centre of the rotor to the load.

3.5.5 Brake Power (BP)

An electrical dynamometer was used in this study, and the brake power was calculated using Equation 3.6 (Taylor, 1985).

$$BP = \frac{2\pi NT}{60x1000} \tag{3.6}$$

Where:

BP is engine brake power in kW

N is the angular speed of the engine in rpm

3.5.6 Brake Specific Fuel Consumption

Brake specific fuel consumption refers to the mass flow rate of fuel consumed per unit power output. It is a significant criterion for economic power production and is expressed in kilograms per kilowatt-hour (kg/kWh). The BSFC was determined using Equation 3.7 (Taylor, 1985).

$$BSFC = \frac{Mx3600}{txBP} \tag{3.7}$$

Where:

BP = Brake power in kW

M = mass of fuel in kilograms

t = time used to consume mass of fuel in seconds

3.5.7 Brake Thermal Efficiency (η_{th})

Brake thermal efficiency expresses the power output of an engine as a fraction of the power obtained from the chemical energy of the fuel supplied. It expressed as shown in Equation 3.8 (Taylor, 1985).

$$\eta_{\mathrm{th}} = \frac{\mathrm{BPx100}}{\mathrm{P_{in}}} \tag{3.8}$$

Where:

η_{th} = thermal efficiency, %

P_{in} = power input

$$= \frac{\text{Energy input}}{\text{Time, t}}$$

and Energy input = Mass of fuel x Calorific value of fuel

3.5.8 Engine Emission Analysis

The analysis of engine emission was performed using a heavy-duty ECON J2KN gas analyzer. The analyzer was fitted with five sensors to measure O_2, CO, CO_2, NO, NO_2, NO_x, SO_2 and combustibles. In addition, the analyzer was fitted with temperature sensors to measure both exhaust gas and ambient temperatures. The concentration of NO, NO_2, NO_x and SO_2 in the emissions was measured in parts per million (ppm) while that of O_2, CO and CO_2 were measured in percentage.

3.6 Economic Analysis

Comparison of the use of WPO and diesel cannot be complete without performing an energy cost and sensitivity analysis. The cost of producing waste plastic oil locally was determined using the methodology shown in Table 3.5 (Wongkhorsub & Chindaprasert, 2013).

3.6.1 Fuel Production Cost Analysis

The investment and expenses of the pyrolysis machine were analysed in order to estimate the production cost of WPO as shown in Table 3.5. The input of the locally assembled pyrolysis machine was one ton per day. The waste plastics used were of the High-Density Polyethylene (HDPE) type and were collected from recycling centres and landfill sites around Kariobangi and Dandora.

Table 3.5: Estimating the Production Cost of WPO

Type of Cost	Unit	Waste Plastic Oil	Pure Diesel
Total Capital Cost	Kshs		
Capital cost	Kshs/day		
Expenses			
Feedstock Expenses	Kshs/day		
Operating Expense	Kshs/day		
Maintenance Expenses	Kshs/day		
Labour Expense	Kshs/day		
Utilities Expense	Kshs/day		
Taxes, Insurance	Kshs/day		
Total Expenses	Kshs/day		
Profit 30%	Kshs/day		
Total production	Kshs/day		
Oil production	Litre/day		
Production cost	Kshs/litre		

Source: Wongkhorsub & Chindaprasert (2013)

3.6.2 Energy Cost Analysis

The efficiency of engine performance varies often, depending on the type of fuel. Therefore, the indicator that is more applicable to all situations in predicting the use of oil in view of economic analysis should be the energy consumption cost per power output calculated using Equation 3.9 (Wongkhorsub & Chindaprasert, 2013).

$$\varphi_E = b_{sfc} x \frac{Cost_{wpo}}{\rho_{wpo}} \tag{3.9}$$

Where:

φ_E is the cost of energy consumption per power output in Ksh/kWh,

b_{sfc} is the brake specific fuel consumption in kg/kWh

$Cost_{wpo}$ is the cost of waste plastic oil in ksh/kg

ρ_{wpo} is the density of waste plastic oil kg/m^3

CHAPTER FOUR

RESULTS AND DISCUSSION

This chapter will illustrate and discuss the results of the study in line with the objectives of the study. It will outline the fuel properties of diesel, WPO and blends as determined during laboratory tests. Secondly, the chapter will discuss the results of the performance tests with the aim of determining the suitability of WPO and its blends with diesel as alternative fuels to diesel. Thirdly, the chapter will discuss the emission results obtained during an analysis conducted using a specialized gas analyzer with the aim of determining the most suitable fuel for running an engine with minimal adverse impact on the environment. Lastly, the chapter will tabulate and discuss the results of the economic analysis carried out during the study.

4.1 Properties of Diesel, WPO and Blends

4.1.1 Density

Using the specific gravity method, the densities of diesel, waste plastic oil and their blends at different temperatures were determined and recorded as shown in Table 4.1

Table 4.1: Density of Pure Diesel, WPO and Blends at Different Temperatures

Temp (^{0}C)	**Density (kg/m^3)**					
	Diesel	B20	B40	B60	B80	WPO
15	837	823	815	800	793	780
20	834	821	811	796	781	776
25	829	819	808	793	774	771
30	826	817	800	792	770	764
35	821	813	799	790	765	760
40	817	802	796	784	761	756
45	812	798	793	782	760	752
50	811	792	789	784	759	741
55	796	783	780	763	751	739
60	791	780	773	768	746	732

The standard test method EN 3675 was used to determine the density of the diesel fuel, as well as WPO and its blends. The experimental data were correlated by the empirical linear equation obtained from regression analysis. The mathematical expression of the equation as a function of the WPO fuel fraction was given as shown in Equation 4.1

$$\rho = Ax + B \tag{4.1}$$

Where: ρ is the density expressed in kg/m3

x is the quantity of WPO fuel fraction in blends

A and B are regression coefficients (A is slope of the line and B the intercept).

Using regression analysis on Microsoft excel, the regression coefficients were determined as: A= - 0.55714 and B = 835.857 at 15^0C and A = -0.60714 and B = 833.5238 at 20^0C. Therefore, Equation 4.2 shows the linear empirical equation between the fraction of WPO in fuel sample and the density at 15^0C while equation 4.3 represents the linear relationship between the fraction of WPO in the blended fuel and the density of the blended fuel at 20^0C.

$$\rho = 835.857 - 0.55714x \tag{4.2}$$

$$\rho = 833.5238 - 0.60714x \tag{4.3}$$

Table 4.2 shows the results of the experiment and represents both experimental and calculated values from Equation 4.2 and Equation 4.3.

Table 4.2: Calculated and Measured Densities of WPO and Blends at 15^0C and 20^0C

WPO (%)	$\rho_{15\ exp}$ (kg/m^3)	$\rho_{15\ calc}$ (kg/m^3)	$\rho_{20\ exp}$ (kg/m^3)	$\rho_{20\ calc}$ (kg/m^3)
0	837	835	834	833
20	823	824	821	821
40	815	813	811	809
60	800	802	796	797
80	793	791	781	784
100	780	780	776	772

It was observed that the densities of the blended fuel samples decreased with increase in the percentage of WPO in the blend at all temperatures and decreased with increase in temperature for all the fuel samples under test. The results that were obtained clearly indicate that the density of pure diesel oil is higher than the density of WPO and their blends. Lee et al. (2015) established the same finding. There was a linear decrease in density with increasing ratio of WPO fuel in the blended fuel as shown in Figure 4.1.

The American standard methods ASTM D287 and ASTM D 1298, the European standard methods EN 3675 and EN 12185, and the Kenya Bureau of Standards (KEBS) standard KS 1309-1 specify the range of density of pure diesel as 820-870 kg/m^3 at 20^{0}C. Obviously, the obtained WPO is the lightest (first) fraction with a density range of 776-780 kg/m^3 at 20^{0}C. The densities of both pure Diesel and B20 fuel blend were within the specifications of all the standards at a temperature range of 15-25 ^{0}C. As such, WPO can be used for mixing with heavier diesel fraction, such as diesel, with density of approximately 850 kg/m^3 in order to obtain a fuel with a higher density. A higher density is associated with high cetane number and is desirable because it indicates complete combustion due to lack of ignition delay (Guibet, 1997).

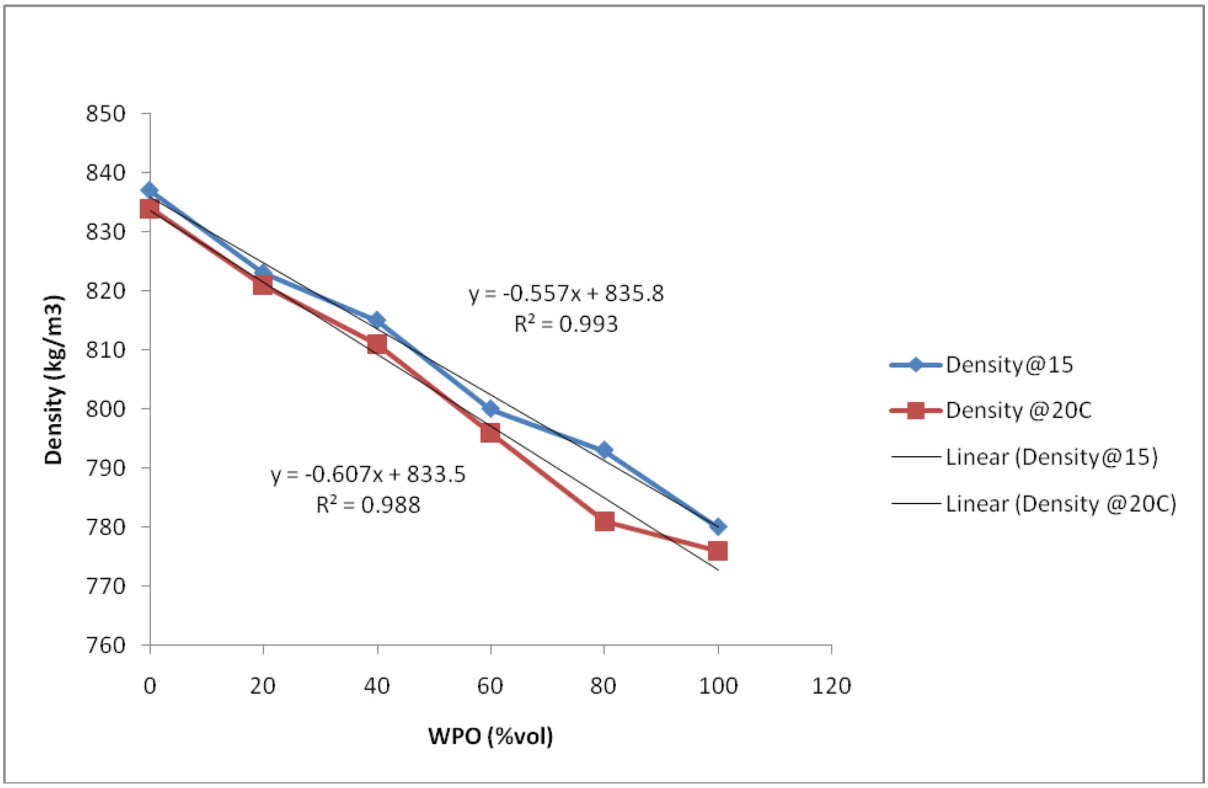


Figure 4.1: Regression Analysis of Density of WPO-Diesel Blended Fuels

4.1.2 Viscosity

The standards EN ISO 3104:1996 or ASTM D445 are usually used to determine kinematic viscosity and calculate dynamic viscosity. The limits for viscosity of fuels ensure that a fuel will flow easily during cold starting. Often, a minimum limit is specified to avoid the possibility of a serious power loss at high temperatures. The test measurements for kinematic viscosity were performed at 40^0C and values recorded as shown in Table 4.3.

Table 4.3: Viscosities of WPO-Diesel Blends at various Temperatures

Temperature (^{0}C)	**Viscosity, mm/s^2**					
	Diesel	**B20**	**B40**	**B60**	**B80**	**B100**
15	5.71	5.37	5.17	4.99	4.37	3.95
20	5.43	5.16	4.73	4.28	3.88	3.54
25	5.03	4.94	4.41	3.73	3.01	2.88
30	4.84	4.61	3.98	3.21	2.49	2.42
35	4.52	3.62	2.94	2.64	2.18	2.01
40	3.95	3.1	2.62	2.17	1.98	1.44
45	3.89	2.84	2.52	2.14	1.77	1.42
50	3.61	2.69	2.44	2.04	1.68	1.37
55	3.42	2.52	2.36	1.94	1.55	1.34
60	3.38	2.48	2.17	1.76	1.35	1.28

Both linear equation and polynomial equation of second order did not fit the data well. As such, an empirical polynomial equation of third order was used to correlate the experimental data as a function of the fraction of WPO. Equation 4.4 shows the mathematical expression of the equation as a function of the fraction of WPO in the blends.

$$v = Ax^3 + Bx^2 + Cx + D \qquad (4.4)$$

Where ν is the kinematic viscosity (mm/s^2) and A, B, C and D are coefficients

x is the fraction of WPO in blended fuel

Using polynomial regression analysis on Ms Excel, the following coefficients of a third order polynomial equation were obtained: A = -4.1E-06, B = -0.00074, C = 0.0579 and D = 3.9426. The viscosity of pure diesel is higher than the viscosity of the obtained WPO and its blends. Blending of alternative waste plastic oil with pure diesel has a measurable effect on viscosity of the blended fuels. The experimental value of kinematic viscosity for pure diesel at 40^0C was 3.95 mm^2/s and was higher than the measured viscosity of WPO at the same temperature, $\nu = 1.44$ mm^2/s (Table 4.3).

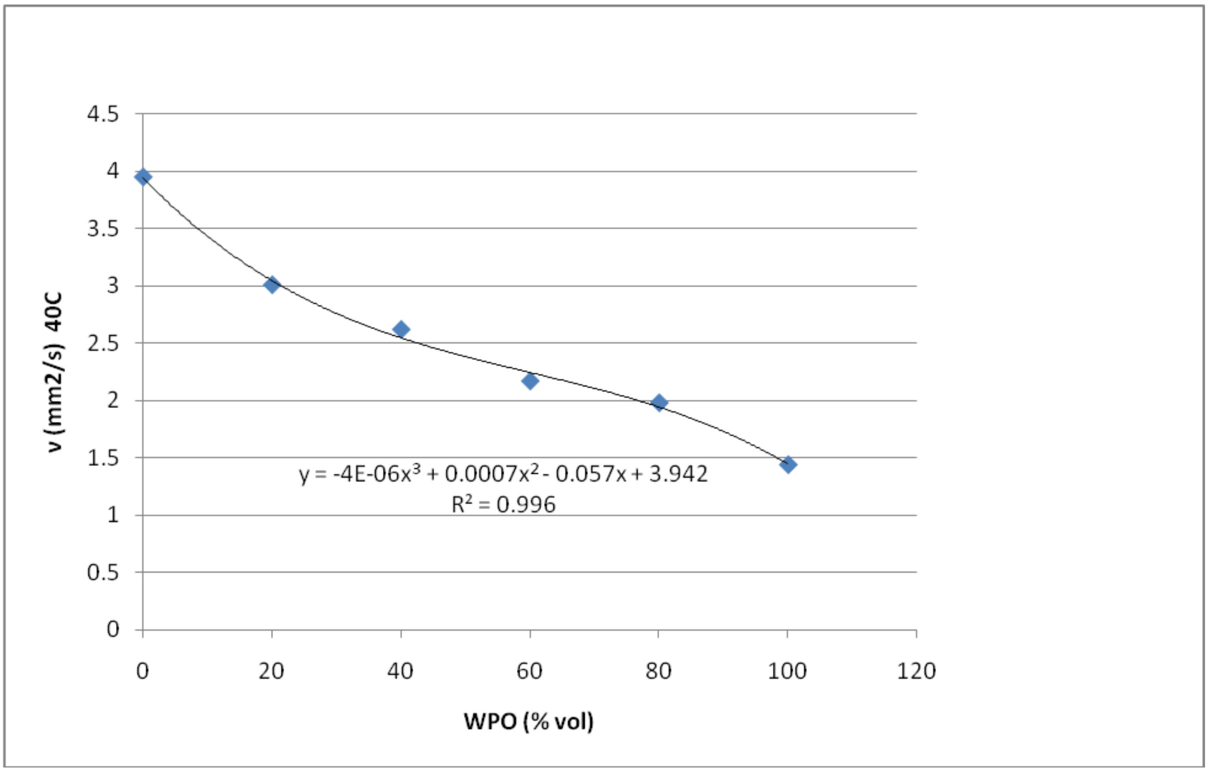


Figure 4.2: Viscosity of WPO-Diesel fuel blends at 40^0C

As observed in Figure 4.2, the viscosity of the fuel blends decreases with an increase in the fraction of WPO in the blends. However, the effect of the presence of WPO in the fuel blends is less significant in the middle fractions of between 40% and 80%. The above graph depicts that a polynomial relationship of the third order is a good fit for the experimental data. The final values of kinematic viscosity obtained from the experiments (Table 4.3) indicate that all the WPO-Diesel blends are within the limits of the standard ASTM D 445. However, WPO, with a viscosity of 1.44 mm^2/s, does not meet the minimum limit of 1.9 mm^2/s and is therefore not suitable for use on its own as it could lead to fuel leakages and poor lubrication of the engine.

Table 4.4 shows selected properties of diesel and its blends with WPO as determined in laboratory analysis during the study.

Table 4.4: Selected Properties of Diesel and its blends with WPO

Property	Units	Diesel (DF2)	B20	B40	B60	B80	WPO
Density @ 15^{0}C	Kg/m^3	837	823	815	800	793	780
Viscosity @ 40^{0}C	mm^2/s	3.95	3.01	2.62	2.17	1.98	1.44
Flash Point	^{0}C	54	47	41	35	29	24
Heating Value	MJ/kg	42.63	43.05	43.45	44.02	44.70	44.86
Lubricity	µm	480	424	390	357	330	300
Cetane No		56.20	52.3	48.1	46.3	44.6	42
Cloud Point	^{0}C	-16	-10	-2	0.72	2	4
Pour Point	^{0}C	-19	-15.3	-12	-10	-9	-7
Water Content	% Vol	0.05	0.05	0.074	0.97	0.12	0.16
C	%	85	77	71	68	61	58
H	%	11	9.6	9.1	8.4	7.1	5.7
O	%	1.0	2.8	4.9	8.7	13.2	23
N	%	ND	ND	ND	ND	ND	0.2
S	%	0.015	0.017	0.017	0.019	0.2	0.26
Oxidation Stability at 110^{0}C	h	7.52	7.01	6.84	6.7	6.3	6.3

4.1.3 Heating Value

The calorific or heating value is one of the most important properties of a fuel and serves as indicator of the amount of energy that is released after combustion. The heating (calorific) values of the diesel, WPO, and WPO-Diesel blends were determined using the Bomb

Calorimeter method and their experimental values recorded as shown in Table 4.4. As shown in the table, the calorific value of WPO was determined as 44.86 MJ/kg while that of Diesel was determined as 42.63 MJ/kg. The study established a correlation between the heating value of the blended fuels and fraction of WPO in the blended fuels in the form of a linear equation as shown in Equation 5.4 and is represented in Figure 4.3

$$CV = Ax + B \qquad (4.5)$$

Where CV is the Heating/Calorific Value of fuel in MJ/kg

A & B are coefficients (A is slope of the graph and B the Y intercept)

x is the fraction of WPO in the blended fuel

Using linear regression on Ms Excel, the values of A and B were determined as 0.023 and 42.59 respectively. The value of R^2 was 0.984, which showed a good fit of the trend line. The heating value of pure diesel is lower than the heating value of the obtained WPO and its blends. From the study, it was observed that blending diesel with WPO improved its heating value.

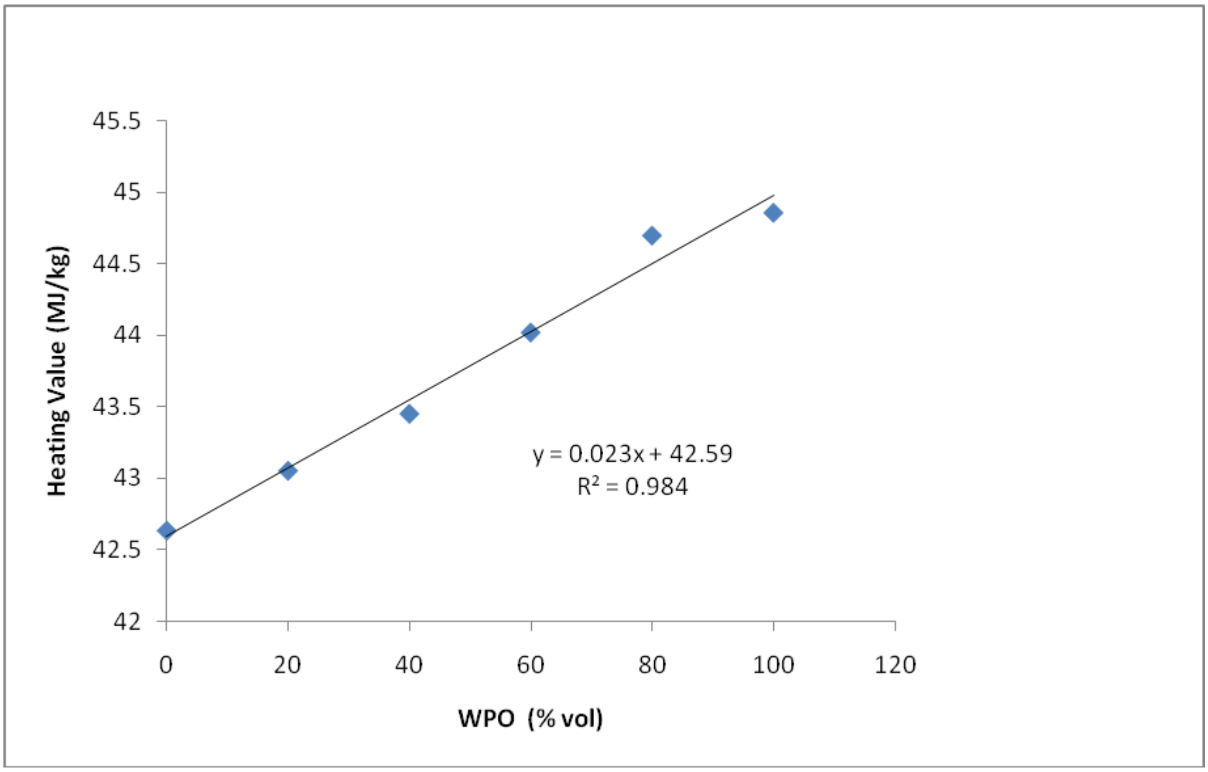


Figure 4.3: Heating Value versus % WPO in blended fuels

4.1.4 Ignition Quality

The Cetane Numbers of Diesel, WPO and WPO-Diesel blends were calculated using Near Infrared (NIR) spectroscopy method. Table 4.4 shows the values of Cetane No as obtained during the study. The Cetane Number (CN) of WPO was determined as 42 while that of Diesel was determined as 56.20. However, blending WPO with Diesel improved its CN. The study established a correlation between the variation of the CN of a fuel and the fraction of WPO in a blended fuel in the form of a linear equation as shown by Equation 4.6.

$$Ce\tan eNo = Ax + B \tag{4.6}$$

Where A and B are coefficients (A is the slope of the equation and B the Y intercept)

x is the fraction of WPO in the blended fuel

Using linear regression on Ms Excel, the values of A and B were determined as 0.137 and 55.1 respectively. An R^2 value of 0.967 shows a relatively good fit of the linear equation.

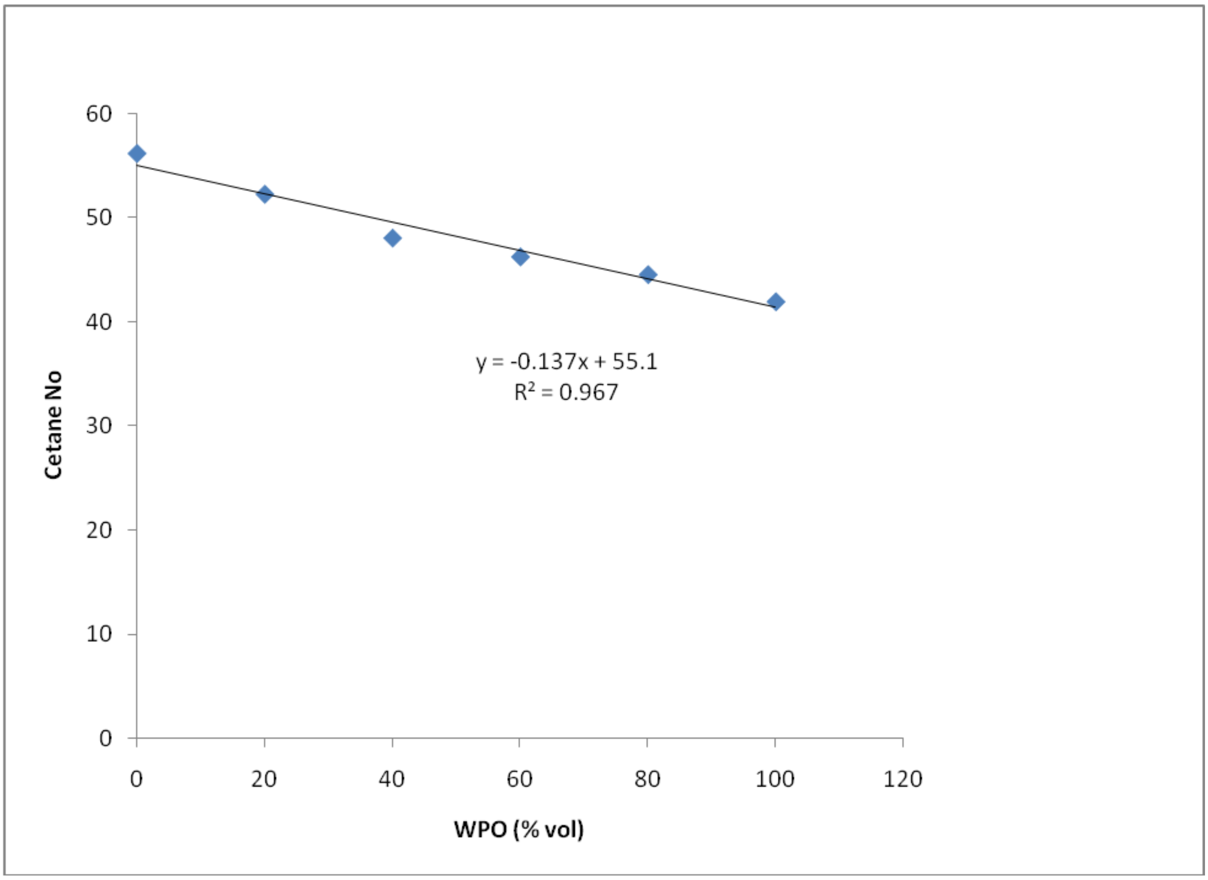


Figure 4.4: Cetane versus % WPO in Diesel-WPO Blends

Figure 4.4 shows that the Cetane No of the fuel blends decreased with increase in fraction of WPO in the Diesel-WPO blends. However, all the Cetane No's of the WPO-Diesel blends were determined to meet the minimum value of 40 as stipulated by the ASTM D 613 method. Therefore, WPO and its blends with Diesel have good ignition quality and can be readily used in compression ignition engines.

4.1.5 Flash Point

The flash point of the WPO-Diesel blends was determined using ASTM D 93, which is Flash Point by the Pensky-Martens Close Cup (PMCC) method and the values obtained listed in table 4.4. Only the Flash Point of Diesel (54^0C) was found to meet the minimum limit of 52^0C as stipulated by ASTM D 93. The Flash Point of WPO and its blends with Diesel ranged between 24^0C and 47^0C, and was found to be below the minimum limit of 52^0C for diesel. It was observed that the flash point decreased with increase in fraction of WPO in the test fuels. From Figure 4.5 and assuming a linear relationship between the variation of flash point and fraction of WPO in the blends, then the maximum allowable fraction of WPO in the blend is 5%.

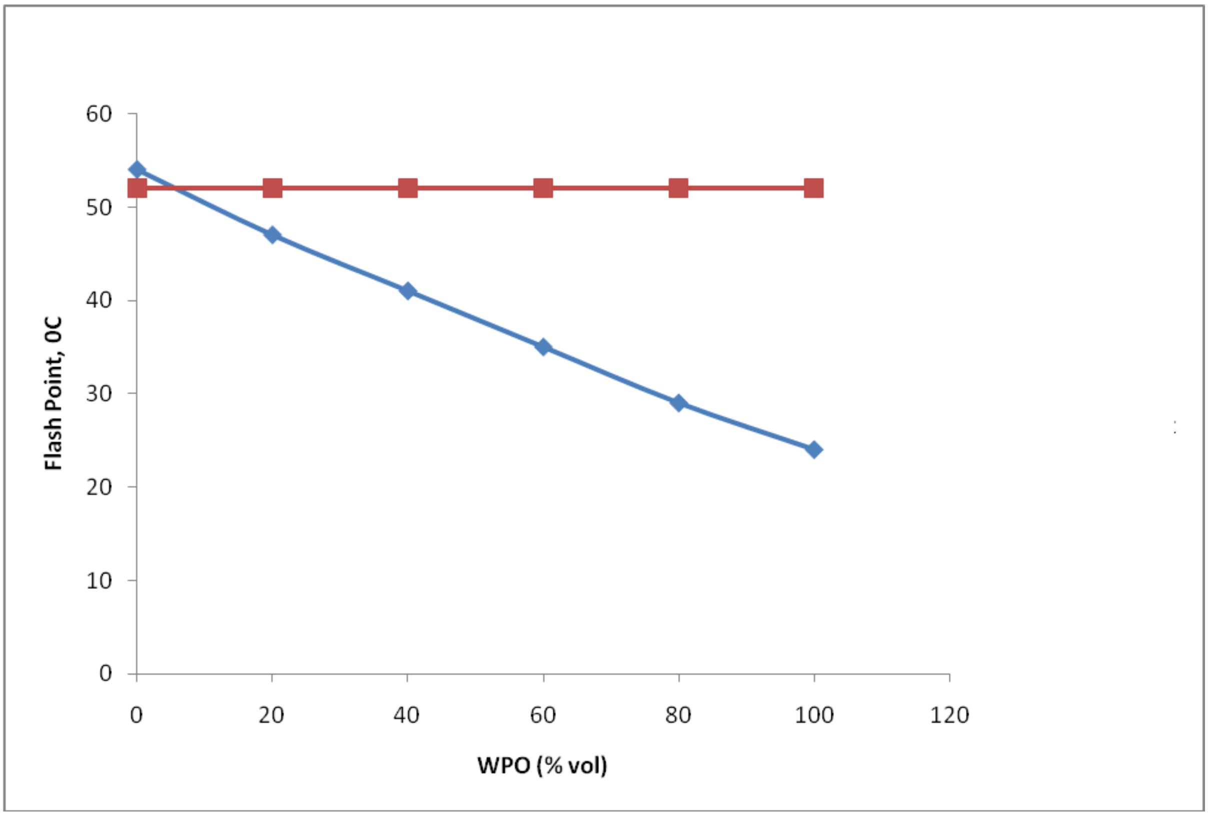


Figure 4.5: Flash Point versus % WPO in Diesel-WPO Blends

4.2.6 Cold Temperature Characteristics

The cloud point was used to characterize the cold temperature characteristics of diesel, WPO and WPO-Diesel blends. The test was conducted according to European standard EN 23015 method and the values recorded in Table 4.4. The EN 25015 standards stipulate that the cloud point should be 6^0C higher than the tenth percentile minimum ambient temperature of the region. Therefore, a temperature range of -10^0C to 4^0C may be acceptable for use of the blended fuels in this region.

4.2.7 Sulphur Content

The sulphur content of the test fuels was determined using the ASTM D 5453 method and the values recorded as shown in Table 4.4. It was observed that WPO had the highest amount of Sulphur by mass of 0.026% while diesel had the lowest amount of Sulphur of 0.015%. The Sulphur content of all the test fuels, including the blends, fell within the maximum limit of diesel grade 2 of 0.5%. It was observed that the sulphur content increased with increase in fraction of WPO in the blended fuels as shown in Figure 4.6. However, the effect of WPO in the blends is not significant for small fractions, up to 40%. A correlation between the variation of sulphur content and the fraction of WPO in the blends was established in the form of a second order polynomial equation using regression analysis as shown in Equation 4.7.

$$SulphurContent = Ax^2 + Bx + C \tag{4.7}$$

Where A, B and C are coefficients

x is the fraction of WPO in the blended fuel

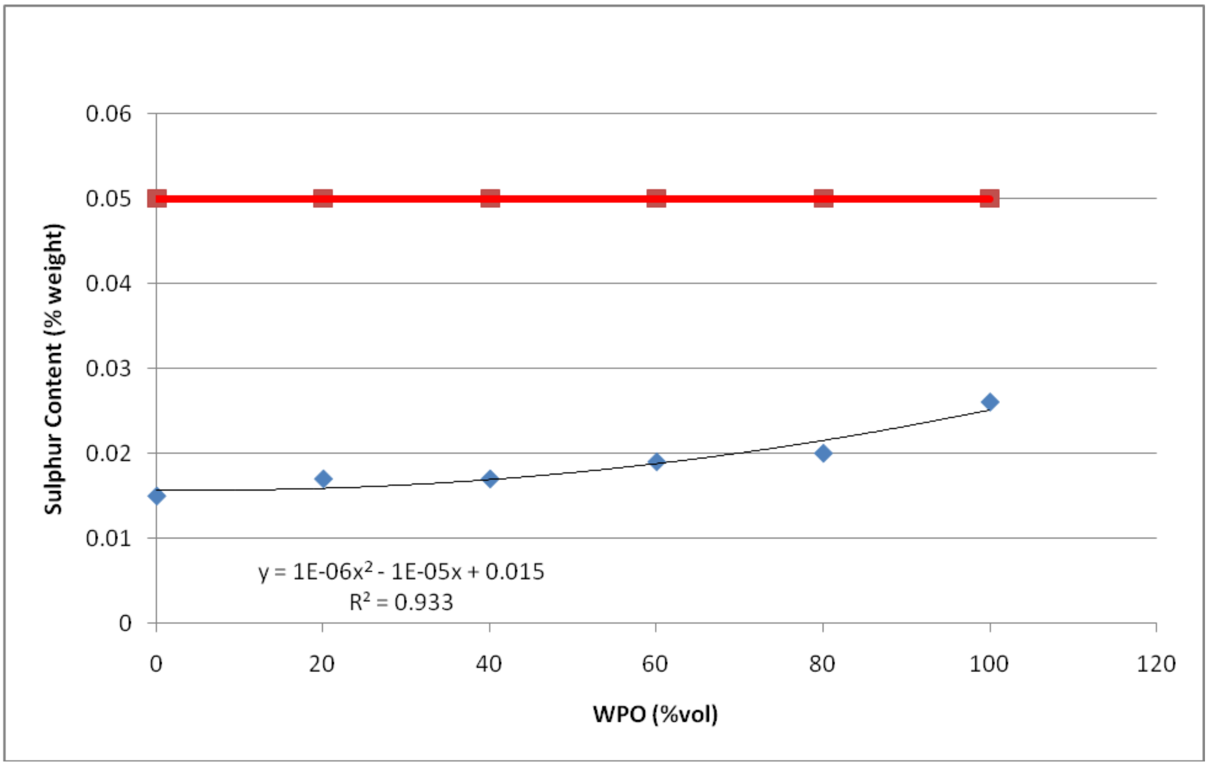


Figure 4.6: Sulphur Content versus % WPO in Blended Fuels

4.2 Engine Performance

The performance of the engine when using diesel, WPO and its blends with diesel was evaluated with respect to brake specific fuel consumption, brake thermal efficiency and exhaust gas temperature.

4.2.1 Effect of blending on Brake Specific Fuel Consumption (BSFC)

From Figure 4.7, the BSFC for diesel, WPO and its blends with diesel decreased with increasing brake power up to about 1 kW after which it levelled. The BSFC subsequently started rising when the engine approached 80% of the rated loading, which is a typical trend of the BSFC curve for the CI engine. The BSFC decreased with increase in the fraction of WPO in the blended fuels. The BSFC of diesel was marginally higher than that of WPO and its blends with diesel for the entire range of loading of the engine, except for B40 which was considered an outlier due to a possible experimental error. It was observed that blending diesel with WPO improved its BSFC. The higher BSFC value for diesel was attributed to its high density compared to the densities of WPO and its blends. Since the fuel injection system of the engine is calibrated to inject a fixed volume of fuel, the use of the less dense WPO and its blends resulted in less fuel mass being injected into the engine leading to lower BSFC.

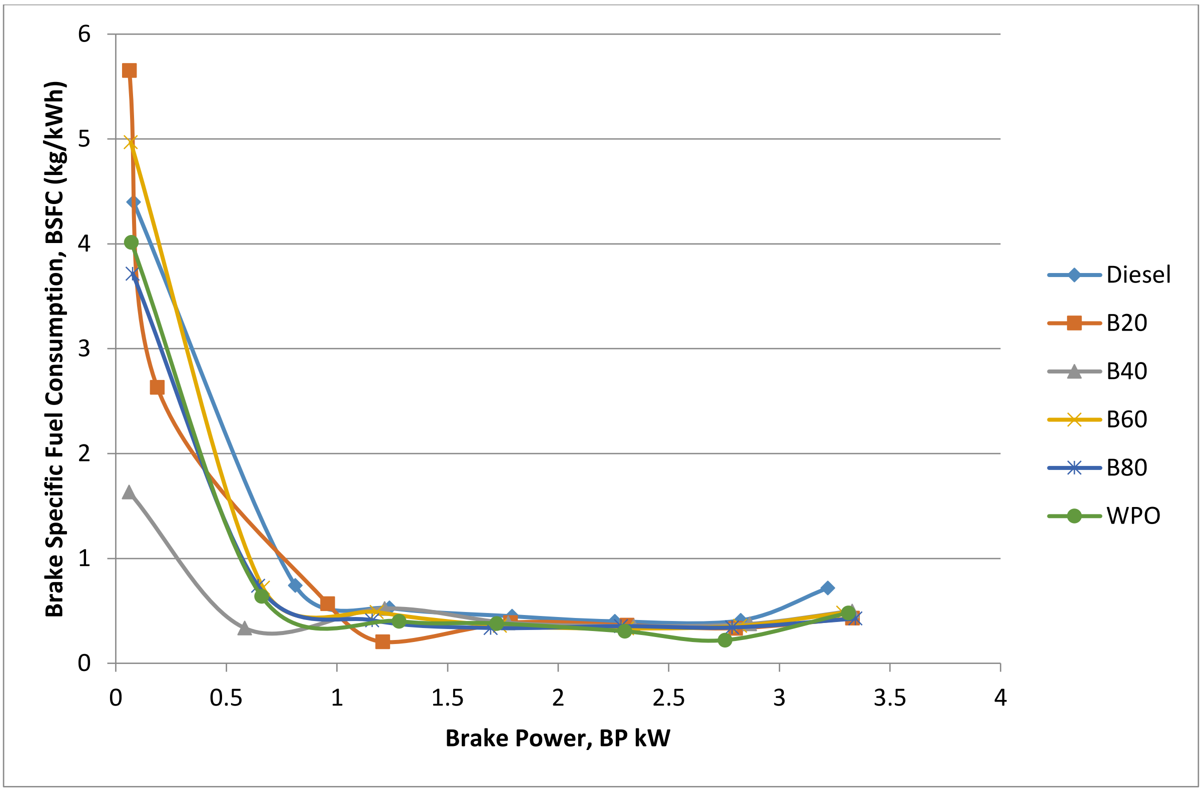


Figure 4.7: Brake Specific Fuel Consumption versus Brake Power for Diesel, WPO and Blends

4.2.2 Effect of blending on Brake Thermal Efficiency

As shown in Figure 4.8, the brake thermal efficiency for diesel, WPO and its blends with diesel increased with increasing brake power up to about 80% of the rated brake power after which it started decreasing, which is a typical trend of the brake thermal efficiency curve for the CI engine. The brake thermal efficiency increased with increase in the fraction of WPO in the blended fuels. The brake thermal efficiency of WPO and its blends with diesel was significantly higher than that of diesel for the entire range of loading of the engine. As a result, it was observed that blending WPO with diesel had a significant improvement on the brake thermal efficiency of the test fuels. The lower brake thermal efficiency value for diesel was attributed to its high brake specific fuel consumption compared to that of WPO and its blends.

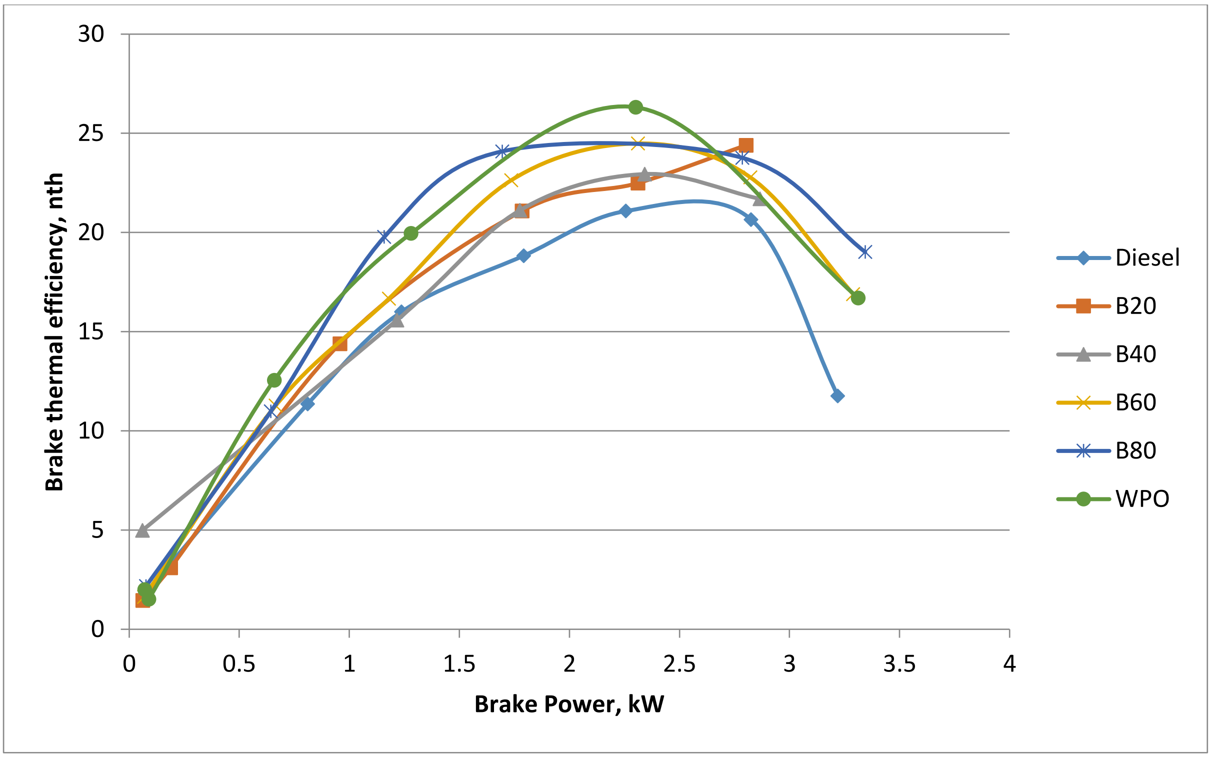


Figure 4.8: Brake Thermal Efficiency against Brake Power for Diesel, WPO and Blends

4.2.3 Effect of Blending on the Exhaust Temperature

As shown in Figure 4.9, the exhaust temperatures for diesel, WPO and its blends increased with increase in brake power. It was observed that the exhaust temperatures for diesel were significantly lower than those for both WPO and its blends with diesel. This observation could be attributed to the higher calorific value and low Cetane Number of WPO.

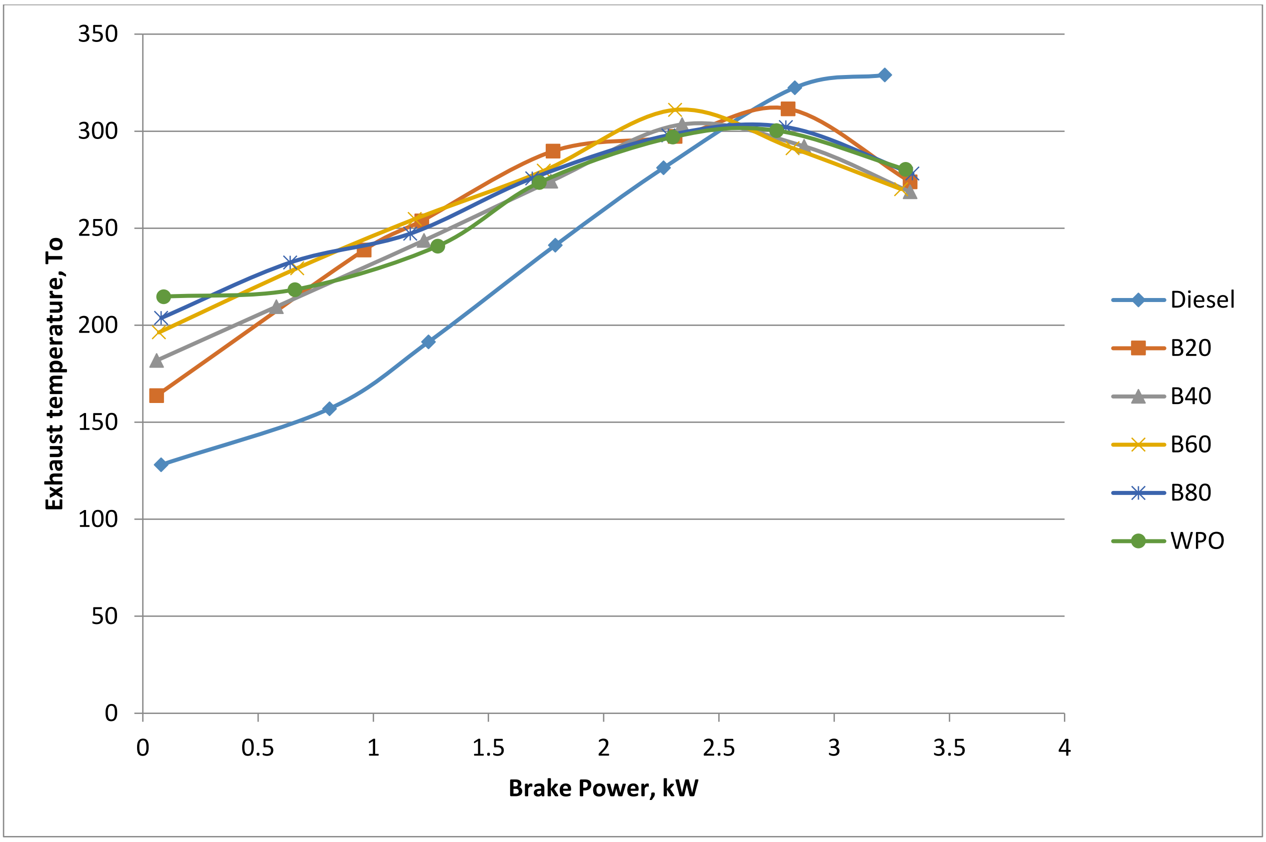


Figure 4.9: Exhaust Temperature versus Brake Power for Diesel, WPO and Blends

4.3 Engine Emissions

The emissions of the engine when using diesel, WPO and its blends with diesel were evaluated with respect to oxides of Nitrogen, carbon monoxide, carbon dioxide, oxygen and sulphur dioxide.

4.3.1 Nitrogen Oxides (NO_x) Emissions

Figure 4.10 shows the variation of Nitrogen Oxides with brake power for diesel, WPO and its blends with diesel. It can be observed that the amount of Nitrogen Oxides increases with an increase in brake power for diesel, WPO and WPO-Diesel blends. Higher peaks loads are associated with high peak pressures, and thus temperatures, leading to increased levels of Nitrogen Oxides. Further, it was observed that the level of nitrogen dioxide emission for WPO operation was higher in the entire loading range compared to the level of NO_x emission during operation with diesel. The reason for the increased NO_x emissions during WPO operation is the higher heat release rate. WPO as a fuel is associated with a higher aromatic content and a ring structure. According to Mani et al. (2011), fuels with a ring structure often possess a higher adiabatic flame temperature thus leading to higher heat release rates.

Because of the high release rate, the in-cylinder temperature increases with increase in fraction of WPO in the WPO-Diesel blend.

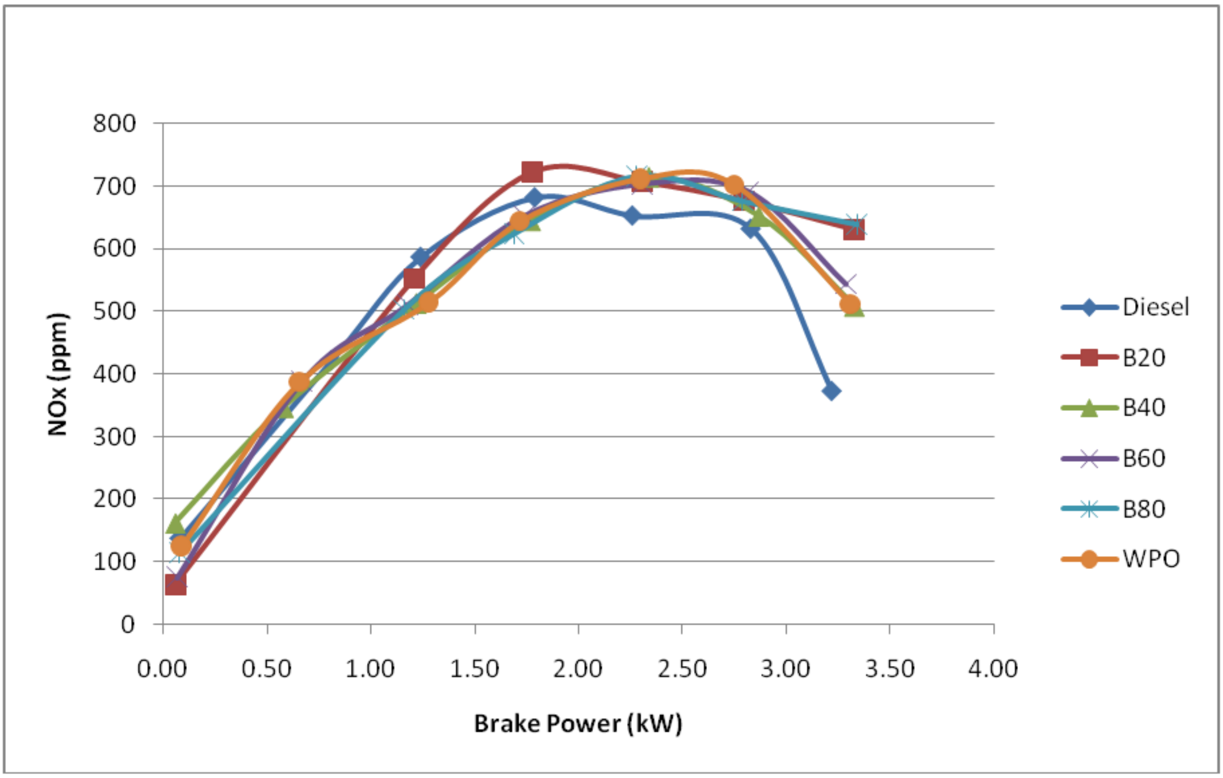


Figure 4.10: Nitrogen Oxides (NO_x) versus Brake Power for Diesel, WPO and Blends

4.3.2 Carbon Monoxide Emissions

The emission of Carbon Monoxide (CO) is primarily because of the lack of Oxygen, poor entrainment of air, preparation of mixture and incomplete burning during the combustion process (Mani et al., 2011). Consequently, the emission of carbon monoxide is highly dependent on the equivalence ratio; a rich mixture results in high CO emission level, and vice versa. Usually, CI engines run with lean mixtures and thus the level of emission of CO will be low.

Figure 4.11 shows the variation of carbon monoxide emission with brake power for diesel, WPO and its blends with diesel. It was observed that CO emissions for diesel, WPO and its blends with diesel were higher at lower loads before decreasing at the 80% range of operation. This can be attributed to air and fuel achieving a stoichiometric ratio leading to lean combustion. Further, it was observed that the amount of CO emission for WPO and its blends with diesel was higher than that during diesel operation. This can be attributed to local rich regions, poor preparation of mixture and reduced in-cylinder temperatures.

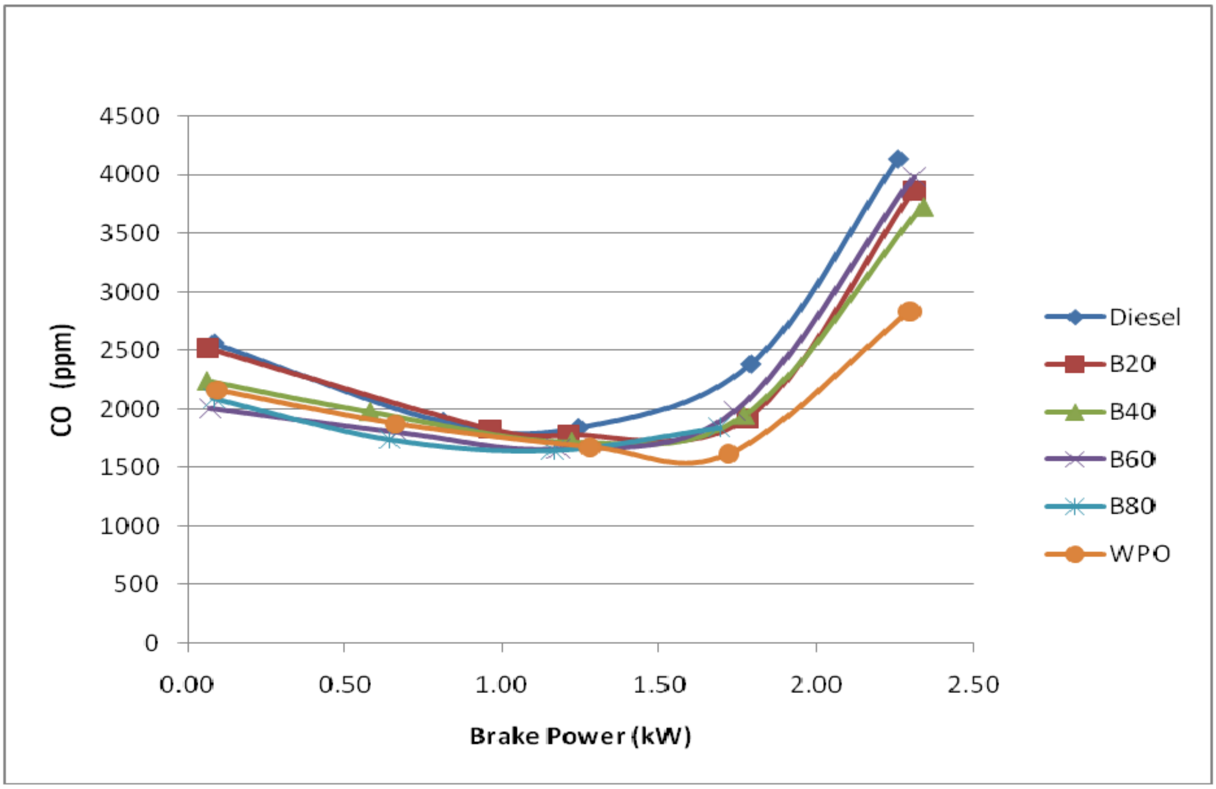


Figure 4.11: Carbon Monoxide (CO) versus Brake Power for Diesel, WPO and Blends

4.3.3 Carbon Dioxide Emissions

Figure 4.12 shows the variation of carbon dioxide emission with brake power for diesel, WPO and its blends with diesel. It was observed that CO_2 emission for diesel, WPO and its blends with diesel were lower at lower loads and higher at higher loads. This can be attributed to the lean running of the CI engine. Further, it was observed that that the levels of CO_2 emitted during operation WPO and its blends with diesel were lower than the levels of CO_2 emission during diesel operation. This observation was attributed to delayed ignition of fuel resulting in incomplete combustion (Mani et al., 2011).

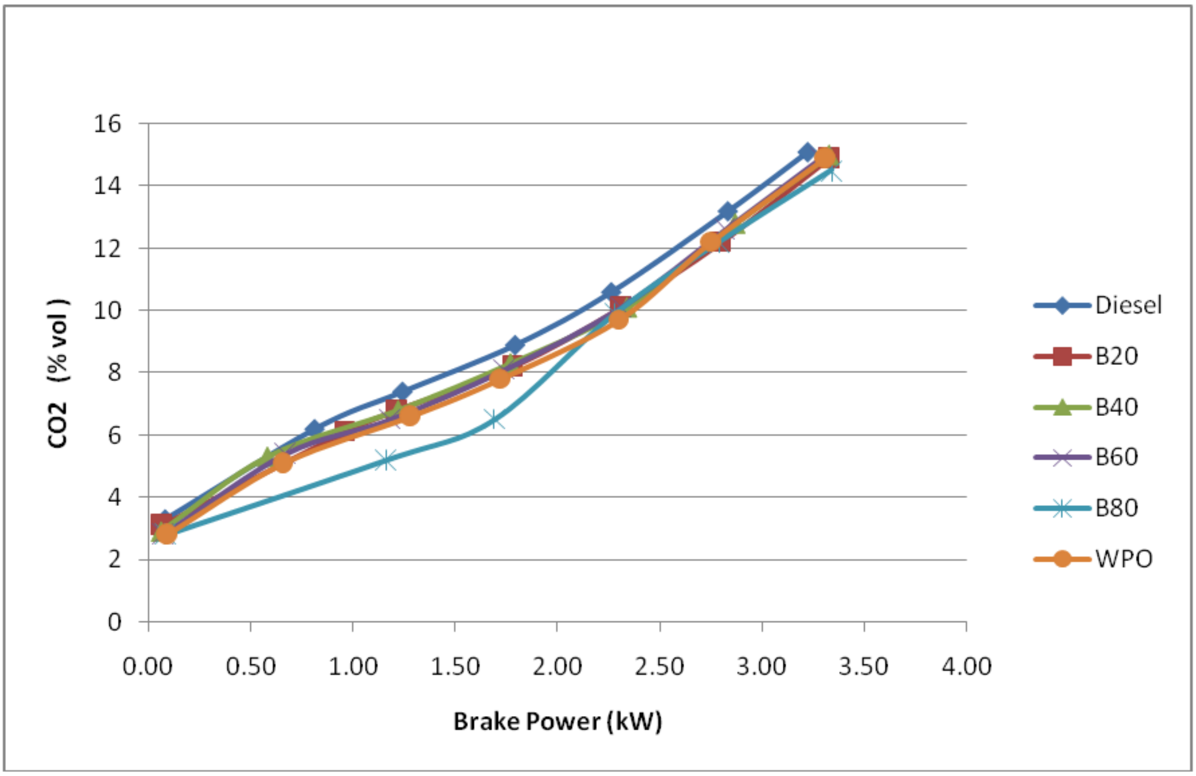


Figure 4.12: Carbon Dioxide versus Brake Power for Diesel, WPO and Blends

4.3.4 Oxygen

Figure 4.13 shows the variation of oxygen levels with brake power for diesel, WPO and its blends with diesel. It was observed that the oxygen present in the exhaust gas decreases with increase in the load. Due to improved burning, there is increased combustion temperature, which together with increased amount of oxygen, leads to the formation of high levels of Nitrogen Oxides (NOx) during operation with WPO and WPO-Diesel blends. Oxygen levels are a good indicator of a lean operating CI engine (Mani et al., 2011).

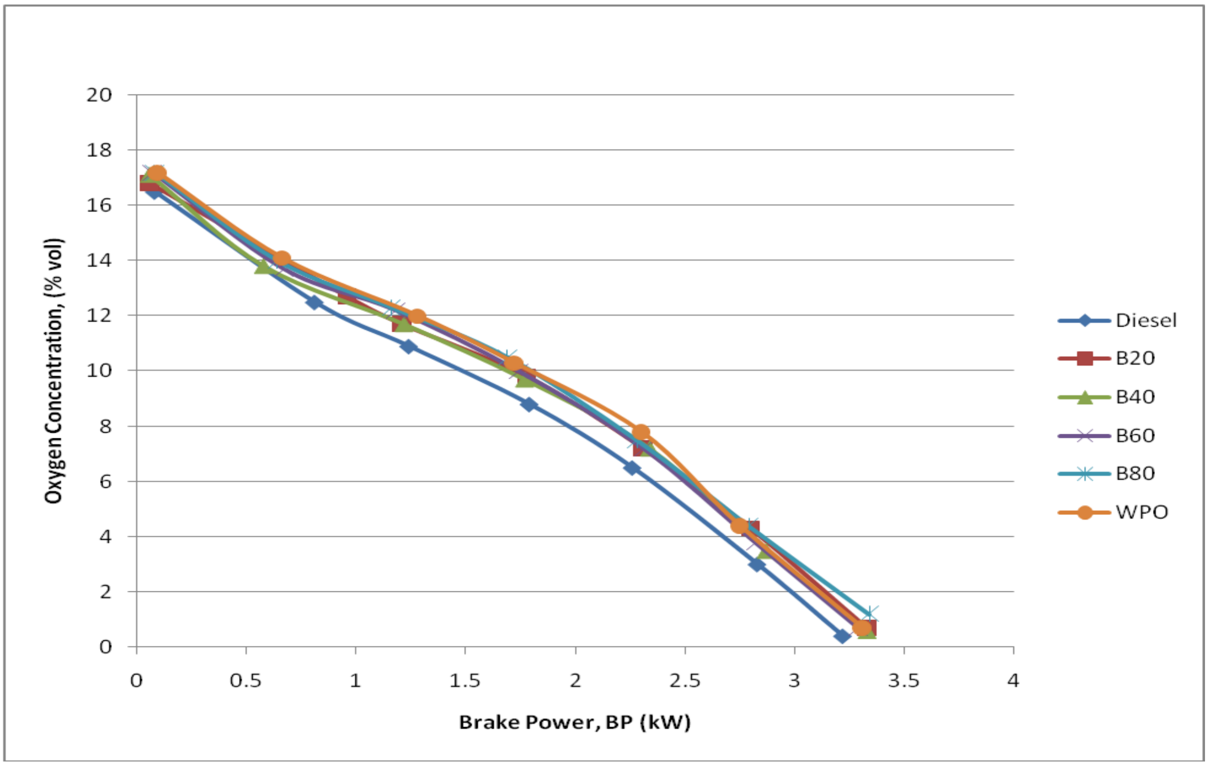


Figure 4.13: Oxygen Concentration versus Brake Power for Diesel, WPO and Blends

4.4 Economic Analysis

4.4.1 Fuel Production Costs

The investment and expenses of the pyrolysis machine were analyzed and their values tabulated in order to estimate the production of WPO as shown in Table 4.5. The capital and production costs, as well as the production capacity of the pyrolysis machine were obtained from the owner and operator of the machine at Kariobangi South. The price of diesel was determined as the prevailing pump price at the time of this study.

Table 4.5: Estimating the Production Costs of WPO

Type of Cost	Unit	Waste Plastic Oil	Pure Diesel
Total Capital Cost	Kshs	1,385,000	
Capital cost	Kshs/day	3,795	
Expenses			
Feedstock Expenses	Kshs/day	19,650	
Operating Expense	Kshs/day	1,965	
Maintenance Expenses	Kshs/day	800	
Labour Expense	Kshs/day	2,000	
Utilities Expense	Kshs/day	2,000	
Taxes, Insurance	Kshs/day	800	
Total Expenses	Kshs/day	27,215	
Profit 30%	Kshs/day	8,165	
Total Production	Kshs/day	39,175	
Oil Production	Litre/day	800	
Production Cost	Kshs/litre	**49**	**85**

4.4.2 Energy Cost Analysis

Using the values obtained in Table 4.5, the cost of producing 1 litre of WPO-Diesel blends was determined volumetrically. Then using the BSFC and density of diesel, WPO and its blends with diesel, the energy consumption cost per power output was determined for each blended fuel. The values obtained were used to plot a graph showing variation of cost of energy consumption with brake power as shown in Figure 4.14.

It was observed that energy consumption cost for diesel, WPO and its blends with diesel was high during initial loading and decreased with increased loading up to 80% of the loading before it started to increase again. This observation was attributed to the brake specific fuel consumption trend, which is due to improved combustion as stoichiometric ratio is achieved. The energy consumption cost per kWh for WPO and its blends with diesel was observed to be lower than that of diesel. This was attributed to the significantly lower cost of WPO (Ksh 49) per litre compared to that of diesel (Ksh 85), as well as WPO’s higher heating value. This observation was true for the entire range of engine operation during the study. For instance, energy consumption cost of WPO between 30% and 80% loading was 11.5 Ksh/kWh while that of diesel was 28.5 Ksh/kWh, which represents a 59.6% improvement in economic performance.

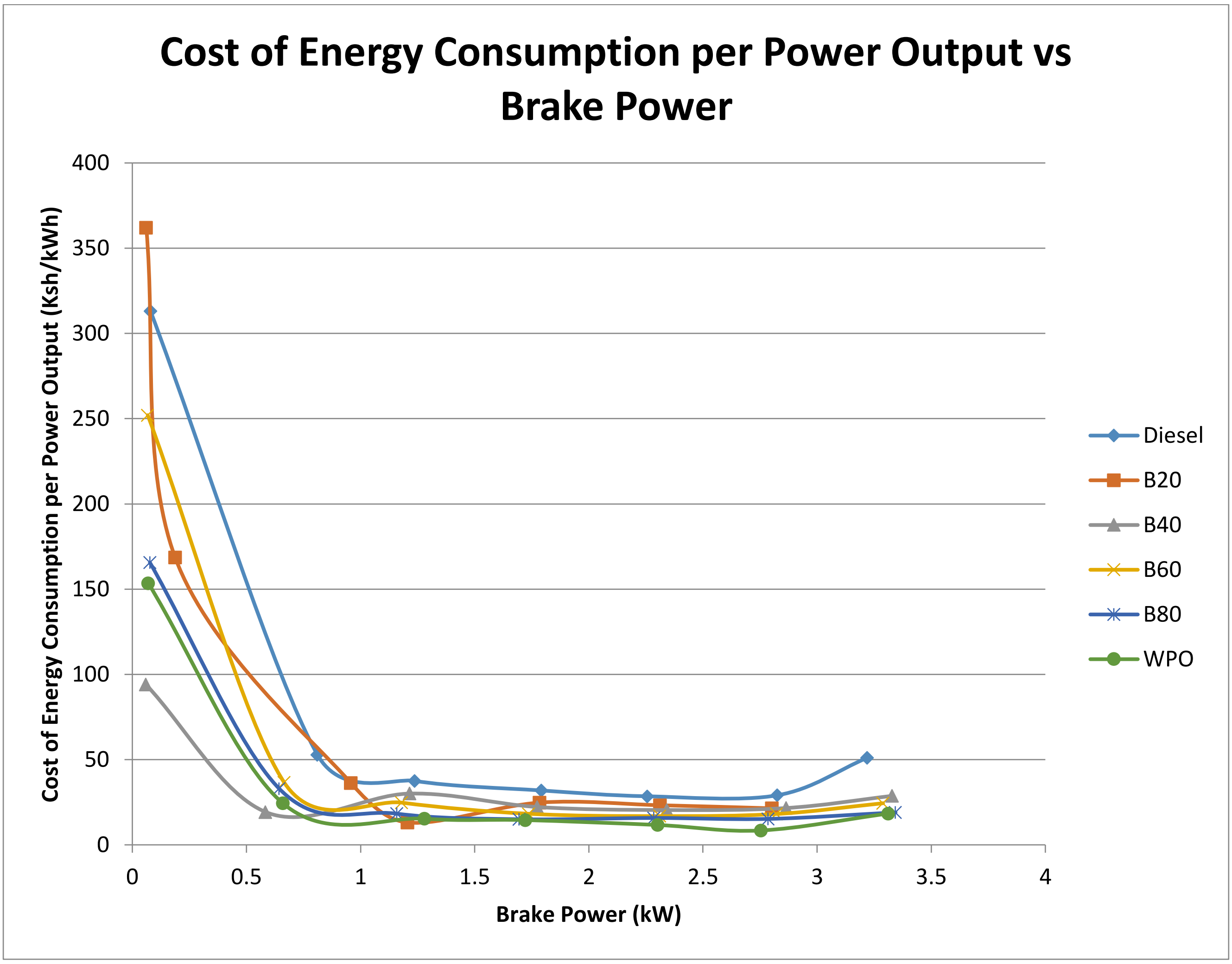


Figure 4.14: Energy Consumption Cost per kWh with Brake Power for Diesel, WPO and Blends

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The purpose of the study was to investigate the suitability of Waste Plastic Oil (WPO) as an alternative fuel for compression ignition (CI) engines. WPO was obtained through pyrolysis of High Density Plastics (HDPE) in a locally assembled batch pyrolysis machine in the presence of a catalyst. The resulting WPO was evaluated with respect to its properties and characteristics, engine performance and engine emissions, as well as engine's economy of performance.

The study concluded that:

1. Except for density and flash point, fuel properties and characteristics of WPO are comparable to those of diesel. The American standard methods ASTM D287 and ASTM D 1298, the European standard methods EN 3675 and EN12185, and the Kenya Bureau of Standards (KEBS) standard KS 1309-1 specify the range of density of pure diesel as 820-870 kg/m^3 at 20^{0}C. The only blend that met the specifications of the standards above was B20 with a density of 821 kg/m^3. The flash point of WPO and its blends with diesel ranged between 24^{0}C and 47^{0}C, and was found to be below the minimum limit of 52^{0}C as stipulated by the American standard method ASTM D 93. Only the flash point of diesel (54^{0}C) was found to meet the minimum limit of 52^{0}C.

2. Blending WPO with diesel improved its fuel properties and characteristics to within the minimum and maximum accepted standards, with the exception of density and flash point. The kinematic viscosity of WPO was determined as 1.44 mm/s^2 at 40^{0}C and therefore failed to meet the minimum limit of 1.9 mm/s^2 as stipulated by the American standard method ASTM D 445. The kinematic viscosities of diesel and all the other blends met the minimum limit of 1.9 mm/s^2. Blending WPO with diesel improved its Cetane Number from 42 to 52.3 for the B20 blend.

3. Short-term engine performance tests revealed that WPO and its blends had a 13% lower brake specific fuel consumption than diesel fuel, and a 14% higher brake thermal efficiency than diesel.

4. Blends of diesel with up to 20% WPO in the blend can be used in diesel engines without drastically compromising the fuel's properties and characteristics, and with better brake specific fuel consumption and thermal efficiency. Except for flashpoint, which has no significant influence on an engine's performance, all the other properties and characteristics of the B20 blend met the specifications stipulated by the American Society of Testing and Materials.
5. Blends of WPO and diesel can be used in diesel engines without exceeding emission limits, as their emission characteristics and levels are comparable to those of diesel operation.
6. Blends of WPO and diesel have a better fuel economy compared to diesel, which translates into energy cost savings for the user. For example, the energy consumption cost of WPO between 30% and 80% loading was 11.50 Ksh/kWh while that of diesel was 28.50 Ksh/kWh, which represented a 60% improvement in economic performance.

5.2 Recommendations

The study recommends that further work be carried out to investigate the suitability of waste plastic oil as an alternative fuel for internal combustion engines. In particular, the study notes that, unlike diesel and biodiesel, there exist no standards for production of waste plastic oil under pyrolysis, which in turn affects various properties of the fuel including the density, viscosity, heating value among others. For instance, waste plastic oil from pyrolysis could have a higher or lower heating value than diesel depending on the type of plastics, reactor and catalysts used, as well as the level of temperatures and pressures attained during the production process. Currently, all the properties of waste plastic oil have to be evaluated against the standards of both diesel and biodiesel.

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APPENDICES

APPENDIX A: Requirements for Diesel Fuel Oils (ASTM D 975-97)

Grade Property	Grade LS#1	Grade LS#2	Grade No. 1-D	Grade No. 2-D	Grade No. 4-D
Flash point ^{0}C (min)	38	52	38	52	55
Water and sediment, % vol (max)	0.05	0.05	0.05	0.5	0.05
Distillation temperature, ^{0}C at 90% (min)	-	282	-	282	-
(max)	288	338	288	338	-
Kinematic viscosity, mm/s^2 at 40^{0}C (min)	1.3	1.9	1.3	1.9	5.5
(max)	2.4	4.1	2.4	4.1	24.0
Carbon residue on 10%, % mass (max)	0.15	0.35	0.15	0.35	-
Ash, % mass (max)	0.01	0.01	0.01	0.01	0.01
Sulphur, % mass (max)	0.05	0.05	0.05	0.05	2.00
Copper strip corrosion, 3 hours at 50^{0}C (max)	No. 3	No. 3	No. 3	No. 3	-
Cetane No (min)	40	40	40	40	30
Cetane Index (min)	40	40	-	-	-
Aromaticity, % vol (max)	35	35	-	-	-
Cloud point, ^{0}C	Determined by local climate.				

Source: Gerpen et al. (2004)

APPENDIX B: Kenya Bureau of Standards (KEBS) Diesel Requirements

Serial No. characteristics	Requirements
Kinematic viscosity at 40^{0}C, centistokes	Min - 1.6 Max - 5.5
Copper strip corrosion, 3 h at 100^{0}C, max	1 A
Distillation recovery at 365^{0}C, % (v/v)	Min - 90 End point ^{0}C max, 400
Density at 20^{0}C g/ml	Min - 0.820 Max - 0.870
Flash point, Pensky Martens closed up, ^{0}C (min)	60
ASTM, colour max	3.5
Cetane Index (calculated), min	48
Cloud point	Report
Cold Filter Plugging point (CFPP),^{0}C	12
Sediment, % m/m, (max)	0.01
Water, v/v (max)	0.05
Ash, % m/m (max)	0.01
Sulphur content, % (m/m)	0.5
Carbon residue Conradson on 10% Residue, % m/m (max)	0.15
Neutralization value; strong acid no., mgKOH/g	Nil
Total Acid no. mgKOH/g	0.5

Source: Kenya Bureau of Standards

APPENDIX C: ASTM D 6751 Biodiesel Specifications

Property	ASTM Method	Limit	Unit
Flash point, closed cup	D 93	100 min	^{0}C
Water & sediment	D 2709	0.05 max	% volume
Kinematic viscosity, 40^{0}C	D 445	1.9-6.0	mm^2/s (Cst)
Sulphated Ash	D 874	0.02 max	Wt-%
Total sulphur	D 5453	0.05 max	Wt -%
Copper strip corrosion	D 130	No.3 max	
Cetane No.	D 613	40 min	
Cloud point	D 2500	Report	^{0}C
Carbon residue, 100% sample	D 4530	0.05 max	Wt-%
Acid Number	D 664	0.8 max	MgKOH/g
Free Glycerin	D 6584	0.2 max	Wt-%
Total Glycerin	D 6584	0.24 max	Wt-%
Phosphorous	D 4951	10	ppm
Vacuum distillation end point	D 1160	360^{0}C max, at T-90	
Storage ability	To be determined	To be determined	To be determined

Source: American Society for Testing and Materials (2002)