"PERFORMANCE EVALUATION OF USED EDIBLE OIL AS DIESEL FUEL"

by

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A THESIS

Submitted to
The University of Nairobi
in partial fulfilment of the requirements
for the degree of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

Department of Mechanical and Manufacturing Engineering

(2009)

ABSTRACT

In this study, used vegetable oil was collected from restaurants and processed to biodiesel through transesterification. Various properties of the biodiesel were determined and compared to those of diesel. Biodiesel was then subjected to engine tests in order to evaluate its performance as compared to diesel. Variables in engine performance were monitored for diverse blends of biodiesel and diesel. The effect of preheating biodiesel on engine performance was also studied.

The properties evaluated included: density, copper strip corrosion, viscosity, heat of combustion, cetane index, sulphur content, distillation and cloud point. The values of the properties were found to be within or varied slightly from the standard specifications in ASTM D 975 for diesel fuel.

The engine performance was evaluated in terms of the Brake Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency. The engine was initially run on diesel to establish basic performance characteristics. Engine tests were then carried out using biodiesel from used vegetable oils, biodiesel-diesel blends, biodiesel preheated to 35 and 47°C, and a subsequent comparative analysis done of their performance. From the tests, the average Brake Specific Fuel Consumption (BSFC) of biodiesel was found to be higher than that of diesel by approximately 12%. The fuels were then blended volumetrically to 20 (BD20), 40 (BD40), 60 (BD60) and 80% (BD80) biodiesel levels. Because of the greater energy density and better viscous properties of diesel, the engine was capable of generating the lowest BSFC while running on the reference diesel fuel. A small difference in BSFC was observed with BD20 and BD40 blends. As for BD60 and BD80, due to the energy differences previously noted, they produced a much higher BSFC than diesel fuels. But in general, all blends showed a lower BSFC as compared to neat biodiesel.

Neat biodiesel was then preheated to 35 and 47°C. It was observed that preheating biodiesel from ambient conditions to 35°C reduced the BSFC from 12 to 7.8 % above that of diesel.

Results of this study show that used vegetable oils can be processed to biodiesel of acceptable quality and used as fuel or additive to diesel fuel for use in diesel engines.

DECLARATION

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

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

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ACKNOWLEDGEMENT

The success of this work is attributed to several individuals who willingly gave their assistance.

First and foremost I would like to express my deep gratitude to my supervisors, Dr. J.A Nyanga'ya and Dr. J. M. Onyari for suggesting the research topic. Their guidance and support throughout the process is highly appreciated. I am glad for having to participate in such an interesting research.

Acknowledged is the support given to me by the entire technical staff of Mechanical and Manufacturing Engineering department, especially Mr Kogi for working tirelessly with me in the thermodynamic laboratory. I would also like to express my appreciation to my colleague, Mr R. Kimilu for his assistance in collecting data. I am also thankful to Mr. Mwangi of the Physical Chemistry Laboratory of the Department of chemistry.

Finally, special thanks go to my parents for their inspiration and support.

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List of symbols and abbreviations

cST	Centistokes
DF 2	Number 2 diesel fuel
ASAE	American Society for Agricultural Engineers
ASTM	American Society for Testing of Materials
MJ	Mega joules
kg	Kilograms
l	Litres
FFA	Free fatty acids
°C	Degrees centigrade
mm	Millimetres
cc	Cubic centimetres
°F	Degrees Fahrenheit
ml	Millilitres
kWh	Kilowatt hour
BSFC	Brake Specific Fuel Consumption

HP	Horse power
BHP	Brake horse power
ρ	Density
K	Dynamometer constant
t	Time
CO_2	Carbon dioxide
CO	Carbon monoxide
NO_x	Oxides of Nitrogen
HC	Hydrocarbons
N	Speed in revolution per minutes
W	load
NaOH	Sodium hydroxide
KOH	Potassium hydroxide
EIA	Environmental Impact Assessment
BDx	Biodiesel-Diesel blend whereby x denotes the percentage biodiesel content in the blend.

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1 CHAPTER ONE: INTRODUCTION

1.1 Background

1.1.1 Alternative fuels

Since the first oil crisis in 1970s, various alternative fuels have been investigated as potential supplements to conventional petroleum based supplies. The interest then was fuel supply and security. Currently, attention has shifted to the use of renewable fuels in order to reduce environmental effects of combustion of fossil fuels (Scholl and Sorenson, 1993). One type of fuel that is well suited for diesel engines is that based on vegetable oils. Tests with vegetable oil based fuels in diesel engines indicate that their performance is comparable to that of diesel fuel, and they are presently rated among the energy fuels considered as the most promising substitute for the highly priced and diminishing fossil fuels (Munavu and Odhiambo, 1984). Methanol and ethanol are two other fuels that have the potential to be produced from biomass sources. However, neither of these fuels is suitable for use in diesel engines since they require the use of high compression ratios, ignition improvers and ignition assistance devices. One way of using alcohol is to react it with vegetable oils through the transesterification process to form the corresponding ester of vegetable oil (biodiesel) (Scholl and Sorenson, 1993).

1.1.2 Biodiesel

Biodiesel is defined as the mono alkyl esters of long chain fatty acids derived from vegetable oils or animal fats for use in compression ignition engines. It is produced by reacting vegetable oils or animal fats with an alcohol in the presence of a catalyst to form the corresponding ester in a process known as transesterification (Gerpen J.V. et al., 2004). This process produces a fuel with properties close to those of conventional diesel. Modern diesel engines have direct injection fuel systems that are more sensitive to fuel spray quality than indirect injection engines (Wright and Purday, 1950). Since the diesel engine is optimized for diesel fuel, a fuel with properties closer to those of diesel is desired to avoid engine modifications. Therefore, research efforts have focused on transesterification of vegetable oils before using them in diesel engines. The most commonly used alcohol for transesterification is methanol. However, other alcohols such as ethanol, isopropanol and butyl alcohol can also be used. Methanol is the most preferred alcohol since it is cheaper and more readily available as compared to other alcohols. Methanol is also considerably easier to recover and recycle therefore minimizing operation costs and environmental impacts. For the reaction to take place in reasonable time, a catalyst has to be used. Both acids and bases can be used as catalysts. However, base-catalyzed reactions are preferred because they are simpler to carry out and have a higher reaction rate.

Fats and oils are composed of molecules called triglycerides. Each triglyceride is composed of three long chain fatty acids of 8-22 carbons attached to a glycerol backbone. Biodiesel is composed of fatty acid chains that are chemically bonded to one methanol molecule. The glycerol molecules are always removed from the final biodiesel (Kinast, 2003).

The overall chemistry of transesterification with methanol is represented by the equation below (Gerpen J. V. et al., 2004).

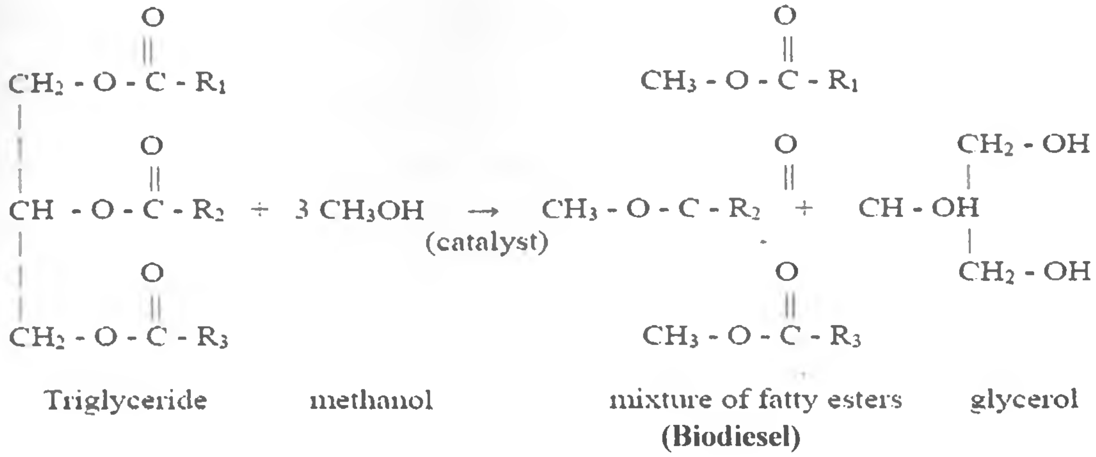

Figure 1-1 Transesterification reaction of triglycerides with methanol to form Biodiesel

Neat biodiesel is known as B 100. The primary advantages of biodiesel are that: it is renewable, non-toxic, biodegradable and can be used in most diesel engines without requiring extensive engine modifications (Gerpen J. V. et al., 2004). In various developing countries, oil producing plants have been proposed as a means of generating income as well as reducing dependency on imported oil (Guibert, 1997). Of the known oil-bearing crops, those with the greatest production potential are sunflower, safflower, soybean, cottonseed, rapeseed, canola, corn, and peanut oil (Peterson, 2005). Edible oils are expensive for use as fuel for diesel engines due to their high demand as food. However, their residual product (that is waste edible oils that are normally discarded) can have a residual value as a source of energy if processed to biodiesel.

1.1.3 Waste vegetable oils

Deep fried foods are popular on account of the fast and convenient preparation techniques. The main characteristics of these foods that make them be appreciated by consumers include: color, flavor, texture and palatability. During deep-frying, the food is cooked by immersion in hot oil. Due to heat and exposure to air, oxidative and hydrolytic reactions take place resulting in physical and chemical changes in the oil and the formation of new compounds (Yunsheng, 2005), leading to deterioration of the frying oil. Highly oxidized and heated fats may have carcinogenic properties because they contain potentially toxic substances (Chang and Peterson, 1978). Used-frying oil should therefore no longer be used as human food. Excessive use of cooking oil can also affect the quality of fried food. For example; increase in crispness since the crusts cooks faster than the interior, darkening in colour, bad odour and flavour and an increase in the final oil content in the food (Yunsheng, 2005). So for this reason, used oil is normally drained as waste oil and replaced with fresh oil after specific duration of cooking.

Used vegetable oils and fats derived from cooking activities in hotels, restaurants, schools etc, pose a major disposal problem in many parts of the world, more so in the context of stringent environmental audits and EIA requirements. In the past, much of these waste products have been used in the production of animal feeds. Disposal in this manner has since diminished. It is currently acknowledged that one of the most attractive disposal method is the use as bio-fuel in diesel engines. Kenya's domestic production of edible oils is estimated at 380,000 tonnes, which is about one-third of its annual demand, the remainder is imported (Export Processing Zones Authority Report, 2005). Considering the high quantities of vegetable oils consumed in the country, used vegetable oil generated country wide does present an opportunity for economical conversion to biodiesel. Vegetable oils are an attractive source of biodiesel but present some technological challenges due to the high percentage of free fatty acids (2-10%). Used vegetable oils are known as yellow grease while biodiesel which is processed from this oil is known as yellow grease methyl ester.

1.1.4 Free fatty acids

When fatty acid chains break off the triglyceride molecules, they are known as free fatty acids (FFA). During frying, triglycerides decompose in the presence of moisture and heat to form free fatty acids. This occurs when moisture escapes from food and mixes with frying oil at high temperatures (Kinast, 2003). Elevated levels of FFA causes the oils to generate smoke during frying, excessive oil absorption by the food being fried, hastens oxidative degradation and contributes to off-flavours. Usually, the amount of FFA increases with increasing frying time. When the FFA concentration increases, the smoke and flash points of oil decrease (Yunsheng, 2005).

1.2 Statement of the problem

Most developing countries in Africa rely on imported petroleum products as a source of energy as they fast track their economic growth. This has led to an increase in dependence on imported oil despite the increase in prices and environmental pollution regarding its use. The cost of living in these countries is directly affected by the increasing prices of petroleum products and this causes a strain on their economies.

Kenya, for example, has had no known petroleum reserves despite the fact that petroleum accounts for 20 % of the total energy consumed in the country. During the period 1989/99-2002/03 petroleum imports averaged 2.5 million metric Tons per annum, accounting for 25% of the country's annual import bill. This demand is projected to rise by 2 % per annum on average to reach 2.93 million tones by financial year 2009/2010 (National Energy Policy Sessional paper No 4 of 2004 on energy). With improved economic performance, the figure could surpass the projected level of demand. There is a risk of the economic growth being slowed down by the rising cost of energy. A similar scenario occurred during the 1973 oil crisis when Kenya's economy that was steadily growing at 6.5 per cent slackened to 5 percent during the period, and the country encountered a serious balance of payment deficit as a result of the increased prices of oil. (The Kenya High Commission Website. Accessed in May 2007). Investments in biodiesel production could save the country huge amounts in foreign exchange in addition to generation of income to farmers as well as in conservation of the environment.

1.3 Research objectives

I. To process used vegetable oils into biodiesel through transesterification.

II. To determine the characteristics of the biodiesel processed and compare to biodiesel standards.

III. To carry out comparative engine tests on both conventional diesel, biodiesel and biodiesel-diesel blends.

IV. To investigate the effects of preheating of fuel on performance of engine operated on biodiesel from used vegetable oil.

1.4 Significance of the study

National Energy Policy Sessional paper No.4 of 2004 on energy states that Kenya has had no experience with the use of biodiesel, although the potential for its production from locally grown crops exists. It further states that in order to utilize biodiesel, a system for production, distribution and use will need to be put in place from scratch. There is therefore need for research on the potential of biodiesel as an energy supply option. It is hoped that research into this area will lead to a clear understanding of the use of vegetable based oils as a source of energy and in particular, as fuel for the diesel engine. Though biodiesel will not replace diesel fuel, it will substantially reduce dependence on imported petroleum products especially when used as an additive. Furthermore, it has the potential to create jobs, spur economic growth in the country and contribute in the address of environmental problems ranging from desertification to climate change that are associated with fossil fuels.

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Diesel engine

2.1.1 History of the diesel engine

Rudolph Diesel (1858-1913) developed a theory that revolutionized the engines of his day. He designed an engine that would serve as an alternative for the inefficient fuel consumption of the steam engine. His initial intention was to utilize the constant temperature heat addition of the Carnot cycle, feeding coal dust into the combustion chamber. However the impartibility of coal dust was soon recognized and it was abandoned in favor of fuel oil. On February 27, 1892, Diesel filed for a patent at the Imperial Patent Office in Germany and in 1893, he developed the first model with an efficiency of 26%, remarkably more than double the efficiency of the steam engines. His first engine suitable for practical use was a 25 hp unit which was completed in February of 1897. Diesel demonstrated this engine at the Exhibition Fair in Paris, France in 1898. This engine was fuelled by peanut oil. He noted that the utilization of biomass fuel was the real future for the engine. The early diesel engines were neither small nor light enough for anything but stationary use due to the size of the fuel injection pump. They were produced primarily for industrial and shipping in the early 1900's. Ships and submarines benefited greatly from the efficiency of this new engine, which was slowly beginning to gain popularity (Encyclopaedia Britannica, 1974)

Over the years, the diesel engine has been a subject of research. The increased research was prompted by the 1973 energy crisis that led to an increase in the price of diesel fuel which was initially cheap and abundant. The initial emphasis was to develop products and procedures that could substantially cut down on fuel consumption of the motor vehicle like air deflectors, radial tires and fan clutches. In the 80's, the emphasis was on the development of equipment that could boost the brake mean effective pressure hence minimizing on fuel consumption of the motor vehicle like turbo chargers and intercoolers (Emslie et al., 2002). Currently, research has shifted to the use of alternative fuels which have reduced environmental effects and that can be produced on sustainable basis.

2.1.2 Diesel combustion

Diesel engines are usually classified into two categories, direct and indirect injection engines. In the indirect injection engine, the fuel is injected into an auxiliary chamber that is adjacent and connected to the main chamber. Combustion starts in this chamber and burning gasses exit this chamber with high velocity giving a greater ability for mixing of the fuel and air. Fuels of poorer quality can be used with this type of engine.

In direct injection diesel engines, fuel is injected into the combustion chamber under high pressure with the aid of a fuel pump through nozzles with single or multiple tiny orifices. This results in fuel spray with very fine droplets making it easier to vaporise and burn. The power developed by the engine depends on the spray quality, the percentage of the combustion chamber volume accessible by the fuel spray and the evenness of distribution of the droplets in the chamber (Wright and Purday 1950).

Diesel engines are commonly four stroke engines. With the four stroke cycle, an air charge is drawn into the cylinder in the first stroke followed by the compression stroke where the air charge is compressed. Fuel is injected into the cylinder at the end of the second stroke and compression induced ignition of the air-fuel mixture starts the combustion process in the third stroke. Products of combustion are exhausted in the final stroke. Most diesel engines are equipped with electrically heated glow plugs to assist with starting the engine under cold conditions. The power of the engine is controlled by varying the volume of the fuel injected into the cylinder. The timing of combustion process must be precisely controlled to provide low emissions with optimum fuel efficiency.

The combustion process in compression ignition engines is divided into four stages as follows [Benson and Whitehouse, 1979)

1. Ignition Delay - This is a short period between the start of fuel injection and the start of compression induced combustion.
2. Pre-mixed combustion - Rapid and uncontrollable combustion takes place due to the presence of many ignition points and the high temperature present in the combustion chamber. This stage extends to the point of maximum pressure.
3. Mixed control - A lower rate of combustion after the peak pressure, that is determined by the rate of air and fuel mixing after the fuel that was prepared during the ignition delay is exhausted.
4. A very low rate of combustion occurring down the expansion stroke.

2.1.3 Vegetable oils in diesel engines

The use of vegetable oils to run a diesel engine was first recorded in 1898 when Rudolph Diesel designed a diesel engine and ran it on peanut oil. His intention was to convert a variety of plant oils to fuel. However, it was about this time that drilling technologies and exploration techniques were developed and together, they ushered in the age of cheap and plentiful fossil fuels.

Consequently focus shifted from use of vegetable oils to fossil fuels as the diesel engine became more widely adopted in the subsequent years. Unlike fossil fuels, vegetable and animal based oils have the potential to be produced on a sustainable basis.

A large amount of research has gone into examining Diesel's dream of using raw vegetable oils as fuels. Work has been conducted to examine these oils as petroleum based fuel replacements or additives (Munavu and Odhiambo, 1984; Romano, 1982; Hofman et al., 1981). While neat vegetable oils can be used in diesel engines and produce acceptable short-term performance, experience has shown that they may cause significant problems that can affect their viability for use as fuel in the long term. The problems associated with use of vegetable oils in diesel engines are due to their physical and chemical properties.

A study by Hofman et al. (1981) indicated that while vegetable oil based fuels and their blends had encouraging results in short term testing, problems occurred in long-term durability tests. In their research they noted that carbon build-up, piston ring sticking and lubricating oil contamination caused engine failure when vegetable oils were used in high percentages (50% or more) as diesel fuel additives. Romano (1982) noted that under the high temperatures commonly found in the internal combustion engines, the oils decompose to liberate FFAs and glycerol. The free fatty acids will corrode engine parts while glycerol will be transformed to acrolein, which in turn polymerizes to give solid deposits in the engine. According to Duke (1983), the engine can quickly become gummed-up with the polymerized oil, and engine failure can occur in as little as 20 hours.

Munavu and Odhiambo (1984) examined seventeen non-conventional oil seeds as potential source of vegetable oils for use as fuels for diesel engines in Kenya. They noted that while their density and heat of combustion compared favourably with that of conventional diesel, their viscosity was 10 to 20 times higher than that of diesel. No engine performance tests were done.

Other problems that may be encountered with the use of vegetable oils include difficulty in cold starting, gumming up of injectors and choking-up of valves and exhaust (Pullan, 1981). The viscosity of vegetable oils and animal fats varies from hard crystalline solids to light oils at room temperature. In most cases, the fats and oils are a complex mixture of various fatty acids triglycerides with the various components having widely varying melting points. This may give the oil or fat a temperature range over which solidification occurs, with the oil gradually thickening from a thin liquid, through to a thick liquid, then a semi-solid and finally to a solid (Calais and Clark, 2007). High melting points or solidification ranges can cause problems such as partial or complete blockage in the fuel system as the triglyceride thickens and finally solidifies when the ambient temperature falls (Pullan, 1981):

From the above studies, it can be noted that raw vegetable oils can cause problems when used in diesel engines. Different ways have been considered as a means of minimizing these problems. They include: blending with diesel, micro-emulsion with short chain alcohol, thermal decomposition, catalytic cracking and combining with an alcohol to form the corresponding ester (Schuchardt et al., 1998). Among these alternatives, transesterification has been preferred because the physical characteristics of fatty acid esters produced are very close to those of conventional diesel. Therefore, the methyl or ethyl esters can be burned directly in diesel engines without engine modifications. The transesterification process also neutralizes the FFAs, or transforms them to methyl esters, thus minimizing corrosion that is associated with use of raw vegetable oils (Munavu and Odhiambo, 1984). The methyl esters formed are not susceptible to decomposition under normal engine running conditions and they also reduce carbon build up in the engine (Romano, 1982).

2.2 Biodiesel in diesel engines

Good results have been reported with the use of biodiesel in internal combustion engines, both in its pure and blended states.

Nye et al. (1983) prepared esters of used frying oil to determine their effects on engine performance and emissions. The esters of methanol, ethanol, 1-propanol, 1-butanol and 2-ethoxyethanol were prepared using sulphuric acid and KOH as acid and base catalyst respectively. They found out that all acid-catalyzed fuels had low viscosities, but all base catalyzed fuels had high viscosities except for methanol based fuel. In that study, the three fuels with the lowest viscosities (methyl esters prepared with base catalysts, ethyl esters prepared with acid catalyst and butyl esters prepared with acid catalyst) were tested in half hour runs in a high-speed diesel engine and in a Perkins low-speed engine and no problem was reported.

Peterson et al., (1997) characterized and ran engine tests on ethyl and methyl esters of canola, rapeseed, soybean and beef tallow, and then performed a comparison to diesel fuel. The physiochemical properties and performance of the esters were found to compare well with those of diesel fuel. The energy content of the ethyl and methyl esters was 9 to 13 % on mass basis lower than that of diesel, this caused 7 % increase in fuel consumption (g/s) over that of diesel. The density was higher for biodiesel. Viscosities were 1.3 to 2.1 times higher than that of diesel fuel while the sulphur content was found to be 20 to 50 % less than for diesel fuel. In general all the fuels properties were within the requirements set forth in the ASAE Engineering Practice

Standards. The results showed no difference in the thermal efficiencies of the esters compared to diesel.

2.3 Biodiesel performance in internal compression engines

The primary concern for considering an alternative fuel is whether it will perform differently from the conventional petroleum-based diesel fuel in the engine. The main parameters considered are power output, wear characteristics, fuel consumption and environmental concerns.

2.3.1 Power, efficiency and fuel consumption

Power output is the most important characteristic of an engine since it determines the suitability of an engine to a particular purpose. The performance of any fuel can be judged by the power and torque output it generates. Studies conducted indicate that biodiesel and its blends with diesel result in small decreases in overall power output of engines. The actual efficiency at which the chemical energy in the fuel is converted to mechanical energy is the same for both biodiesel and petroleum based diesel fuel (Peterson et al., 1997; Monyem, 1998; Canakci and Gerpen, 2003). The brake specific fuel consumption is a parameter used to characterize fuel economy. Biodiesel has lower energy content per unit volume as compared to diesel. Because of the lower energy content, using biodiesel without any change in the fuel injection system would result in a slight loss of engine power (Christopher et al., 2004). This means that in order to make up for the power loss, more fuel will have to be injected into the combustion chamber leading to high fuel consumption.

2.3.2 Lubrication properties, wear characteristics and durability

Rubbing and moving components of the engine such as the piston, cylinder liner and fuel pump depend on the operating fuel for lubrication. Biodiesel has been studied for its effects on long term engine wear, with respect to these components.

Work on the lubricity of biodiesel performed by Masjoki and Sapuan (1995) established a clear advantage of using biodiesel, while blends improved the lubrication properties of diesel fuel. These workers studied the performance and effects of palm oil diesel and its blends on the piston ring, cylinder liner and other rubbing parts of the engine. The experiments were done on a 7 HP four-stroke single cylinder diesel engine. During the tests lubrication oil samples were collected at 0, 3, 6, 10, 15, 20, 25, and 30 hours. The samples were subjected to viscosity measurements and wear debris analysis using Atomic Absorption Spectrometer (AAS) method. The oil analysis focused on aluminium from piston and bearings, chromium from cylinder liner, iron from camshaft and piston and copper from piston rings and bearings. Their results showed that when Palm oil methyl ester was used, concentration in the lubricant sump of all metals reduced tremendously except for aluminium. As for the blends, the concentration of the metals exhibited an increase with increase in diesel content in the blends. This was due to palm oil acting both as a combustible product as well as a lubricant between the cylinder liner and the piston rings.

In another study by Peterson et al., (1999), a 1,000 hour durability test was carried out on three diesel engines fuelled with three different blends of hydrogenated soy ethyl ester. The main objective was to determine their long term effect on the engines performance and wear. Fuels used in the test were 25, 50 and 100% blends of hydrogenated soy ethyl ester (HySEE) with type 2-diesel fuel (DF2). The primary factors evaluated in the study were engine brake power and torque, carbon deposition, and engine component wear based on oil analysis. The tests were performed on the three engines simultaneously and lubrication oil was analyzed for contamination at 100 hour intervals. It was found that methyl ester Biodiesel was equivalent to no. 2 diesel on the basis of long-term engine performance. At each oil change intervals, oil analysis results for wear metals for the 100% HySEE engine were equal to or lower than either the 25% HySEE or the 50% HySEE fuelled engine. The engine fuelled with 100% HySEE was cleaner and brighter internally than either the 25% HySEE or the 50% HySEE fueled engine.

2.3.3 Emissions

Biodiesel has good environmental credits. Mittelbach and Tritthart (1988) investigated the effects of methyl esters prepared from used frying oil on diesel engine emissions. They noted slightly lower HC, CO, sulphur and particulate emissions, but an increase in NOx values with the esters than when diesel was used. Canacki and Gerpen (2003) also observed the same results.

2.3.4 Biodegradability of biodiesel

Xiulin et al. (1998) studied the biodegradability of biodiesel in aquatic environment by the CO_2 evolution method. They found out that biodiesel fuels are readily biodegradable compounds and have a relatively high biodegradation rate in the aquatic environment (85-88 % within 28 days which was four times faster than diesel fuel). As for blends they noted that biodiesel promotes and speeds up the biodegradation of diesel. Their results showed that the more biodiesel present in the blend, the faster the degradation rate. For example for a 50-50 blend, the rate will be two times faster than pure diesel. Biodiesel can thus be used in environmentally sensitive areas where petroleum spills can cause more serious environmental problems.

2.4 Properties of Fuel for diesel engines

For a fuel to be used in a diesel engine, its parameters must meet certain standard specifications. The important parameters and their effects on diesel engines are discussed in the following sections. Biodiesel and ASTM D975 standard specifications for Diesel Fuel are shown on Table 2-1.

2.4.1 Heat of combustion

The calorific value is the amount of heat released during combustion, it determines the suitability of a substance for use as fuel. Biodiesel is denser than diesel fuel, this is of special importance for diesel engines since the fuel is metered volumetrically. The high density of biodiesel partly compensates for the low energy content. Other things being equal, the fuel consumption tends to be in inverse ratio to the heat of combustion (Wright and Purday, 1950). A fuel with lower heating value will cause the engine to produce less peak power, therefore more fuel will be injected to make up for the power loss leading to high fuel consumption.

Table 2-1 Standard specification for No 2-Diesel and biodiesel

	Requirements	
Property	Diesel	biodiesel
Flash point °C, minimum	52	100
Distillation temperature, °C, 90%		
Minimum	282	-
Maximum	338	360
Kinematic viscosity, cST at 40 °C		
Minimum	1.9	1.9
Maximum	4.1	6.5
Sulphur,	0.50% mass	0.05 %wt
Copper strip corrosion, max 3 hours at 50 °C	No 3	No 3
Cetane number, min	40	47
Cloud point, °C, max	Determined by local climate	

Source: Kinast (2003)

2.4.2 Viscosity

For complete combustion to take place, proper air and fuel mixing is necessary. On injection the fuel is atomized into fine droplets to ensure sufficient penetration and even distribution of droplets in the combustion chamber. The quality of spray on injection is attributed to the viscosity of the fuel. Very high and low viscosity affects combustion performance in a number of indirect ways. High viscosity tends to reduce atomization and increase penetration of droplets on injection thereby causing incomplete combustion. This is more prominent with small high speed engines. On the other hand, very low viscosity will result in finer atomization but shorter penetration. For both high and low viscosity, the result will be loss of power due to the uneven mixing of air and fuel. A tendency of fuel to leak in the pump and atomizers may also be observed with very low viscosity, again, the effect will be loss of power.

Apart from the effects on combustion, viscosity is linked to lubrication and durability of fuel system parts. Very low viscosity fuels are deficient in lubrication properties and this may give rise to wear on fuel pump and injector parts since the fuel system depends on the operating fuel for lubrication (Wright and Purday, 1950). For high viscosity at low temperatures, excessive heat will be generated in the rotary distributor pumps or cause stress in the fuel pump components. This will result in early pump life failure or seizures (Joint Fuel Injectors Equipment Manufacturers statement, issued 2002). The viscosity of a liquid varies with temperature and is therefore reported at a particular temperature. To ensure sufficient lubrication without straining injector parts, ASTM recommends 1.9 and 6.5 cST at 40 °C as minimum and maximum operating limits for viscosity of biodiesel.

2.4.3 Cetane number

The principle property of fuel for diesel engines is its readiness to ignite at temperatures and pressures present in the cylinder when the fuel is injected. The Cetane number is the measure of ignition quality. It gives an indication of the behaviour of an engine in respect of smooth or rough running as influenced by combustion delay and rate of pressure rise. Ignition quality may be defined as a measure of the time required for combustion to start after the commencement of fuel injection, the shorter the time the higher the ignition quality. If the delay is too long, a large fraction of fuel may be injected before burning begins, and when it occurs, it proceeds with an accelerated intensity resulting in a rapid rise of pressure. Therefore a high cetane number indicates ease of starting from cold at low speeds and smoothness of running (Wright and Purday, 1950).

2.4.3.1 Cetane index

The Cetane index is a calculated quantity that is intended to approximate the Cetane number. It is much cheaper to determine than the engine based Cetane number, but it does not provide an accurate indication for non-pure petroleum fuels. ASTM gives the following empirical equation to compute the Cetane index (Gerpen, 2004b).

ASTM D 976

$$\text{Cetane Index} = 454.74 - 1641.416\,D + 774.74\,D^2 - 0.554\,T_{50} + 97.803[\log10\,(T_{50})]^2$$

Where D = fuel density at 15°C in g/ml.

T_{50} = the temperature corresponding to the 50 % point on the distillation curve in degrees C.

2.4.4 Flash point

This is the temperature at which the oil gives off sufficient inflammable vapour from its surface to ignite in the presence of a small flame (Wright and Purday, 1950). The flash point has no effect on the combustion performance of the engine, but it is important property with regard to storage and safety. A fuel with high flash point makes it relatively safe fuel to store and handle than one with a low flash point.

2.4.5 Sulphur content

Sulphur has no effect on combustion in the Diesel engine. However, on burning sulphur forms sulphur oxides which dissolve in condensed water arising from the combustion of hydrogen to form sulphuric acids. Therefore, corrosion effects are liable to be experienced in turbo blowers, silencers and exhaust pipes with increase in sulphur content (Wright and Purday, 1950).

2.4.6 Cloud point

This is the temperature at which a cloud of wax crystals first appear in a liquid when cooled down. The cloud point is a critical factor in cold weather performance of diesel engines since the wax crystals can clog up the fuel filter and impede fuel flow to the engine.

2.4.7 Volatility

Volatility is the tendency of a liquid to vaporize. The degree of volatility depends upon the fuel's vapor pressure and its distillation range. The distillation range of a fuel is the temperature at which a liquid actively starts to vaporize, this is the liquid's boiling point. The lower the volatility, the slower the fuel vaporizes.

2.4.8 Copper strip corrosion.

This test measures the level of corrosion of a fuel by use of copper strips. In this test polished copper strips are placed in the fuel for three hours at 50 °C. The strips are then washed in a solvent and compared to the descriptions in Table 2-2 below.

Table 2-2 Copper strip corrosion test classification for biodiesel

Classification	Designation	Description
1	Slight Tarnish	a. Light orange, almost the same as freshly polished strip b. Dark orange
2	Moderate Tarnish	a. Claret red b. Lavender c. Multicoloured with lavender blue or silver, or both, overlaid on claret red d. Silvery e. Brassy or gold
3	Dark Tarnish	a. Magenta overcast on brassy strip b. Multicoloured with red and green showing (Peacock), but no gray
4	Corrosion	a. Transparent black, dark gray or brown with peacock green barely showing b. Graphite or lustreless black c. Glossy or jet black

Source: Gerpen et al., 2004b

3 CHAPTER THREE: MATERIALS AND METHODS

3.1 Oil processing

The oil used in this study was obtained from The University of Nairobi cafeteria kitchens and fast food restaurants within Nairobi. The method that was used to process the oil is described below.

3.1.1 Materials and apparatus

- Thermometer
- 50 ml flask
- Dropper
- Mixer / blender
- Weighing scale (accurate to 0.01 grams)
- Methanol 99% purity
- Funnel
- Phenolphthalein indicator
- Graduated pipette
- Potassium Hydroxide (KOH) 85 % purity
- Sodium Hydroxide (NaOH)
- One litre high density polythene container
- Two 20 litre capacity settling and separation containers with tap at the bottom
- Used vegetable oil (yellow grease)

3.1.2 Procedure

Step one: purification

- Collected used cooking oil was heated to about 100°C for about thirty minutes while stirring to reduce water content in the oil.
- The oil was then passed through a sieve while still hot to filter off solid particles and debris.

Step two: titration

To determine the amount of KOH required for titration of free fatty acids, the following procedure was used.

- 1 gram of NaOH was dissolved in one litre of distilled water in the high density container to make a 0.1 % lye solution.
- 1 ml of dewatered used vegetable oil was mixed with 10 ml of isopropyl alcohol in a 50 ml flask.
- The mixture was then warmed by standing it in hot water while stirring until the oil completely dissolved in alcohol.
- Two drops of phenolphthalein indicator were added to the oil using a dropper.
- The lye solution was added drop wise to the resulting mixture while stirring in a swirling action until the solution turned and stayed pink for about 15 seconds.
- The number of millilitres of lye solution used for titration plus 3.5 (amount required for fresh oil) is the number of grams of NaOH required per litre of oil.

Since KOH was to be used for transesterification, the basic lye quantity had to be adjusted to equivalent strength of KOH.

Example:

If 1.5 ml of 0.1% NaOH solution was used to titrate the FFAs.

Basic amount required for one litre of fresh oil is 3.5 grams NaoH

Titration result 1.5 ml

Total 3.5 + 1.5 = 5 grams of NaOH for every litre of used oil

Amount of 85 % KOH that will give the equivalent strength of 5 g of NaOH

5 x 1.65 = 8.25 grams of KOH per litre of used vegetable oil.

(1.65 - convert quantity for 85% KOH)

Step three: Transesterification

- Potassium-methanoxide was prepared by dissolving the predetermined amount of KOH (8.25 grams) in 200 ml of methanol (in a high density polythene container) for every litre of cleaned used vegetable oil to be processed.
- The oil was heated to 60°C then mixed with potassium-methanoxide at a ratio of 5:1 respectively. The mixture was vigorously stirred in a 10 litre capacity blender for about 45 minutes then transferred to a settling container to allow glycerol to separate from biodiesel.

Step four: Separation

- Since glycerol has a higher density than biodiesel, it settled at the bottom of the container. After 24-hours of separation, the tap beneath the container was opened and glycerol was drained off.

Step four: Washing and drying.

- Crude biodiesel was washed three times by agitation with clean water to remove traces of methanol and KOH from the oil. After each wash, the oil was transferred to the settling container for about four hour where it was allowed to separate. The amount of water used in each wash was equal to the amount of oil being cleaned. Water was then drained off after separation. It was noted that using warm water hastened the separation processes.
- Finally the oil (biodiesel) was heated to about 110°C for about thirty minutes while stirring to evaporate off residual water from the washing process.

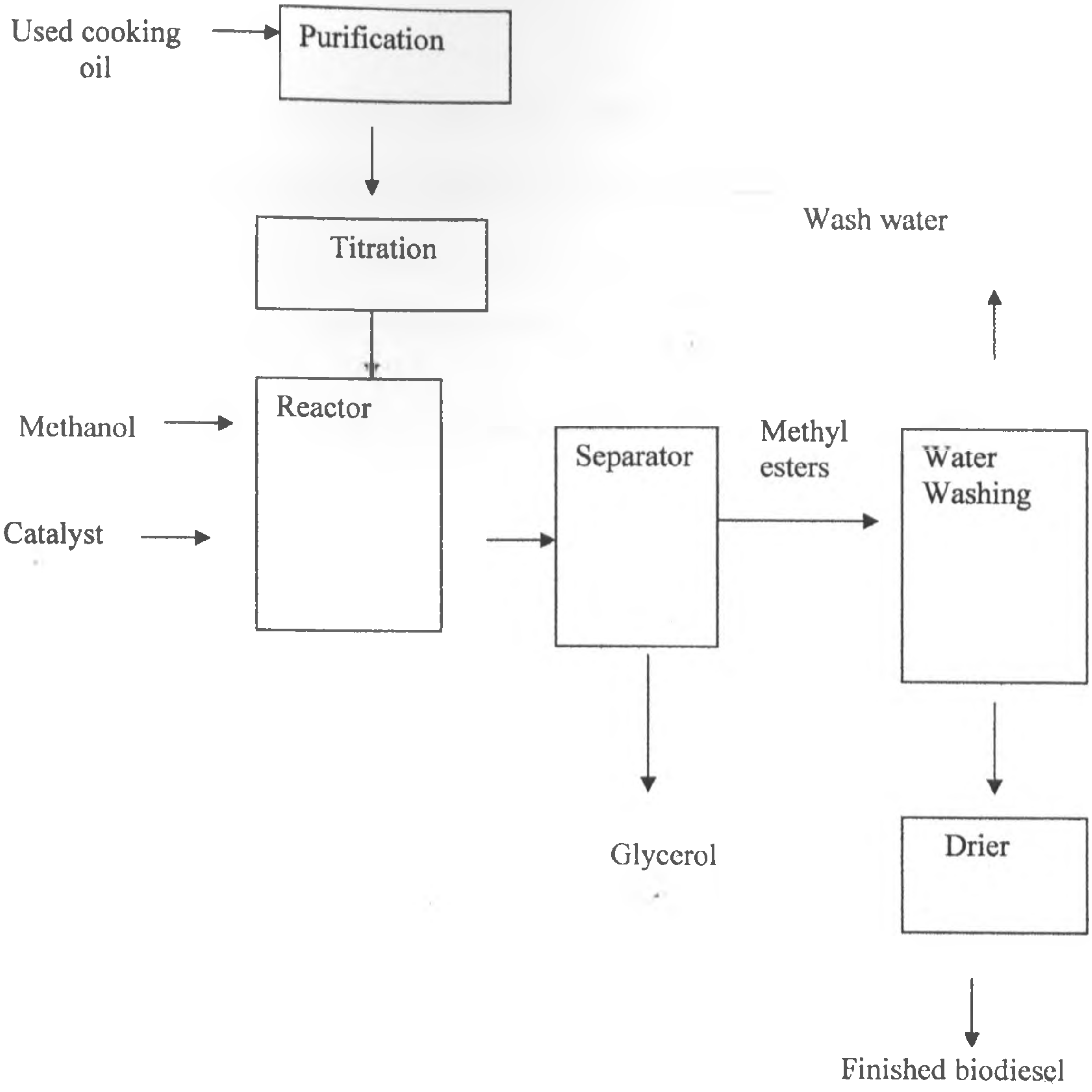

Figure 3-1 Process flow chart for biodiesel production from used edible oils.

3.2 Fuel characterization

The density at 20 and 15°C, viscosity, cloud point, sulphur, copper corrosion and distillation were determined by Kenya Petroleum Oil Refinery. Experiments on the effects of temperature on viscosity and density of the fuel were conducted at the Department of Chemistry while the calorific value was determined at the Department of Mechanical Engineering.

The equipments and procedures used are as described below.

3.2.1 Density

The density of the oil was determined using density bottles. An empty bottle of known volume and mass was filled with a fuel sample. The bottle and the fuel sample were then raised to the desired temperature using a heated water bath whose temperature was held at the desired level by use of an electric water heater. The bottle was then weighed and the mass was noted. This procedure was repeated several times and the average value for mass was used to compute the density. The density was calculated using the following equation.

$$\rho = \frac{m_l - m_0}{U_0}$$

Where ρ = density of the oil

U_0 = volume of the bottle

m_0 = mass of empty bottle

m_l = mass of empty bottle + mass of fuel sample

3.2.2 Viscosity

A U-Tube viscometer was used to determine the viscosity of the oil samples. The viscometer is illustrated in Figure 3-2 while the picture of the arrangement is shown in Photo No.1. The tests were conducted with the U-Tube viscometer immersed in a water bath that was maintained at a constant temperature using an electric water heater. The heater current was regulated by a Contact thermometer. The fuel sample was introduced into the viscometer up to the point marked A. It was then sucked to point B then allowed to flow down. The time taken for the level to reach point C was recorded. The test was done several times and the average time noted. The procedure was repeated with water.

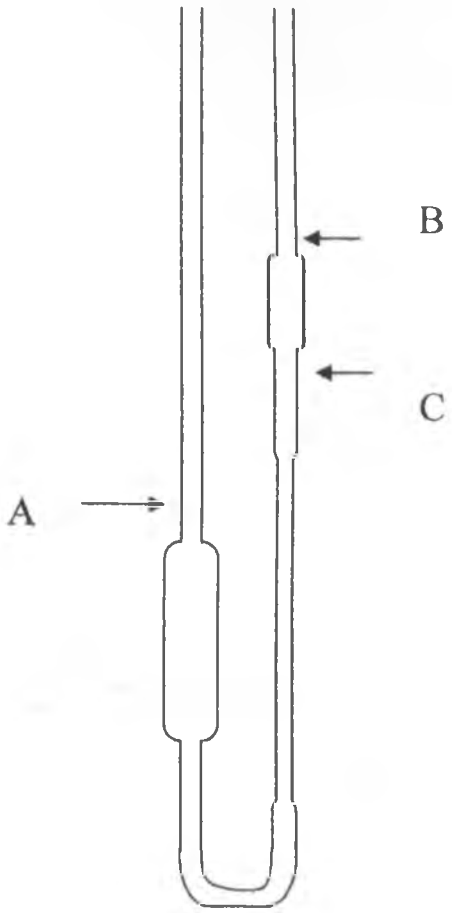

Figure 3-2 U-Tube viscometer

Viscosity was computed using the following equation.

$$\upsilon_o = \frac{t_o \upsilon_w}{t_w}$$

Where υ_o – kinematic viscosity of the oil

υ_w – kinematic viscosity of water

t_o – time taken for oil to flow from point B to C

t_w – time taken for water to flow from point B to C

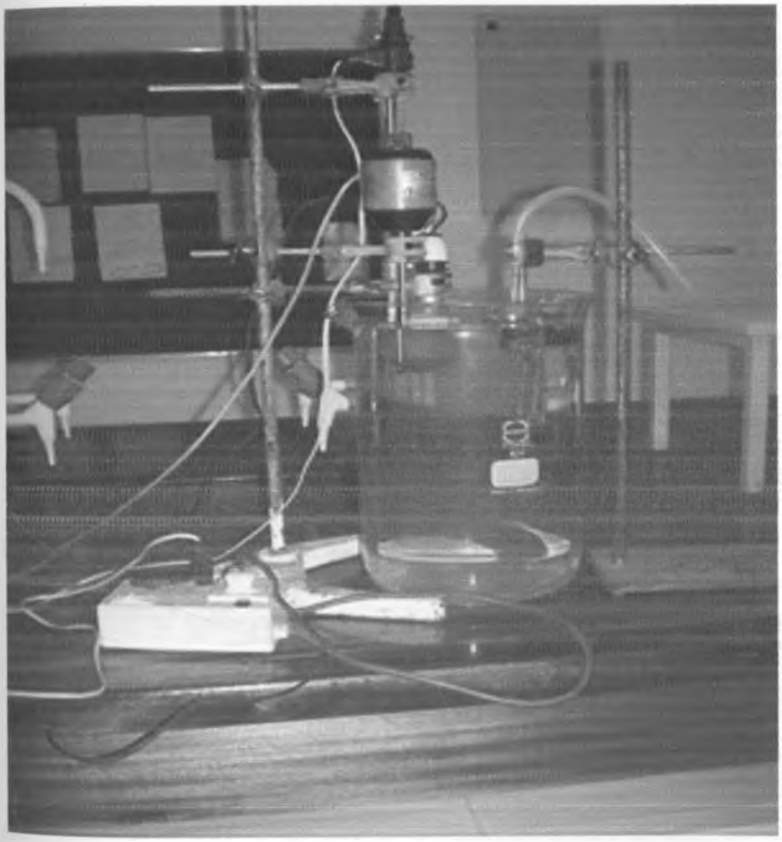

Photo No. 1 U-tube viscometer used to determine the viscosity

Photo No. 2 Bomb calorimeter used to determine the calorific value

3.2.3 Calorific value

Calorific value was determined using a bomb calorimeter. Benzoic acid was used to standardize the calorimeter. One gram of sample was put in a crucible and weighed. It was then placed in the bomb, which was pressurized to 23 atm with oxygen. The bomb was placed in a vessel containing a measured quantity of water (1750 ml). The ignition circuit was connected, the stirrer switched on and the water temperature noted. After the temperature had stabilized, the bomb was fired and the temperature rise was recorded every minute until a constant temperature was noted. The pressure was released and the bomb was inspected to ensure that the sample was completely burnt. The calorific value was computed using the following formula and according to sample calculation in Appendix D.

$$\text{Calorific value} = \frac{\text{Total water equivalence} \times \text{specific heat capacity of water} \times \text{temperature rise}}{\text{Weight of sample}}$$

Temperature rise = $t_o - t_n +$ Cooling correction

$$\text{Cooling correction} = nv + \left((v_1 - v)/(t_1 - t)\right) \left\{\sum_{1}^{(n-1)} (t) + 0.5(t_o + t_n) - nt\right\}$$

Where:

- n = time in minutes between firing and the first reading after the temperature begins to fall from the maximum.
- v = the rate of fall of temperature per minute during the pre-firing period
- v_1 = the rate of fall of temperature after the maximum temperature
- t and t_1 = the average temperature during pre-firing and firing periods.
- $\sum_{1}^{(n-1)} (t)$ = sum of readings between during the period between firing and the start of cooling
- t_o = temperature at the moment of firing
- t_n = first temperature after the rate of change of temperature becomes constant

Source: Eastop and Mc Conkey (1996).

3.2.4 Cetane index

The Cetane index was calculated using the equation provided by ASTM D 976 (section 2.4.3.1).

3.3 Engine performance tests

3.3.1 Engine set up

The engine performance tests were conducted in the Thermodynamics laboratory at The Department of Mechanical and Manufacturing Engineering. The engine used in this study was a commercial plant that had been retrofitted for laboratory use. It is a 6-cylinder, direct injection and turbo charged diesel engine rated at 85 BHP. The parameters of interest were the Brake thermal efficiency and Brake specific fuel consumption.

Table 3-1 Parameters of the engine used in performance tests

Make	Ford
Type	Six cylinder open combustion chamber
Bore	100mm
Stroke	115mm
Displacement	5416cc
Compression ratio	16:1

The power developed by the engine was controlled by varying the volume of the fuel injected into the cylinder. The engine manufacturers test data is shown in Appendix H. The engine was coupled to a G-type Froude Hydraulic dynamometer for measuring the engine output over the entire range of operation. The engine was loaded by regulating the amount of water going into the dynamometer. This was done by adjusting knobs provided on the dynamometer in steps of one Pound. The load and the engine speed were displayed on dials on the dynamometer. The Dynamometer cross-section diagram is shown in Appendix I. A photographic view of the engine test set up is given in Photo No. 3. Other features of the arrangement are hereby described.

3.3.2 Cooling water system

The cooling water to the engine was circulated by a pump. The external circuit was via a header tank, fitted with a thermometer. The water temperature in the header tank was kept constant at120° F (49°C) by supplying water from the mains while allowing the same amount of hot water to drain off. Thermometers were provided to measure the inlet and outlet water temperatures to and from the engine.

3.3.3 Fuel flow rate

The fuel consumption was measured using a calibrated pipette. The supply from the fuel tank was allowed to fill the pipette to the 150ml level. The fuel tank supply was then cut off and the time taken to consume the 150ml of fuel in the pipette was recorded.

3.3.4 Fuel heating system

A heat exchanger was designed and installed between the fuel filter and fuel pump for preheating of fuel. It consisted of a ¼ inch diameter copper tube coil immersed in a 20-liter water bath. The water bath was heated using an electrical hot plate. The temperature of the water was held to the desired level using a calibrated thermostat.

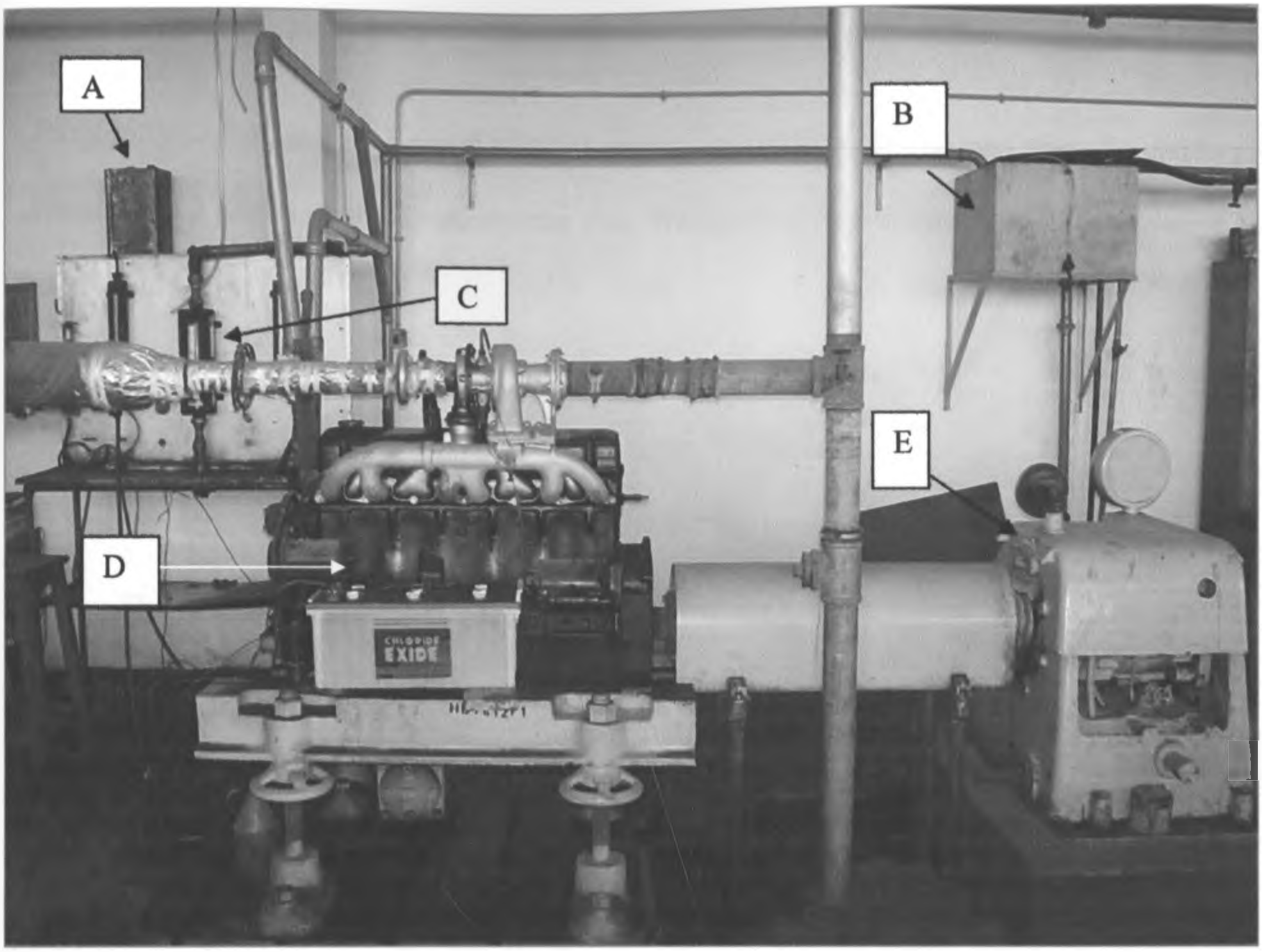

Photo No. 3 Engine test setup used in performance tests

A.	Fuel tank
B.	Cooling water tank
C.	Fuel flow pipette
D	Engine
E	Dynamometer

3.3.5 Engine test procedure

The throttle was set to give a speed of 1750 rev/min at a light load. The load was adjusted to give a reading of 2 pound on the dynamometer dial. When conditions were steady, the following data was recorded.

- Speed
- Load
- The time taken to consume 150ml of fuel
- Cooling water outlet temperature
- Cooling water inlet temperature
- Exhaust air temperature
- Ambient temperature

The above procedure was repeated for loads of 3,4,5,6 7 and 8 lb at the same speed for all fuel samples tested. Before the tests began the engine was warmed up using diesel fuel. The fuel lines were then drained of at each change of fuel. One litre of the test fuel was run through the system to purge of any remaining fuel from previous tests.

3.3.6 Calculations

The following formulas were used to evaluate the thermal efficiency and the Brake specific fuel consumption. Sample calculations are shown in Appendix A.

$$\text{Power input} = \frac{\text{density} \times \text{volume} \times \text{heating value}}{t} \ (\text{kW})$$

$$\text{Brake power} = \frac{W \times N \times 0.7457}{200} \ (\text{kW})$$

$$\text{Thermal efficiency} = \frac{\text{Brake power}}{\text{Power input}} \ (\%)$$

$$\text{Brake specific fuel consumption} = \frac{\text{Density} \times \text{volume}}{t \times \text{Brake power}} \ (\text{kg/kWh})$$

4 CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Fuel properties

Fuel characterisation data is shown in Table 4-1. The standards for diesel and biodiesel were used to ascertain the suitability of the fuel. Additionally, the obtained results were compared to those reported by Kinast (2003), who evaluated the properties of seven methyl esters namely that of soy, canola, lard, edible tallow, inedible tallow, low FFA Yellow grease and High FFA yellow grease. The results attributed to Kinast (2003) are shown in Table 4-3.

4.1.1 Copper strip corrosion

Results obtained for copper strip corrosion of biodiesel, diesel and their blends indicate that they have a minimum corrosion level of 1A on the defined scale on Table 2-2. 1A means that the strip was slightly tarnished and looked almost the same as a freshly polished strip after the test. ASTM D 975 allows a maximum value of 3B. Therefore biodiesel and its blends conform to this standard and so are the results reported by Kinast (2003), where a value of 1A was obtained for all the methyl esters evaluated.

4.1.2 Heat of combustion

The heat of combustion of diesel was determined to be 43.38 MJ/kg while that of biodiesel was found to be 38.52 MJ/kg, which is a difference of 11.2 %. The density of biodiesel was higher than that of diesel fuel (879 kg/m^3 and 842 kg/m^3 respectively at 25°C). Since injection pumps operate volumetrically, the energy content on volume basis is 36.53MJ/L for diesel and 33.86 MJ/L for biodiesel. This results in a theoretical increase in BSFC of 7.3 %. The mean values for heat of combustion of the methyl esters evaluated by Kinast (2003), was 7.7% lower than that of diesel on mass basis.

Table 4-1 Fuel characterization data for biodiesel, diesel and biodiesel-diesel blends

Sample identity	Biodiesel	BD80	BD60	BD40	BD20	DIESEL
Property						
Density @ 20°C (kg/m^3)	882.1	874.4	867.8	861.2	854.9	847.9
Density @ 15°C (kg/m^3)	886.6	878.3	871.2	865.4	858.3	851.3
Cetane index	45.35	47.47	49.58	49.68	49.54	51.22
Viscosity (cST)	6.55	5.56	4.75	4.32		3.36
Cloud point	12	9	4	6	7	7
Sulphur	0.02	0.11	0.16	0.30	0.39	0.535
Copper corrosion	1A	1A	1A	1A	1A	1A
Calorific value	38.52	39.72	40.38	41.38	42.68	43.38

4.1.3 Cloud point

ASTM D 975 does not specify the limits for cloud point but notes that it varies with local climatic conditions. From Table 4-1, biodiesel had a cloud point of 12°C, this means that the fuel should not be used in areas where the local temperatures fall below 12°C. Blending biodiesel with diesel reduced the cloud point such that BD20, BD40, BD60, BD80 and diesel recorded a cloud point of 7, 6, 4, 9 and 7 °C respectively. Results reported by Kinast (2003) on the seven methyl esters showed that the cloud point varied from as low as -3 °C to as high as 42 °C.

4.1.4 Sulphur content

From Figure 4-1, the sulphur content of the fuel samples studied exhibited a decrease with increase in biodiesel concentration in the blend. Biodiesel had the lowest sulphur content of 0.02% which is within the standard specification of 0.05 %. The sulphur content for the blends was 0.11, 0.16, 0.3, 0.39 and 0.535% for BD80, BD60, BD40, BD20 and Diesel respectively. This indicates that the use of biodiesel as an additive results in a decrease of sulphur content. The maximum Sulphur content permitted by the standard D 975 for diesel is 0.5 %, diesel fuel surpassed this value by 0.035%. In Kinast's study, all the seven Methyl esters were found to contain sulphur levels that were less than 0.05% mass.

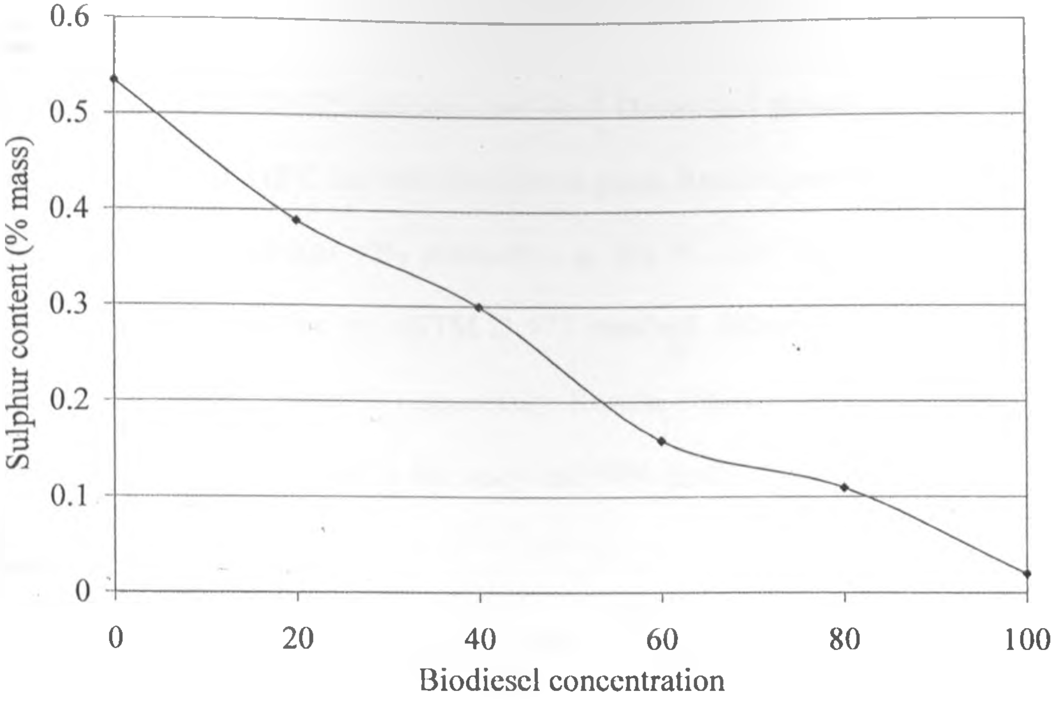

Figure 4-1 Variation of Sulphur content with increase in biodiesel concentration in the blend

4.1.5 Cetane index.

Biodiesel and its blends met the minimum acceptable cetane index of 40 that is recommended by ASTM D 975 standard. Biodiesel had a cetane index of 45.35 while that of diesel was 51.22. There was a small difference between blends of B20, BD40 and BD60 as seen in Table 4-1. Kinast (2003) noted that apart from Soy Methyl Ester whose cetane number was 47.2, all the methyl esters had cetane numbers that was higher than that of diesel.

4.1.6 Distillation

The standard ASTM D 975 indicates that No 2 Diesel fuel should have a lower limit of 282 °C and upper limits of 338°C for 90% distillation point. Results presented in Table 4-2 show that B 100, BD20 and BD40 had 90% distillation at 326 °C, 321 °C and 329 °C. These values were within the range specified by ASTM D 975 standard. BD60, BD80 and Diesel surpassed this limits by 11 °C, 17°C and 9 °C respectively. Results obtained by Kinast (2003) show that all the seven-methyl esters analyzed in his study had 90% distillation temperatures that were above the maximum limits.

Table 4-2 Test results for Distillation of biodiesel, diesel and biodiesel-diesel blends

Observation point	Temperature °C					
	Biodiesel	BD20	BD40	BD60	BD80	Diesel
IBP	192	112	182	190	110	170
5%	202	285	256	238	210	218
10%	260	298	285	251	230	226
20%	319	310	304	280	262	249
30%	321	315	312	293	275	265
40%	323	320	317	304	290	280
50%	324	322	323	311	298	290
60%		328	328	320	311	301
70%		330	332	325	320	310
80%		335	339	328		326
90%		344	342			336
95%			345			
FBP	326	347	349	329	321	335
	@60%	@95%	@90%	@84%	@80%	@95%

4.1.7 Viscosity

The viscosity of biodiesel at 25 °C was 7.3cST, twice that of diesel (3.5cST). When the oil was heated the viscosity dropped with increase in temperature, from 7.3cST at 25 °C to 1.1ct at 95 °C. The effects of heating oil on viscosity are shown in Figure 4-2. As for blends, the viscosity increased linearly with increase in biodiesel content in the mixture (Figure 4-3). The standard ASTM D 975 recommends 1.9 cST and 6.5 cST at 40 °C as optimum operating limits for viscosity of biodiesel. The viscosity of biodiesel @40 °C was 4.35 cST, which is well within the recommended range. From the study by Kinast (2003), the viscosities varied from 4.546 cST for soy methyl ester to 5.62 cST for Low FFA yellow grease.

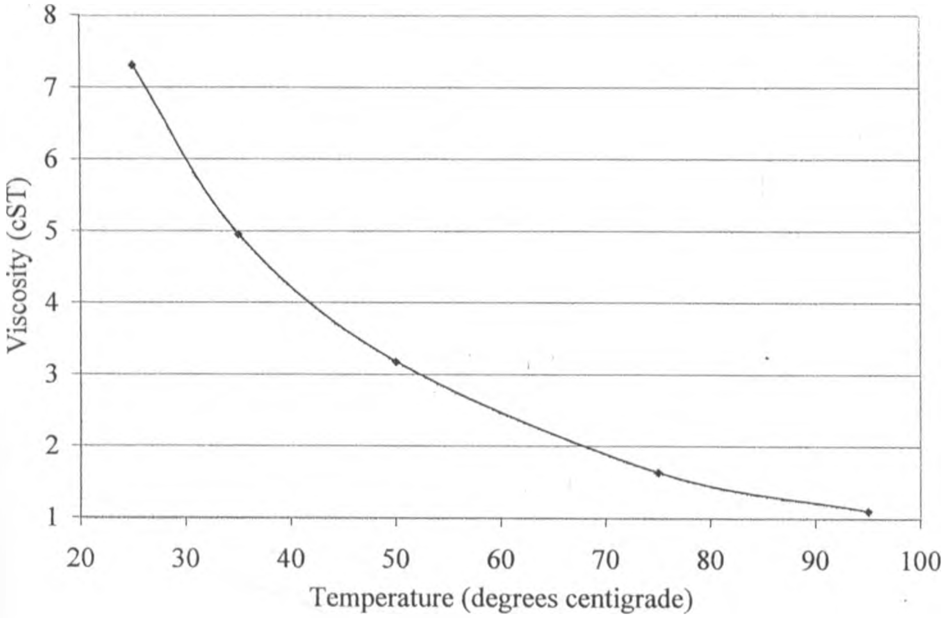

Figure 4-2 Effects of temperature on viscosity of biodiesel

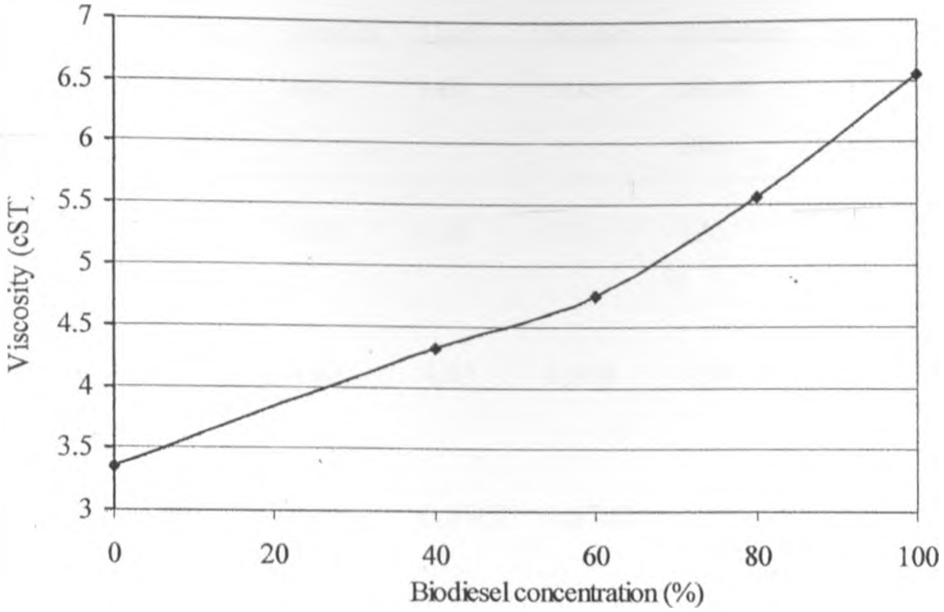

Figure 4-3 Viscosity variation with increase in biodiesel concentration in the blend

Table 4-3 Characterisation results of seven methyl esters reported by Kinast (2003)

Property	Soy ME	Canola ME	Lard ME	Edible tallow	Inedible tallow ME	LFFA Yellow grease	HFFA Yellow grease	2D Diesel
Flash point °C	167	163	128	173	136	160	147	N/A
Viscosity cST	4.546	4.63	4.85	4.908	4.93	5.62	4.66	2.45
Relative density	0.8877	0.8811	0.8762	0.8708	0.8767	0.8789	0.9767	N/A
Cetane No.	47.2	55	63.7	62.9	61.7	57.8	52.8	47
Cloud point °C	2	-3	14	20	23	42	8	-18
Sulphur % mass	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
Copper corrosion	1A	1A	1A	1A	1A	1A	1A	1A
Distillation °C								
IBP	323	316	304	324	322	329	312	N/A
EP	256	355	354	361	357	352	353	

Source: Kinast (2003).

4.2 Engine test results

4.2.1 Effects of biodiesel on engine performance

As shown on Figure 4-4 the BSFC of the engine when operating on biodiesel was higher than when operating on diesel. From the tests, the average BSFC of biodiesel was approximately 12 % higher (282 g/kWh for diesel and 318 g/kWh for biodiesel). The projected increase was 7.3 % (section 4.1.2). When an engine is tested on fuels with different properties, it will yield consumptions that vary by less than the percentage difference in the calorific value since the diesel engine is optimized for diesel fuel (Wright and Purday, 1950). Therefore both the low energy density and the high viscosity of biodiesel were perceived to be the cause of the increased BSFC.

The brake thermal efficiency of the engine when operating on diesel and biodiesel fuels were almost the same as shown in Figure 4-5. Brake thermal efficiency is defined as the actual brake work per cycle divided by the amount of fuel chemical energy as indicated by the fuel's lower heating value. This means that the engine converts the chemical energy of the fuel to mechanical energy with the same efficiency for the two fuels used in the test.

At this point effects of two processes were incorporated in the study, namely preheating of the fuel and blending it with diesel. Preheating the oil was expected to reduce the viscosity and as a result improve its spray and atomization characteristics. Blending with diesel was expected to reduce the viscosity and increase the calorific value of the oil.

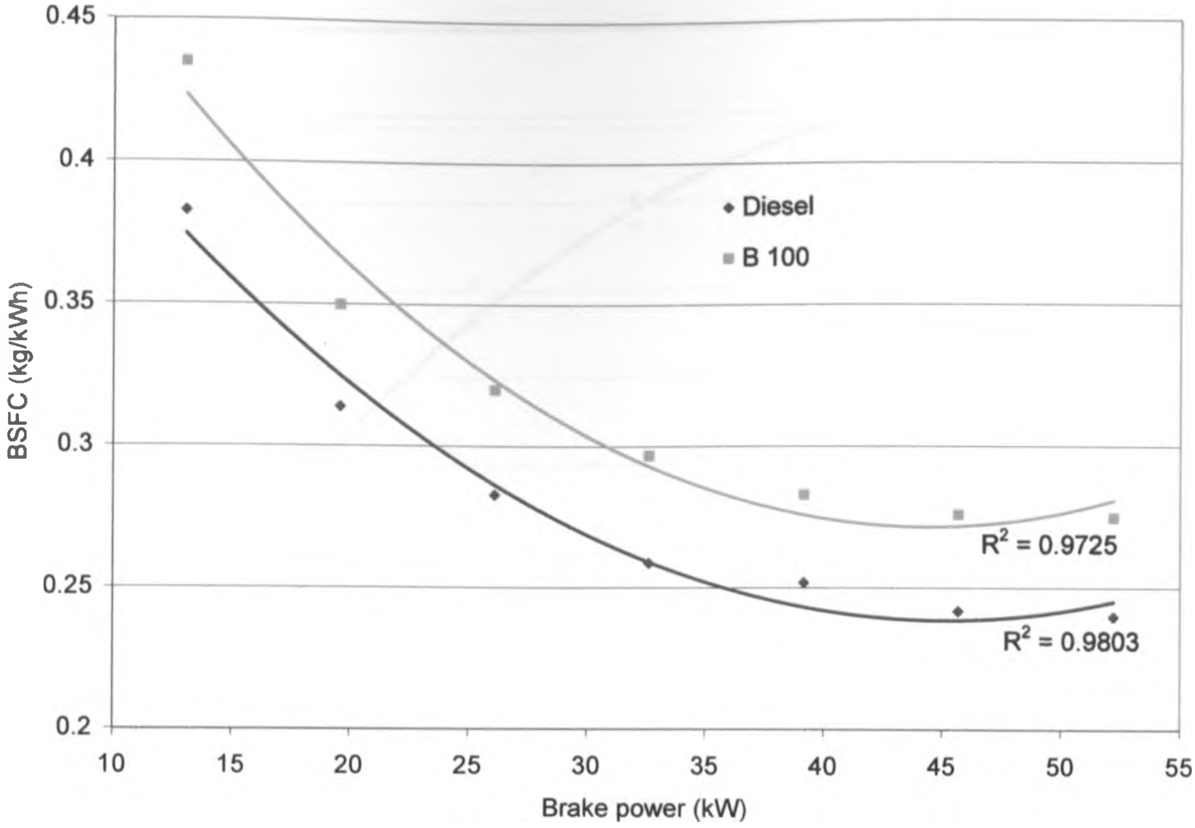

Figure 4-4 Variation of BSFC of diesel and biodiesel with brake power

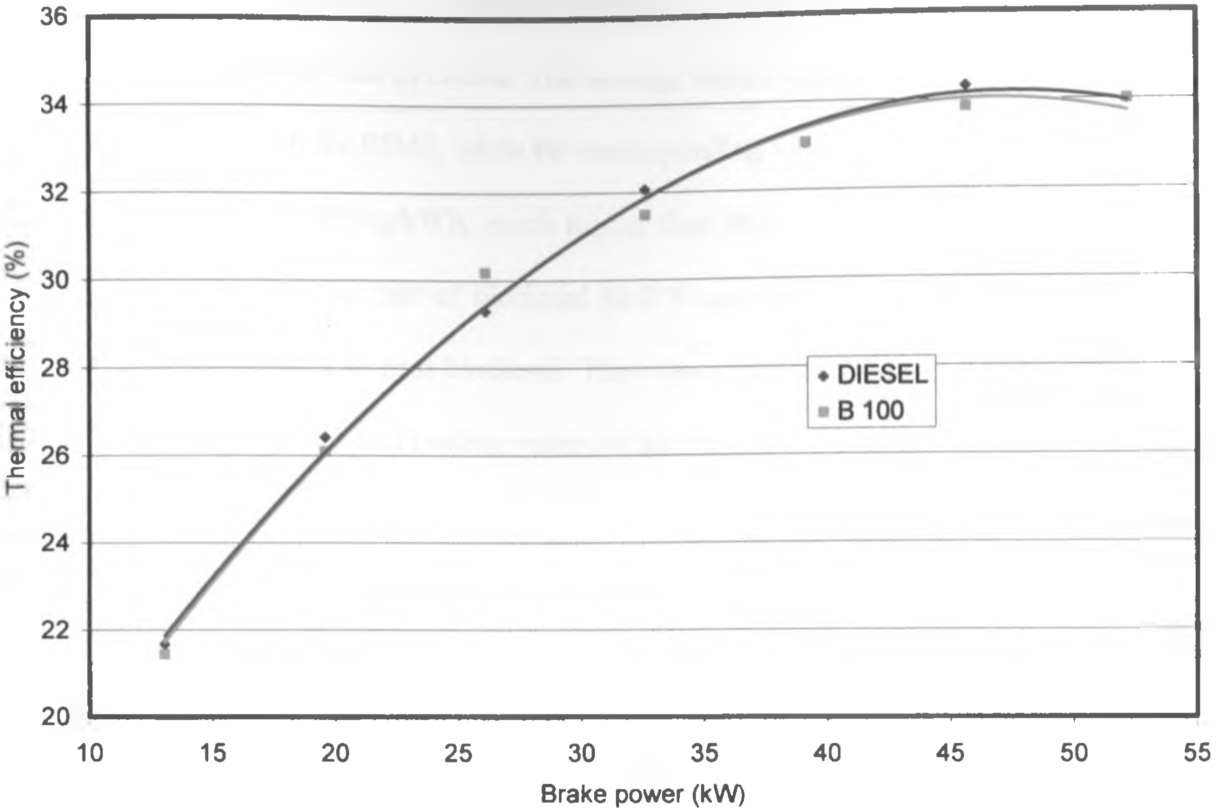

Figure 4-5 Variation of Thermal efficiency of diesel and biodiesel with brake power

4.2.2 Effects of blends on engine performance

The fuels were blended volumetrically to 20 (BD20), 40 (BD40), 60 (BD60) and 80% (BD80) biodiesel levels. Comparison of the BSFC of the engine when running on biodiesel, diesel and their blends is shown in Figure 4 -6. It was observed that the BSFC of diesel, biodiesel and their blends maintained a similar trend, the BSFC reduced with increase in load for all the fuel samples. The BSFC of the fuel samples were also found to increase with increase in the proportion of biodiesel content in the blend. Because of the greater energy density and viscous properties of Diesel, the engine was capable of generating the lowest BSFC while running on the reference diesel fuel. However, a smaller difference in BSFC was observed with BD20 and BD40 blends compared to that of Diesel. The average values were found to be 0.285 kg/kWh for BD20 and 0.290kg/kWh for BD40, while the corresponding value for Diesel was 0.282 kg/kWh. BD60 had a BSFC of 0.307kg/kWh, much higher than that of diesel, while that of BD80 was 0.317kg/kWh, very close to that of biodiesel (0.318 kg/KWh). In general, all blends showed improved BSFC compared to neat biodiesel. This was attributed to the combined effects of the improved viscous properties and heating values of the blends.

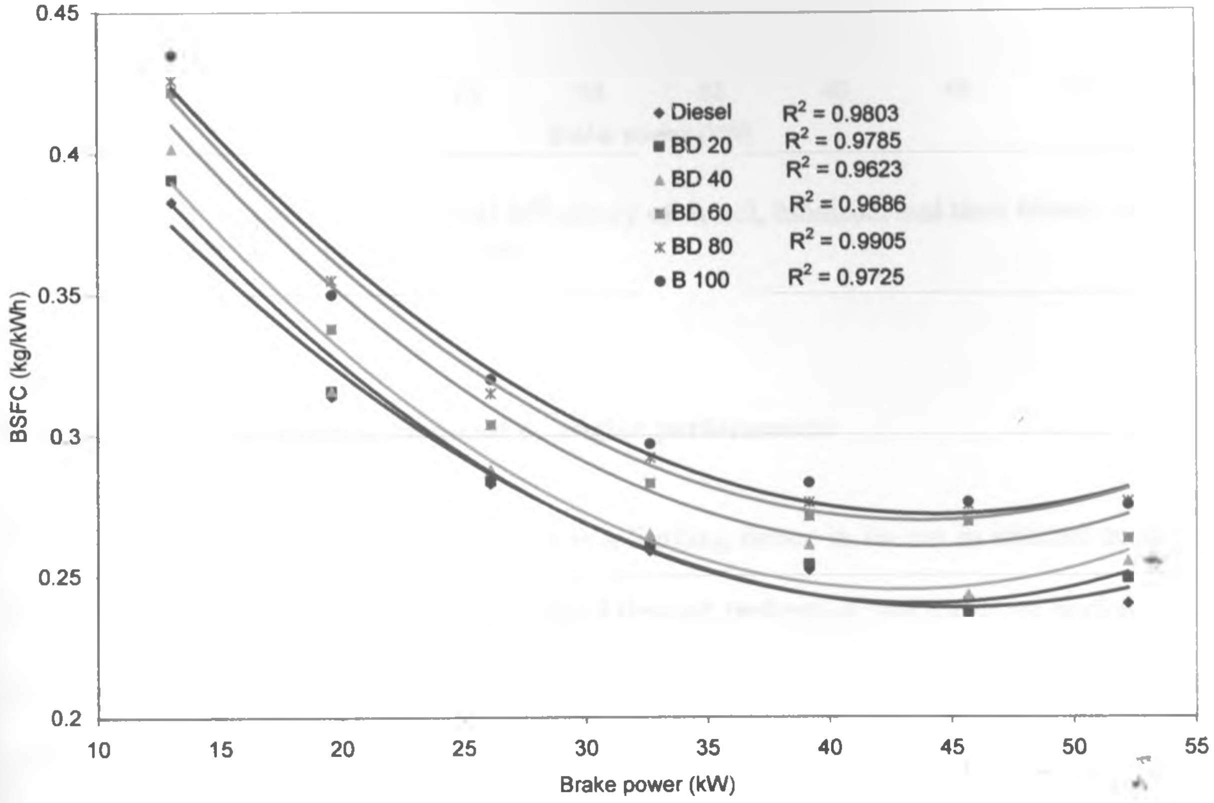

Figure 4-6 Comparison of BSFC of diesel, biodiesel and their blends with respect to increase in load

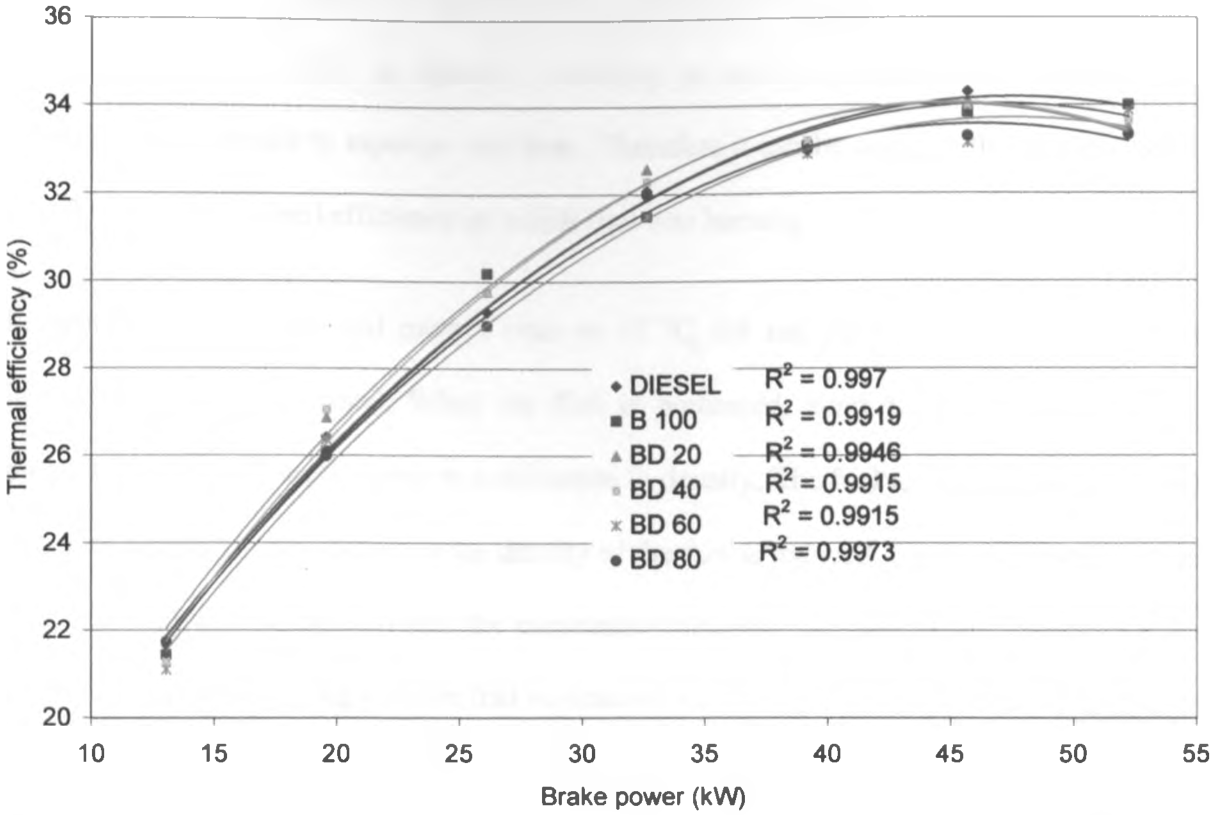

Figure 4-7 Comparison of Thermal Efficiency of diesel, biodiesel and their blends with respect to increase in load

4.2.3 Effects of preheating biodiesel on engine performance

High viscosity of vegetable based oil fuels is a limiting factor in its use in internal combustion engines. Reduction of viscosity of the biodiesel through preheating was therefore performed. The vegetable oil methyl ester was preheated to 35 and 47 °C and engine performance test were carried out. Plots of the effects of preheating biodiesel on engine performance are shown in Figure 4-8 and 4-9. It was observed that preheating biodiesel from ambient conditions to 35 °C reduced the BSFC of the vegetable oil methyl ester from 12 to 7.8 % above that of diesel while the thermal efficiency increased from 30.04 to 31.34%. Preheating the oil reduced viscosity from

7.1 cST to 4.9 cST. The lower viscosity was considered to improve the spray and atomization characteristics of the fuel on injection, resulting in more even distribution of fuel and finer droplets that are easier to vaporize and burn. Therefore it can be deduced that the reduced BSFC was due to the improved efficiency at which fuel was burning.

Preheating the vegetable oil methyl ester to 47 °C did not yield further reduction in BSFC, instead the BSFC increased. When the fuel is preheated, apart from improving the viscous properties of the oil, it also leads to a reduction in density. The fuel is metered to the combustion chamber volumetrically. So when the density of the fuel is reduced, for the same volumetric flow rate, less fuel will be injected into the combustion chamber on mass basis. Therefore there will be a drop in power leading to more fuel injected to make up for the power loss. Hence no further preheating was done beyond this temperature. At 47 °C, the viscosity of vegetable oil methyl ester approximates that of diesel at room temperature.

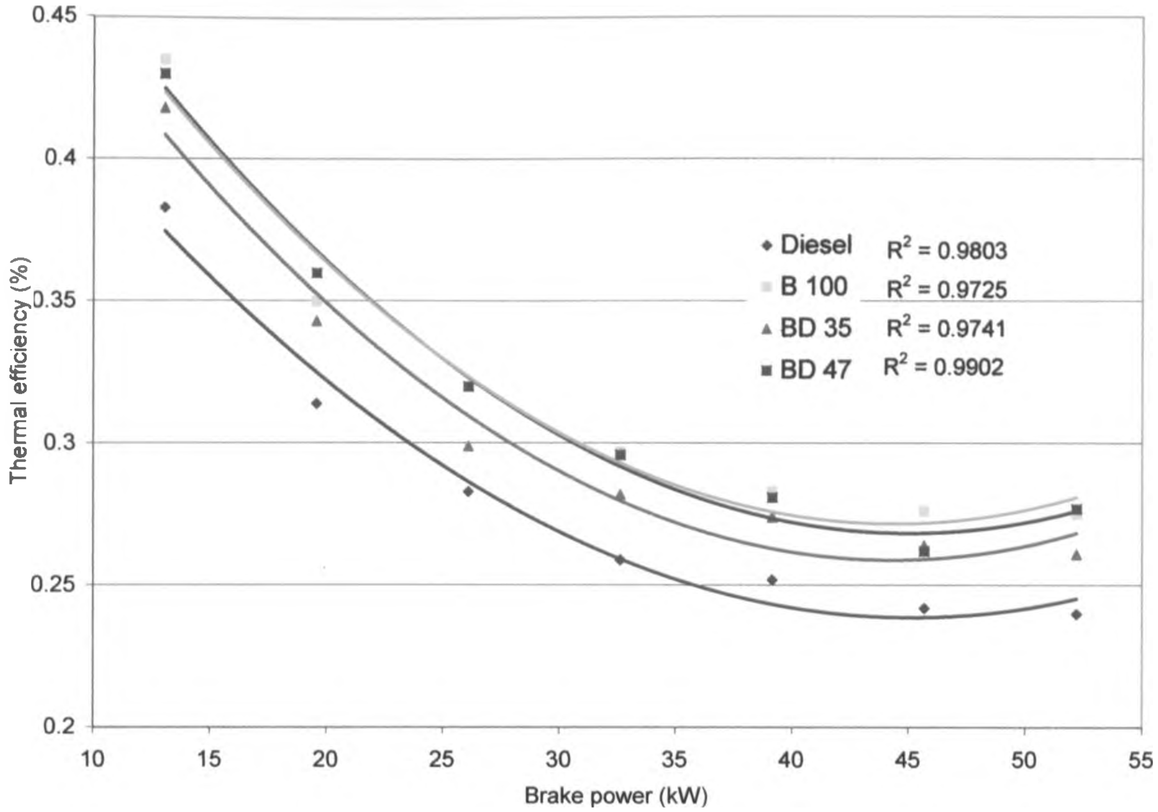

Figure 4-8 Effects of preheating biodiesel on BSFC

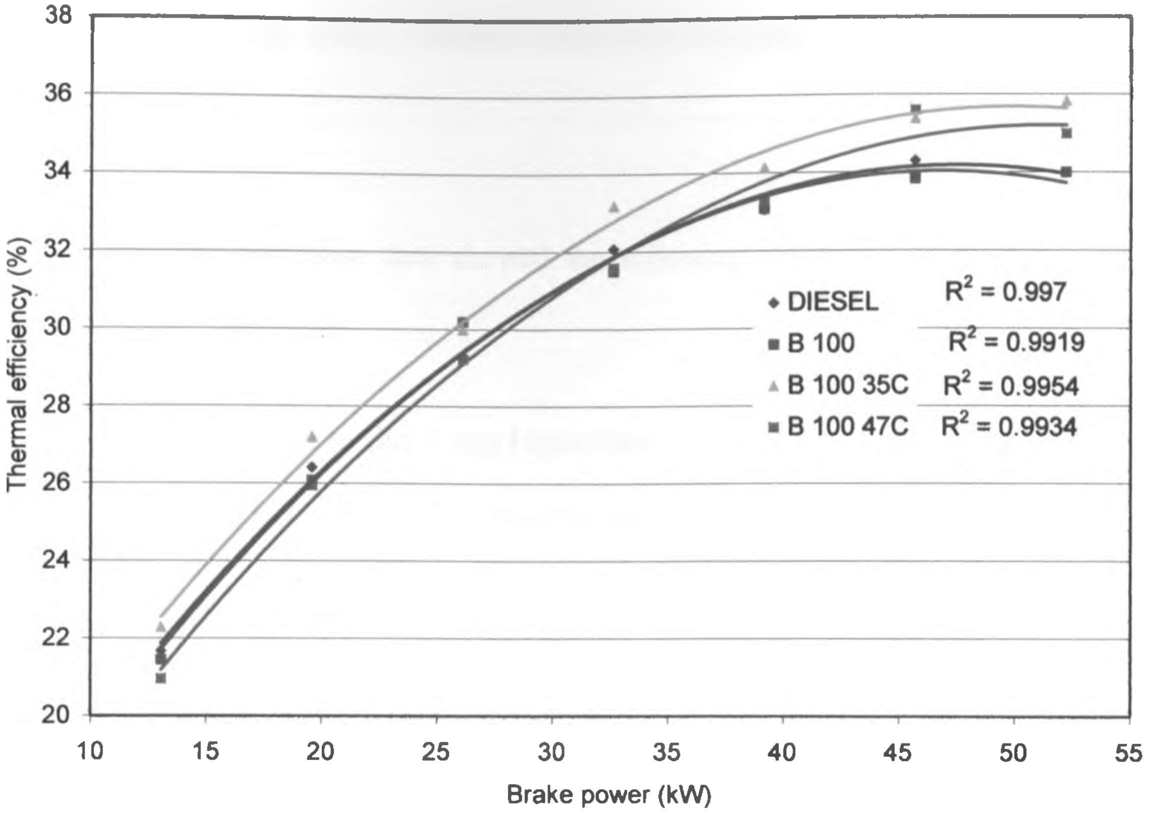

Figure 4-9 Effects of preheating biodiesel on brake thermal efficiency

5 CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

1. Fuel characterization data showed the following similarities and differences between biodiesel and diesel.

    a. Density of biodiesel was higher than that of diesel.

    b. Heat of combustion of biodiesel was 11.2% lower than that of diesel.

    c. The viscosity of biodiesel was twice that of diesel.

    d. The Cetane indexes of the two fuels were comparable.

    e. Sulphur content for diesel was 26.75 times that of biodiesel.

    f. Both biodiesel and diesel recorded the minimum corrosion level on the copper strip corrosion test.

2. BSFC of the engine when operating on biodiesel was 12% higher than when running on diesel. There was no significant difference in thermal efficiencies between biodiesel, diesel and the blends.

3. Preheating biodiesel from ambient conditions to 35°C reduced the BSFC of the vegetable oil methyl ester from 12 to 7.8 % above that of diesel while the thermal efficiency increased from 30.04 to 31.34%. Preheating to 47°C did not yield further reduction in BSFC.

4. BSFC for the blends was found to increase with increase in proportion of biodiesel content in the blend. The engine was capable of generating the lowest Brake Specific Fuel Consumption while running on the reference diesel fuel. A small difference in BSFC was observed with BD20 and BD40 blends. As for BD60 and BD80, due to the energy differences, they produced a higher BSFC than diesel fuel.

5.2 Recommendation for further work

The results of this study confirm that used vegetable oils can be processed to biodiesel and produce acceptable performance when used as fuel in diesel engines. The following areas have been identified for further research.

1. Quantification of available used frying oil in Kenya in terms of location.
2. The economics of production of Biodiesel from used cooking oils.
3. Variation in quality of oil attributed to types of foods cooked and cooking practices.
4. The effects of long-term storage on the possible changes in physical and chemical properties of biodiesel.
5. A study to identify suitable additives that can improve the characteristics of biodiesel (e.g. cloud point).

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7 APPENDICES .

Appendix A Sample calculations for BSFC and thermal efficiency for biodiesel.

Sample data: Time to consume 150ml of fuel (t) – 83.55 seconds

Density of biodiesel 879 kg/m^3

Engine speed (N) 1750 rpm

Heating value 38.52 MJ/kg

Formulas

$$\text{Power input} = \frac{\text{density} \times \text{volume} \times \text{heating value}}{t} \text{ (kW)}$$

$$\text{Brake power} = \frac{W \times N \times 0.7457}{200} \text{ (kW)}$$

$$\text{Thermal efficiency} = \frac{\text{Brake power}}{\text{Power input}} \text{ (\%)}$$

$$\text{Brake specific fuel consumption} = \frac{\text{Density} \times \text{volume}}{t \times \text{Brake power.}}$$

Calculation

$$\text{Brake power} = \frac{2 \times 1750 \times 0.7457}{200} = 13.05\text{kW}$$

$$\text{Power input} = \frac{879 \times 150 \times 38.52 \times 10^{-3}}{83.55} = 60.79 \text{ kW}$$

$$\text{Efficiency} = \frac{13.05}{60.79} = 21.46\%$$

$$\text{BSFC} = \frac{879 \times 150 \times 10^{-6} \times 3600}{83.55 \times 13.05} = 0.435 \text{ kg/KWh}$$

Appendix B Average values and percentage changes in BSFC and thermal efficiency of biodiesel, diesel and their blends.

Fuel type	BSFC (kg/KWh)	% change in BSFC	Thermal efficiency (%)	% change in thermal eff.
Diesel	0.282	_	30.22	_
B 100	0.318	12.77	30.04	-0.60
B 100 at 35^{0}C	0.306	8.51	31.34	3.71
B 100 at 47^{0}C	0.318	12.77	30.38	0.53
BD20	0.285	1.06	30.86	2.12
BD40	0.290	2.84	30.31	0.30
BD60	0.307	8.87	29.70	-1.72
BD80	0.317	12.41	29.75	-1.20

Appendix C Engine performance test results for biodiesel, diesel and their blends.

FUEL	LOAD (lb)	BSFC (kg/kWh)	THERMAL EFFICIENCY (%)
DF 2	2	0.383	21.69
	3	0.314	26.43
	4	0.283	29.31
	5	0.259	32.08
	6	0.252	33.06
	7	0.242	34.31
	8	0.240	34.64
BD20	2	0.391	21.64
	3	0.316	26.92
	4	0.284	29.79
	5	0.261	32.32
	6	0.254	33.10
	7	0.237	35.59
	8	0.249	33.81
BD40	2	0.402	21.29
	3	0.316	27.04
	4	0.288	29.76
	5	0.265	32.24
	6	0.261	32.77
	7	0.243	35.27
	8	0.255	33.63
BD60	2	0.422	21.12
	3	0.338	26.38
	4	0.304	29.0
	5	0.283	31.5
	6	0.271	32.90
	7	0.269	33.14
	8	0.263	33.89
BD80	2	0.426	21.76
	3	0.355	24.88
	4	0.315	28.00
	5	0.294	32.00
	6	0.277	31.80
	7	0.274	33.30
	8	0.278	33.33
B 100	2	0.435	21.29
	3	0.348	26.56
	4	0.310	29.73
	5	0.297	31.85
	6	0.283	33.17
	7	0.276	33.46
	8	0.275	34.14

FUEL	LOAD	BSFC Kg/kWh	THERMAL EFFICIENCY (%)
B 100 at 35^{0}C	2	0.418	21.46
	3	0.343	26.19
	4	0.299	30.00
	5	0.282	31.93
	6	0.274	32.85
	7	0.264	34.00
	8	0.261	34.50
B 100 at 47^{0}C	2	0.43	20.00
	3	0.360	24.98
	4	0.320	28.13
	5	0.296	30.38
	6	0.281	32.01
	7	0.262	34.29
	8	0..277	34.63

Appendix D Sample calculation for the calorific value of biodiesel.

Temperature recorded in °C after every one minute

26.47

26.42

26.40

26.40 *

28.05

29.61

30.19

30.37

30.44 *

30.44

30.39

30.34

30.32

30.29

30.22

$$\text{Cooling correction} = nv + \left((v_l - v) / (t_l - t)\right) \left\{\sum_{1}^{(n-1)} (t) + 1/2(t_o + t_n) - nt\right\}$$

$n = 6$

$v = \dfrac{26.47 - 26.40}{3} = -0.0233$

$v_l = \dfrac{30.44 - 30.22}{6} = 0.0367$

$t = 26.42$

$t_l = 30.33$

$1/2(t_o + t_n) = 1/2(26.40 + 30.44) = 28.42$

$\left\{\sum_{1}^{(n-1)} (t) = 148.65\right.$

Cooling correction = -6 x 0.233 + [(0.0367 + 0.0233) / (30.33 – 26.42)] x (148 + 28.42 - 158.52)

= 0.14

Temperature change = t_n - t_{o} + cooling correction

= 30.44 – 26.40 + 0.14

= 4.18

Calorific value = $\frac{\text{Total water equivalence} \times \text{specific heat capacity of water} \times \text{temperature rise}}{\text{Weight of sample}}$

$= \frac{2270 \text{ x } 4200 \text{ x } 4.18}{1}$

= 39.85 MJ / kg

Appendix E Sample calculation for the cetane index of biodiesel.

ASTM D 976 formula

Cetane Index = $454.74 - 1641.416\ D + 774.74\ D^2 - 0.554\ T_{50} + 97.803[\log10\ (T_{50})]^2$

Data $D = 0.8866$kg/l

$T_{50} = 324^0$C

Calculations

$= 454.4 - 1641.416(0.8886) + 774.78(0.8866)^2 - 0.554\ (324) + 97.803\ (\log_{10} 324^2)^2$

$= 45.35$

Appendix F Sample calculation for density and viscosity of biodiesel at 25 °C.

Density of biodiesel at 25 °C

Mass of density bottle =23.1300g

Mass of density bottle + water = 47.9629g

Mass of water = 47.9629g – 23.1300g = 24.8329

Density of water at 25 °C = 0.99707g/ml

$$\text{Volume of bottle} = \frac{\text{mass of water}}{\text{Density of water}} = \frac{24.8329}{0.99707} = 24.9074 \text{ ml}$$

Mass of density bottle =23.1300g

Mass of density bottle + fuel sample = 45.4020g

Mass of sample = 45.4020 – 23.1300 = 21.9167g

$$\text{Density of sample} = \frac{\text{mass of sample}}{\text{Volume of bottle}} = \frac{21.9167}{24.9074} = 0.8799\text{g/ml} = 879.9 \text{ kg/m}^3$$

Viscosity of biodiesel at 25^0C

$$U'_O = \frac{t_o\, U'_W}{t_W}$$

data Density of water at 25 °C = 997 kg/m^3

Dynamic viscosity of water at 25 ° C = 8.954 millipoise

Kinematic viscosity of water = $\frac{8.954 \times 10^2}{997}$ = 0.895 cST

Time taken for oil to flow (t_o) = 114 seconds

Time taken for water to flow (t_W) = 14 seconds

Kinematic viscosity of the oil (U'_O) = $\frac{114 \times 0.898}{14}$

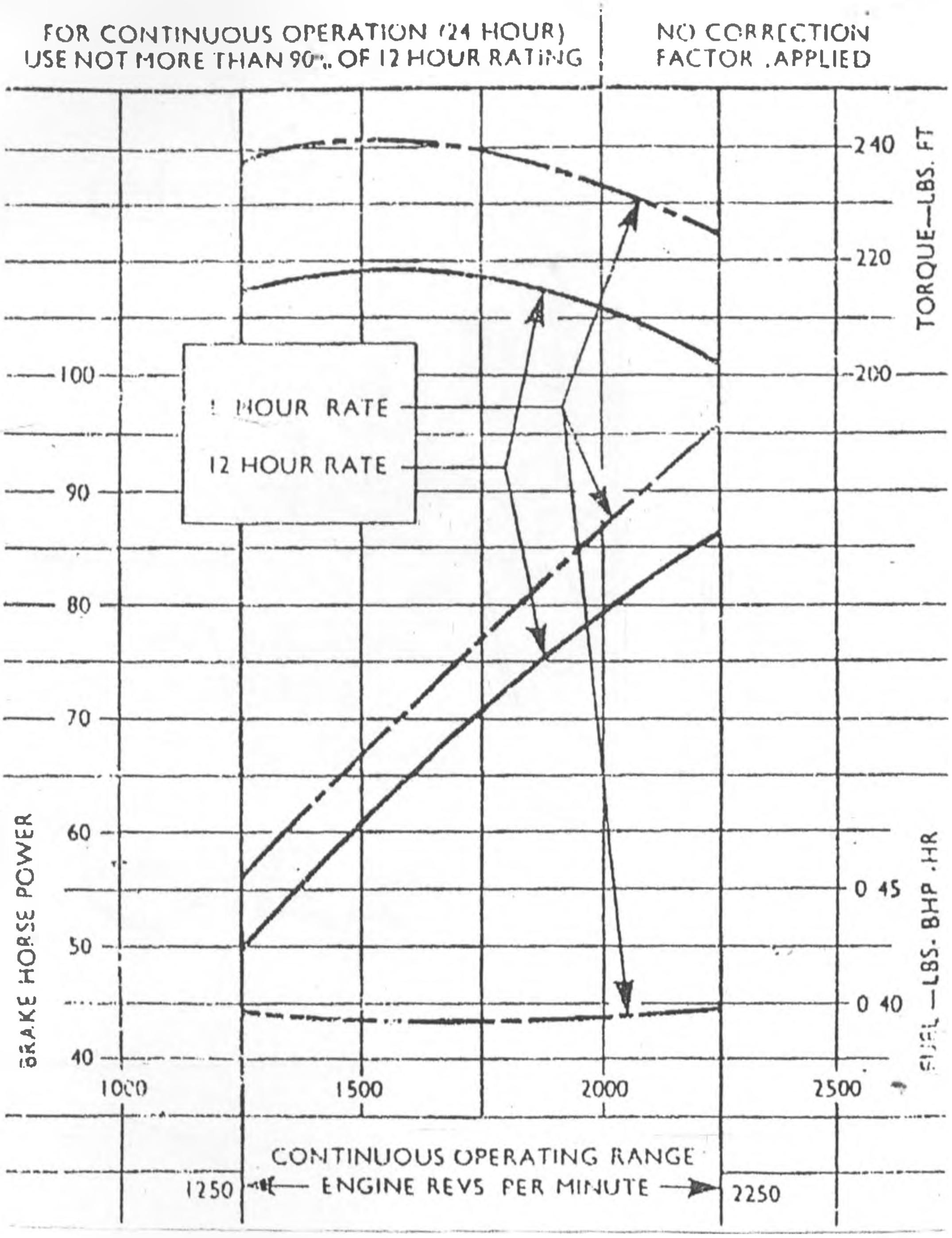
= 7.31 cST

Appendix G Density and viscosity of water at different temperatures

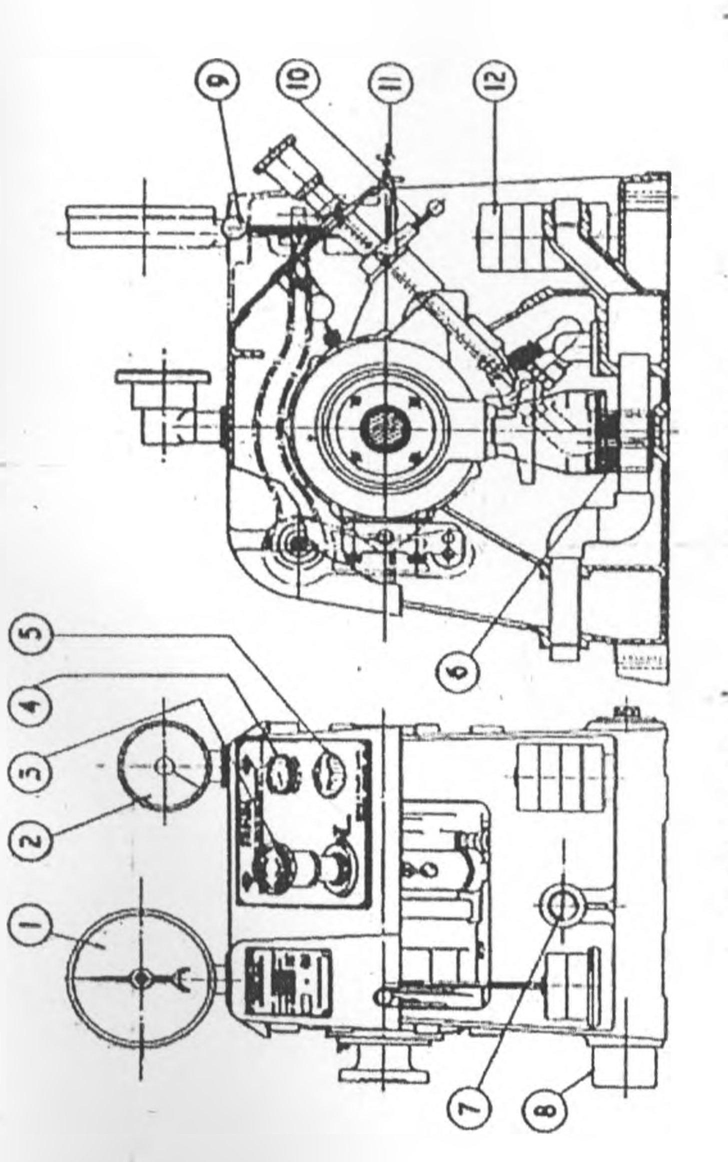
Temperature (°C)	Viscosity (millipoise)	Density (g/cm^3)
15	11.452	0.99913
20	10.087	0.99823
25	8.954	0.99707
30	8.004	0.99567
35	7.211	0.99406
40	6.536	0.99224
45	5.972	0.99025
50	5.492	0.98807
55	5.074	0.98573
60	4.699	0.98324

Source. Lange, N.A. (1941)

Appendix H Engine manufacturers test data.



Appendix I Dynamometer cross-section.



(1) SPRING BALANCE | WITH SWIVELLING DIALS
(2) TACHOMETER.
(3) LOAD CONTROL HANDWHEEL.
(4) WATER OUTLET THERMOMETER.
(5) WATER TEMPERATURE CONTROL.
(6) WATER INLET STRAINER.
(7) WATER INLET.
(8) WATER OUTLET.
(9) RELEASE LOAD CONTROL.
(10) LOCKING CATCH FOR (9).
(11) WEIGHING GEAR DASHPOT.
(12) BALANCE WEIGHTS.