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Effect of Antioxidants on the Performance Characteristic of A Diesel Engine Fuelled With Diesel And Jatropha Biodiesel Blends

اثر المواد مانعة الأكسدة على خصائص اداء محرك الديزل باستخدام خليط الديزل و الجاتروفا

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Sciences (M.Sc.) in Mechanical Engineering (Power)

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March 2019

Dedication

My

Parents;

Beloved wife;

Lovely kids;

Brothers and sisters

Acknowledgement

In the name of Allah, the Most Gracious, the Most Merciful. Praise be to Allah, the Lord of the Worlds; peace and blessings of Allah be upon the noblest of the Prophets and Messengers, our Prophet Mohammed and upon his family, companions and who follows him until the last day. I am truly and deeply indebted to so many people that there is no way to acknowledge them all or even any of them properly.

First of all, I wish to express my deep sense of gratitude and indebtedness to my Supervisor Dr. Abbass Hassan Abbass and express my heart-felt appreciation for his unreserved support in guiding me through this research from its start to the end with limitless help in giving valuable advice, providing supportive materials and constructive comments.

I would like to express my sincere gratitude to Sudan University for their co – operation and for providing the facilities during my study.

I wish to acknowledge the efforts of the Engine Performance Laboratory, Faculty of Mechanical Engineering at University Blue Nile for their standing beside me in the experimental work. Special thanks to Dr Ibrahim Khalil and my friend engineer Mutaz Hassan .

At last and most importantly, I would like to thank my parents, wife and all family members for their open-mindedness and endless support. They are always close to my heart. Without the help and support of all these people, this thesis would not be completed.

Finally, I offer my sincerest apologies to anyone I ungratefully omitted from explicit mention.

Abstract

Biodiesel is a clean-burning alternative fuel produced from renewable resources. However, it is susceptible to oxidative degradation due to autoxidation in the presence of oxygen, which hinders its widespread use. Antioxidant addition is a prospective solution to this problem. It is expected that antioxidants may affect the clean-burning characteristic of biodiesel. The aim of current study is to investigate the feasibility of biodiesel-diesel blended fuel of (30%, 35% and 40% biodiesel) treated antioxidants, as fuel for unmodified diesel engines. The physical and chemical properties such as density, Kinematic viscosity, flash point and Calorific value were carried out for, Jatropha oil and Jatropha Oil Methyl Ester (JOME) produced in the laboratory. The experimental test were conducted to study the engine performance such as brake power, brake specific fuel consumption, brake thermal efficiency, indicated power, indicated specific fuel consumption, indicated thermal efficiency and mechanical efficiency. Experiments were carried out on four cylinders, four stroke, compression ignition engine, at four different (speeds, loads) and five different fuel samples.

According to the results obtained it was found Antioxidant added blends increases the brake power slightly by load compared to the brake power output from engine when using biodiesel fuel, more precisely the blend (D65B35DM) gives the highest brake power and blend (D60B40DM) gives the lowers brake power compared to the other fuel samples and decreases the brake specific fuel consumption by load and speed. Antioxidant blends improve the brake thermal efficiency relatively high slightly compared to the brake thermal efficiency when using biodiesel fuel, more precisely the maximum efficiency was obtained at engine speed of 2000 rpm; and that when using (D70B30DM) blend (47.7%).

المستخلص

يعتبرالوقود الحيوى وقود بديل وامن منتج من الطاقات المتجدده . لكنه يكون عرضه للأكسده و ذلك للأكسده الذاتيه الناتجه من وجود ذرات الأوكسجين فى الوقود، مما يحول دون استخدامه على نطاق واسع . إضافة المواد مانعة الأكسده للوقود الحيوى متوقع ان تكون حل لهذه المشكله بالإضافه الى ذلك يتوقع الحصول على نواتج احتراق نظيفه. الهدف من الدراسه الحاليه هو معرفة اثر الوقود الحيوى المضاف اليه المواد مانعة الاكسده على محركات الديزل غير المعدله وذلك بنسب (30%, 35%, 40%) . تم قياس الخواص الفيزيائيه والكيميائيه للوقود الحيوى المنتج فى المختبر مثل (الكثافه، اللزوجه، القيمه الحراريه ونقطة الوميض). وكذلك تم إجراء الإختبار التجريبى لدراسة اداء المحرك مثل (القدره الفرمليه، معدل استهلاك الوقود، القدره البيانيه، الكفاءه الحراريه والكفاءه الميكانيكيه). التجارب اجريت على محرك إشتعال بالضغط رباعى الاشواط والاسطوانات عند اربعه سرعات مختلفه وخمسه خلطات مختلفه من الوقود ، ايضا اجريت تجارب لنفس العينات مع تحميل مختلف. وفقا للنتائج التى تم الحصول عليها تبين ان إضافة المواد مانعة الأكسده للوقود الحيوى تعمل على زيادة القدره الفرمليه بالنسبه للاحمال ، ووجد أن الخلطه (D65B35DM) تعطى اعلى قدره فرمليه والخلطه (D60B40DM) تعطى اقل قدرة فرملية.ايضا اضافة هذه المواد المانعه للاكسده تعمل على انخفاض معدل استهلاك الوقود فى حالة السرعات والاحمال كما انها تؤدى الى تحسين الكفاءه الحراريه مقارنة مع والوقود الحيوى الذى لاتوجد فيه مواد مانعه للاكسده .كما وجد ان اعلى كفاءه حرارية 47.7% عند اعلى سرعه (2000rpm) باستخدام الخلطه (D70B30DM) .

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Abbreviations & Symbol

A/ Abbreviations:

ASTM	American Society for Testing and Materials
CO	Carbon monoxide
CO_2	Carbon dioxide
HC	Hydrocarbons
EISA	Energy Independence and Security Act
R•	A new carbon based fatty acid radicals
RH	Fatty acid substrate
ROOH	Alkyl hydroperoxides
ROO•	Peroxyl radicals
BJ	Jatropha Bio-diesel
D	diesel
BP	Brake Power
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
IP	Indicated power
ISFC	Indicated Specific Fuel Consumption
ITE	Indicated Thermal Efficiency
CI	Compression Ignition
C.V	Calorific Value
DMBA	4-Dimethylaminobenzaldehyde

B/ List of symbols:

Symbol	Function	Unit
BP	Brake power	kW
BSFC	Brake Specific Fuel	kg/kW.h
C.V	Calorific Value	kJ/kg
A	Cross Sectional Area of Piston	m^2
g	Acceleration due to gravity	m/s^2
L	Length of stroke of engine	=0.09 m
D	Bore of engine cylinder	=0.084 m
m	Mass of load acting on dynamometer	kg
T	Torque	N.m
N	Revolution of engine shaft per minute	RPM
N_c	Number of Cylinder	
n	Number of revolution required to complete one engine cycle	
bmp	Brake Mean Effective Pressure	N/m^2
Q_a	Flow rate of air intake by engine	m^3/s.
R	Arm length acting on dynamometer	=0.211m
X	Volume of fuel consumed	=150ml
M_f	Flow rate of fuel consumed by engine	kg/s
T	Fuel consumption time	sec
ηb_{th}	Brake thermal efficiency	%
ηi_{th}	indicated thermal efficiency	%

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CHAPTER 1

INTRODUCTION

1. Introduction

The energy demand has duplicated in the recent three decades. This is because of change in lifestyle, population growth and rapid economic development. As 97.6% of the world transportation sector relies on fossil fuel, it is estimated that fossil base fuel contribution could decline 30- 35% in 2035 [1]. However, World Energy Forum (WEF) claimed that fossil fuel will reach its peak production in the next 10 decades. Thus, the availability and prices of fossil based fuels will be a severe problem in future as evidenced by the global economic recession in 2007- 2009. Besides, the world today is faced with a serious global warming and environmental pollution. It is believed that 98% of the carbon emissions [carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), sulfur dioxide, particulate matter (PM), soot and hydrocarbons (HC)] in the atmosphere are due to fossil fuel burning [2]. These emissions are responsible for a number of health problems and the accumulation of free carbon in the atmosphere leads to climate change which may affect food productivity, forests activities and the ecology system [3]. Thus, there is a need to find an alternative energy sources that is renewable, clean, reliable and yet economically feasible. According to the Energy Policy Act of 1992 (EPACT, US) biodiesel, methanol, ethanol and natural gas are the main alternative sources to reduce fossil fuel dependency and exhaust gas emissions [4]. Biodiesel, as a replacement for diesel, is easily produced from renewable sources, such as vegetable oil and fats and it possesses similar fuel properties as those of diesel fuel. Despite the advantages of biodiesel, there is still a question about the trade off between biodiesel tendency to oxidize, higher NOx emission, poor cold flow properties and shorten storage time. Many researchers have used different sources (edible- nonedible) for biodiesel production. Among them, Jatropha is more convenient biodiesel source because can be irrigated using waste water. In addition Jatropha can yield up to 10 times higher oil compared to other sources of biodiesel with life expectancy of up to 50 years [5]. It is estimates that, one hectare of Jatropha could yield about 1,892 liters of oil. Jatropha contributes negligibly to the fuel versus food issues because it is not edible for humans or animals use. Thus growing Jatropha for biofuel production neither pulls away nutrients from the food market nor requires valuable due to its preference for arid soils. However, Jatropha biodiesel has lower oxidation stability and emit more NO_x than diesel fuel [6]. Therefore, it is essential to develop an efficient NOx reduction system for Jatropha biodiesel fuelled diesel engine and to improve the lower oxidation stability.

1.2 Problem statement

Conventional fuels, such as coal, natural gas, and fossil fuels, are constantly being depleted; however, the world's dependency on these fuels is still growing. In addition, the price of fossil fuels is ever increasing. For these reasons world are pursuing alternative fuel sources to facing the dependency on conventional fuels. Biodiesel considered one of the main alternative sources to reduce fossil fuel dependency and exhaust gas emissions. The major drawback of biodiesel hindering its commercial use in automobile are oxidation stability, low temperature properties and higher NO_x emission. The oxidation results in insoluble deposit and increase in several physicochemical properties. Fuel based solutions such as antioxidants additives is the promising approaches to improve the low oxidation stability. A few studies in the literature have used antioxidants in biodiesel blend to improve oxidation stability.

1.3 Objective of the study

The aim of this study is to investigate experimentally the performance characteristic of a diesel engine using biodiesel treated antioxidants. The specific objectives of the study are summarized as follow:

1. To explore strategy to improve the lower oxidation stability of biodiesel fuel.
2. To investigate the effect of antioxidant additives on fuel properties and engine performance from a Jatropha biodiesel fuelled diesel engine.

1.4 Scope of the study

This thesis attempts to introduce the jatropha biodiesel blends and antioxidant and to study their effect on fuel properties and engine performance. Several points are listed here to elucidate the scope of the study as follows:

i. Jatropha biodiesel was produced and the property test was conducted to measure its kinematic viscosity, density, flash pint and calorific value.

ii. Fuel properties of the blended biodiesel and antioxidant were investigated to assess the effect of blending on fuel properties and engine performance.

iii. The engine tests were conducted in four -cylinder diesel engine at different engine speeds from 1250 rpm to 2000 rpm and different engine load from 25% to100%.

iv. The final stage explores the engine performance of the biodiesel blends using diesel engine test.

1.5 Thesis Outlines

The thesis consists of five chapters including introduction, literature review, methodology, results and discussions, and finally conclusions and recommendations.

1. Chapter 1 describes the current energy sources and its related environmental problems. The importance of alternative fuels and the problems related to their wide commercialization are discussed. Moreover, it's includes the objectives and the scope of current study.

2. Chapter 2 describes the literature review about biodiesel fuel as diesel fuel substitute. The main focus of the literature review is on biodiesel oxidation stability, its impact on fuel properties, engine performance and stability improvement methods, their benefits and drawbacks regarding their effect on other properties as well as engine performance.

3. Chapter 3 describes the adopted methodology to achieve the objectives. It includes a brief description of the diesel engine test setup and facilities utilized to conduct the engine testing and data collection.

4. Chapter 4 deals with the results and discussion of fuel property and engine performance from the addition of antioxidant to Jatropha biodiesel fuels.

5. Chapter 5 provides a summary of the conclusion and recommendation for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Biodiesel as an Alternative Fuel

Increased energy demand in industries, transport, housing and lifestyle is an indicator of economic growth. However, this energy is based on fossil fuels, which contribute to generation of unwanted greenhouse gases emissions and other serious environmental issues [6]. Thus, the development of sustainable, clean and efficient fuels has gained more attention [7, 8]. Biodiesel is comprised of mono-alkyl esters of long chain fatty acid derived from vegetable oil, animal fats and algae. The interest in biodiesel has increased because of global climate change, pollution emissions and the needs of renewable, sustainable and more secure fuel sources. Recently, many countries have embarked on legislative measures that encourage the use of biodiesel, e.g. in the U.S., the Energy Independence and Security Act (EISA) of 2007 established a 0.5 billion gallon/year requirement for biodiesel and increased to 1 billion gallon/ year in 2009 [9], China increased the production from 2000 ton/year to 200000 ton/year, whereas India cultivated ~ 55.3 million hectare of Jatropha for biodiesel production and expected to increase to 11.2 million [8]. In Thailand the biodiesel production increased from 448 to 1.420 million liters from 2008 to the earlier of 2017 and B5 (5% biodiesel and 95% diesel) is currently used; recently a B10 (10% biodiesel and 90% diesel) is announced to take effect in 2018 [10]. Malaysia as the second largest worldwide palm oil producer, started utilizing palm oil for biodiesel production in 1980's at a capacity of 3000 ton/year [11]. In 2007 the government launched the B5 blend but due to increases in palm oil price as a result of extensive use for both food and fuel, the government postponed the plant to 2010 [12]. However, B5 and B7 were implemented in 2014 and 2015, whereas biodiesel production increased from 451 to 550 million liters 10 respectively [13]. Sudan its large agricultural sector and its potential for large irrigation projects, Sudan has the possibility of being able to develop biofuel production from a number of different technologies include molasses to ethanol, Sugar or starch crops and Lignocellulosic residues (straw) to ethanol and Jatropha oil to biodiesel.

From the early history of biodiesel, this sector is aimed to get advantages in terms of environmental, social, economical and energy security benefits.

2.2 Biodiesel Quality and Standards

For the commercialization and insuring good biodiesel quality is being delivered to the consumer, the biodiesel fuel is required to meet a set of specifications. Even though many countries (India, Malaysia, Japan, China, Brazil, Canada, Thailand, New Zealand and Taiwan) have adopted their own standards, American Society for Testing Materials, ASTM D 6751 and the European biodiesel Standard, DIN EN 14214 are the most internationally accepted standards as shown in Table 2.1. These standards indicate the allowable properties limits such as acid value, glycerol and moisture contents, chemical and physical properties for safe engine operation. Of these, oxidation stability, cold flow properties and free glycerol are most important because they vary the most with changes in biodiesel feedstock and result in carbon deposits, incomplete combustion and fuel system problems. Therefore, to produce high quality biodiesel, the transesterification and separation processes need to be carefully designed.

Table 2.1: Biodiesel standard specifications [8, 14]

Property	Unit	Standard limits			
		ASTM D6751	Test method	EN 14214	Test method
Density at 15°C	g/m^3	880	D1298	0.86-0.9	EN ISO 3675 EN SIO 2185
Viscosity at 40°C	mm^2/s	1.9-6	D 445	3.5- 5	EN ISO 3104
Calorific value	MJ/kg	-		35 min	EN14214
Acid value	mg KOH/g	0.5 max			EN 14104
Cetane number	-	47 min	D 613	51 min	EN ISO 5165
Flash Point (°C)	°C	130 min	D 93	101 min	EN ISO 2719 EN ISO 3679
Cloud Point (°C)	°C	-3 to 12	D2500	-	-
Pour point(°C)	°C	-15 to 16	D97	-	-
Oxidation stability at 110°C	h	3 min	D675	6 min	EN 14112

Methanol content	% max	0.240	D6584	0.2 max	EN 14110
Monoglycerides	% mass	-	-	0.8 max	EN 14105
Diglycerides	% mass	-	-	0.2 max	EN 14105
Triglycerides	% mass	-	-	0.2 max	EN 14105
Free glycerol	% mass	0.02 max	D6584	0.02 max	EN 14106
Total glycerol	% mass	0.24 max	D6584	0.25 max	EN 14105
Water and sediment	% vol	0.05 max	D2709	0.05 max	EN ISO 12937
Total contamination	mg/kg	-	-	24 max	EN 12662

2.3 Biodiesel Degradation

Because of their unsaturated nature biodiesel degrade by autoxidation in the presence of atmospheric air [15]. The autoxidation increases by heat (thermal oxidation), presence of water or moisture (hydrolysis), metal and light, because of the double bond molecule in the free fatty acid [14, 16]. Biodiesels with higher saturation components have higher oxidation stability and cetane number compared to those of unsaturated components. The autoxidized fuel is considered undesirable as it has higher viscosity and acid value (polymeric), more susceptible to contamination and has a lower calorific value [17]. The autoxidation is a series of free radical reactions and is divided into three phases namely initiation, propagation and termination. The initiation phase is formed by abstraction of hydrogen atoms from the polyunsaturated fatty acid by free radicals and other reactive species such as metals to form a carbon based radical [18].

$$RH + I \rightarrow R\bullet + IH \quad \text{............} \quad (2.1)$$

where RH is the fatty acid substrate, I is the initiator radicals and R• is a new carbon based fatty acid radicals. The free radical formed in the initiation phase reacts with the antioxidant available in the biodiesel and leads to the depletion of the natural antioxidant compound. The initiation phase reaction is significantly influenced by reactive species, environment conditions and concentration of the natural antioxidant [19]. During the propagation, the free radical reacts with oxygen and forms hydro peroxides. As the reaction continues, a hydroperoxide radical feeds the reaction and forms alkyl hydroperoxides (ROOH) due to the reaction of alkyl peroxy radicals and hydrocarbons as shown in Equations (2.2) and (2.3) [20].

$$R\bullet + O2 = ROO\bullet \text{.........................} (2.2)$$

$$ROO\bullet + RH \rightarrow ROOH + R\bullet \text{ ………... } (2.3)$$

The termination stage occurs when non-radical products are formed by reaction between two radicals or when an antioxidant reduces the peroxyl (ROO•) to ahydroperoxide while transferring it self into a stable radical as shown in Equations (2.4) and (2.5).

$$R\bullet + R\bullet \rightarrow R - R \text{ ……………………….….} (2.4)$$

$$ROO\bullet + ROO\bullet \rightarrow \text{stable products………... } (2.5)$$

At this stage, the peroxide degradation rate surpasses the peroxide formation rate, while the remaining hydroperoxides is polymerized to sludge or converted into aldehydes or short chain acids. The fuel quality is rapidly impacted because of the acid whereas the sludge clogs the fuel filter and injector [21]. The biodiesel oxidation stability decreases in order of linolenic, linoleic and oleic but it increases with the double bond number, location and degree of conjugation of double bonds [22]. The higher the degree of unsaturated fatty acid chains the more susceptible is the fuel to oxidation.

2.3.1 Effect of Biodiesel Degradation on Fuel Properties

Biodiesel oxidation stability is dependent on the compositions, physical structure and physico-chemical properties. It is an important criteria concerning the fuel properties. The oxidation of biodiesel alters the properties such as density, viscosity, induction period, acid value, cold flow, cetane number and calorific value. Among them, cold flow and oxidation stability are the most critical because they define the suitability of biodiesel feedstock source. Extensive oxidation produce insoluble sediments, hydroperoxides, ketones and aldehydes which change the fuel properties, block the fuel line and filter, injector coking, incomplete combustion and corrosive wear in engine parts such as injection system and piston rings. Therefore, oxidation effects on the fuel properties should be considered.

2.3.1.1 Density

The density is defined as relationship between the mass and volume of the liquid. It is a key property because it affects the atomization of the fuel, mixture formation, the startof combustion and results in change of engine performance and emissions [23]. Consequently, the fuel injection system meters the fuel by volume and a change in density will influence the mass of the fuel injected and deteriorates the combustion behavior [24]. Shahabuddin et al. [25] investigated the oxidation stability of 20% blends of jatropha, palm and coconut biodiesels at storage time of three months. The results indicated that the density of the blends increased due to oxidation products of insolubles and sediments. Similar results were observed by [26] who observed 0.36% increase in density with jatropha biodiesel.

2.3.1.2 Viscosity

Viscosity is defined as the liquid's resistance to free flow. It is an importance property because it influences the quality of oil, the operation of injection system, soot, deposit formation and creates severe effects on engine performance [27]. Biodiesel fuel has a higher viscosity compared to diesel fuel. The viscosity is observed to increase with the oxidized biodiesel fuel due to the condensation reaction and formation of gum, sediments, insolubles and polymer which are responsible of plugging the fuel filters and injection system [21]. The oxidation makes the biodiesel more saturated, hence increases its viscosity [28]. Similar observations were reported by [29, 30]. Lamba et al.[26] reported that the oxidized jatropha biodiesel blends of JB5, JB10, JB20 and JB40 increased the viscosity by 2.1 - 5.14% compared to non-oxidized base line fuel

2.3.1.3 Oxidation Stability

Oxidation stability (OS) is a major factor when assess the quality of biodiesel [31]. It is directly related to the contents of unsaturation fatty acid in the triglyceride or ester [32]. The autoxidation increases in presence of air, heat, metal and light, because of the double bond molecule in the free fatty acid [14]. Several studies have shown that biodiesel stability has decreased with degradation. Yang et al. [33] reported that, the oxidation stability of canola, animal fat and soybean biodiesel decreased with time, but soybean showed the highest reduction of 0.7 h from the initial period of 2.3 h. It was shown that unsaturated fatty acid presence had strong influence on the oxidation stability and the possible of its earlier oxidation increased with the increase in the unsaturated fatty acid content [22]. Das et al. [30] studied the oxidation stability of karanja oil biodiesel over 180 day of storage time. They claimed decreases of oxidation stability with increase in storage time. Similar results were elucidated by Bouaid et al. [29]. Shahabuddin et al. [25] tested palm, jatropha and coconut biodiesel and reported increased oxidation stability in order of palm > jatropha > coconut. The oxidation stability of biodiesel fuel in general increased over time and accelerated with increased temperature [34, 35]. In order to maintain the biodiesel quality it is important to store it carefully in containers that do not facilitate degradation [36-38].

2.3.1.4 Calorific Value

The heating value or calorific value is defined as energy content per unit volume or mass of the combustible fuel. Different feedstocks yield biodiesel with difference calorific values but they are generally about 10% lower than diesel fuel because of their substantial oxygen content. Pattamaprom et al. [39] examined the effect of oxidation on palm oil biodiesel and observed a decrease in calorific value, due to the degradation which resulted in a reduction in carbon and hydrogen molecules in the fuel.

2.3.1.5 Acid Value

The acid value reflects the free fatty acid (FFA) contents in the oil or biodiesel. It is defined as number of milligrams of potassium hydroxide (KOH) required to neutralize the acids of 1g of sample. It is an important factor because it determines the possible route for biodiesel production and quality of the produced biodiesel. Thus, the determination of acid value of the oil or biodiesel is essential in order to produce biodiesel fuels that meet the international standard and to avoid deposits and damage to the engine injector. The acid value of biodiesel fuel was observed to be sharply increase as storage time and temperature increased. Biodiesel fuel has a tendency to hydrolyse to acid and alcohol in the presence of air or oxygen [37].Yang et al. [33] studies the degradation of animal fat, soybean and canola oil biodiesel at a storage time of one year. The results indicated that degradation of biodiesel led to increased acid value. Similar results of increasing acid value were reported in [29, 40, 41].

2.3.1.6 Flash Point

The flash point is defined as the minimum temperature at which the fuel could ignite without external ignition source. It is an important fuel property for storage, combustion mixture formation and handling. In a diesel engine a low auto ignition temperature is preferred because there is no extra mechanism to ignite the fuel. A flash point of 66°C or above is considered safer for handling and storage [42]. Shahabuddin et al. [25] reported that, after 3 months of storage, flash point of palm, jatropha and coconut oil biodiesels were reduced but still remained above the fuel safer limit.

2.3.2 Effect of Biodiesel Degradation on Performance

Biodiesel degradation alters the physic-chemical properties which significantly affect the engine performance. Monyem and Van Gerpen [43] evaluated oxidized and unoxidized B20 and B100 blends at three injection timings (3° advanced, standard and 3° retarded), two different loads (100 and 20%) and 1400 rpm. Compared to diesel fuel, oxidized and unoxidized biodiesels showed higher BSFC of 15.2% and 13.8% respectively. Whereas for oxidized biodiesel the BSFC was 1.2 % higher than unoxidized biodiesel. Thompson et al. [44] studied the effect of oxidized rapeseed biodiesel on engine performance. The power was 2% higher than diesel fuel for both oxidized and non-oxidized fuel. Bannister et al. [45] proved that, the oxidation of biodiesel led to a change in the color with vinegary smell, increase in viscosity, acid value, cetane number and reduced heating value. More studies on engine performance are required for better understanding.

2.4 Biodiesel Stability Improvement

There are different techniques used to reduce the degree of biodiesel oxidation such as molecular structure modifications and antioxidants additives.

2.4.1 Antioxidant

Biodiesel degradation can be avoided by decreasing its contact with air, storing at low temperature or in dark room in stable containers. However, these conditions are difficult to achieve and thus, the use of antioxidants is a new topic of research interest. Antioxidants have the ability to increase the resistance of biodiesel fuel to oxidation without significant effect on fuel properties [46]. Antioxidants are classified as free radical terminators, oxygen scavengers and metal ion chelators [47]. The effectiveness of an antioxidant is determined by a parameter called stabilization factor(F) and is calculated by $F = IPx/IP0$, where IP0 is the induction period without antioxidant and IPx is the induction period with the antioxidant [48].

2.4.1.1 Antioxidant Effect on Fuel Properties

The effect of antioxidant additions on biodiesel fuel properties have been studied by many researcher and different results were reported [38, 50]. The effectiveness of antioxidants depends on biodiesel feedstock source and fatty acid compositions [70], thus the results are conflicting and non-conclusive.

Agarwal et al. [51] evaluated the effect of 2-tert butyl hydroquinone (TBHQ), 2(3)-tert-butyl-4-methoxy phenol (BHA), 2,6-di-tert butyl-4-methyl phenol (BHT), 3,4,5,-tri hydroxyl benzoic acid (PG) and 1,2,3 tri bydroxy benzene (PY) on biodiesel of karanja, neem and jatropha at concenteration of 100- 1000 ppm. The results showed that, oxidation stability of neem, karanja and jatropha biodiesel were 1.39, 1.82 and 3.05 h respectively which do not meet the standard specifications of ASTM D 6751 and EN 14214. With antioxidant additions the stability was increased in range of 4.94-22.49, 2.15-44.5 and 5.56-53.73 h respectively for karanja, neem and jatropha biodiesel; the antioxidants activity was in order of PY> PG> BHA> BHT> TBHQ. However, the effect of antioxidants on other fuel properties were not included.

Rashed et al. [52] showed that, N,N′-diphenyl-1,4-phenylenediamine (DPPD), Nphenyl-1,4-phenylenediamine (NPPD) and 2-ethylhexyl nitrate (EHN) added CB20 (20% calophyllum inophyllum oil biodiesel + 80% diesel fuel) at concentration of 1000 ppm had oxidation stability of 22.7, 18.5 and 15.7 h respectively. However, the oxidation stability of CB individually was 3.6 h which is lower than EN 14214 standard specification. The cloud and pour point temperatures were almot similar; no variation in pour point and density were observed but the calorific value and flash point were improved with antioxidant fuels. cetane number was increased with the addition of biodiesel fuel, but no information was reported with antioxidants. The same author [53] studied the effect of DPPD and NPPD antioxidants addition to MB20 at a concentration of 2000 ppm. The results showed that, the addition of antioxidants had no significant effect on density and pour point temperature but the calorific value and flash point increased. The oxidation stability of DPPD and NPPD added MB20 were 34.5 and 18.4 h respectively compared to base fuel which showed 6.97 h.

2.4.1.2 Effect of Antioxidants on Performance

Antioxidants offer an innovative and effective solution to increasing the oxidation stability, hence, the effect of antioxidants on performance characteristics of a diesel engine is worth discussing for better understanding and ensuring long term sustainability of biodiesel.

Rashedul et al. [54] investigated the use of calophyllum inophyllum oil biodiesel (CIB) treated with 6-Di-tert-butyl-4-methylphenol and 4-methyl-6-tert-butylphenol antioxidant. The results indicated that, the addition of antioxidants increased the density, viscosity, flash point and oxidation stability, but decreased the calorific value. BSFC, NOx and peak cylinder pressure of biodiesel blends, CIB30 (30% CIB + 70% diesel) were higher compared to diesel fuel.

2.5 Chapter Summary

Currently about 95% of worldwide biodiesel production originated from edible feedstocks which affects both the price of biodiesel and the food. The properties of biodiesel fuel is strongly influenced by the individual fatty esters present. The oxidation stability is a key factor hindering the expansion of biodiesel in the automobile sector. It decreases with increasing unsaturation content, storage temperature, exposure to metals and oxygen. The oxidation alters the properties such as density, viscosity, cetane number and heating value and increases acid value and flash point. Hence, it presents a legitimate concern in maintaining the biodiesel quality.

The increase in acid value can be attributed to the secondary oxidation reaction in which highly reactive aldehydes oxidize into acid whereas the increase in density and viscosity are due to formation of higher molecular weight, acidic and polymer.Search for effective method to reduce the impact of biodiesel oxidation.

The improvement of oxidation stability could also be achieved through antioxidants. Biodiesel containing high percentages of saturated acids require less amounts of antioxidants to achieve significant improvement in oxidation stability. The concentration and the effectiveness of antioxidants depend on the biodiesel feedstock source. Hence it necessary to analyze the synergy of antioxidant and biodiesel before the actual application. Further, among the several methods used to counter NOx emission, the addition of antioxidants promise to increase the oxidation stability. However, few information is available on the Jatropha methyl ester stability using antioxidants.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction:

This chapter explains how the whole research was conducted. It details with the procedure adopted for the determination of physical and chemical properties of biodiesel and its blends.

The performance parameter in standard diesel engine was investigated using diesel and biodiesel blends .The experimental setup could be summarized in the following points.

- Measuring the fuel properties
- Performance test for diesel engine (engine test rig)

3.2 Materials

3.2.1 Jatropha biodiesel

Jatropha samples were collected from Elabasia city, southkordfan state, Sudan.The physical and chemical properties of the crude jatropha oil produce was carried out in Central Laboratory for Technical Services and Calibration (CLTSC), Khartoum, Sudan. The properties were determined as per standard methods and reported in Table 3.1.

Table 3.1: Physical and chemical properties of the jatropha oil:

Properties	**Range**
Acid value (mgKOH/g)	8.99
Density (g/ml)	0.9227
viscosity@40^{o}C (cst)	36.66
Calorific value (KJ/Kg)	44430.7
Flash point (^{o}C)	310

3.2.2 Diesel:

Diesel was a volatile, flammable liquid obtained from local fuel diesel station. Hence various biodiesel blends of different volumetric concentrations are made and their performance to be tested. The specification of produced biodiesel and diesel are shown in Table 3.2

Table 3.2: Fuel properties

Parameters	**Jatropha oil**	**Bio diesel**	**Bio diesel added antioxidant**
Density (kg/m3)	9227	884	894
Viscosity at 40 ^{0}C (cst)	36.66	4.1	5
Flash Point (^{0}C)	310	60	62
Calorific value (kj/kg)	44430.7	45625	38658

3.2.3 4-Dimethylaminobenzaldehyde (DMBA)

In this study amine antioxidant**,** 4-Dimethylaminobenzaldehyde was used for the tests. The antioxidant was chosen based on literature review, cost, effectiveness and availability. The antioxidant used in this research from Dawareg Company, Khartoum, Sudan. The chemical structure and the properties of antioxidant used is presented in figure 2.1 below.

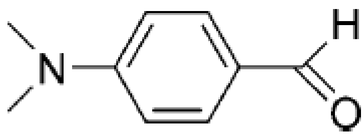


Figure 3.1: chemical structure of 4-Dimethylaminobenzaldehyde

3.3 Blends preparation:

A series of tests was performed to observe the solubility of 4-Dimethylaminobenzaldehyde and biodiesel blends. The fuels were mixed into a homogenous blend in container using stirrer. The blend was kept in cylindrical glass container to study the solubility and phase stability. The constant volume percentage 1g of antioxidant per litter of biodiesel, i.e., 1g of 4-Dimethylaminobenzaldehyde per litter of biodiesel was used in the current research. The whole experimental plan was realized in two stages: (i) running engine with biodiesel blends (ii) running engine with the biodiesel blends and 4-Dimethylaminobenzaldehyde antioxidant. For simplicity fuel abbreviation system was presented in Table 3.3 and the Calorific value of these samples is shown in Table 3.4.

Table 3.3: Tested Fuels Samples Abbreviation

No	**Fuel**	**Blend**
1	70% diesel +30%bio-diesel	D70B30
2	65% diesel +35%bio-diesel	D65B35
3	70% diesel +30%bio-diesel+ DMBA	D70B30DM
4	65% diesel +35%bio-diesel+ DMBA	D65B35DM
5	60% diesel +40%bio-diesel+ DMBA	D60B40DM

Table 3.4: Calorific value of blends:

S. No	**Blend**	**Calorific value (KJ/kg)**
1	D70B30	45625
2	D65B35	44186
3	D70BJ30+ DMBA	41953
4	D65BJ35+ DMBA	41662
5	D60BJ40+ DMBA	41368

3.4 Engine test experimental details:

This section is detected to describe the experimental setups and the important Facilities used. Experimental setups describe the experimental engine test-rig and the main instruments for measurement including the fuel flow, engine speed, and engine's torque. Brief description of the data acquisition system and sensor integration is also provided.

A schematic diagram of the experimental setup and the details of its main components are presented in Figure 3.1. The experimental equipment used in the current study is located at Engine Performance Laboratory, Faculty of Mechanical

Engineering, University Blue Nile, Sudan. Figure 3.2 shows the various components of the experimental engine test-rig.

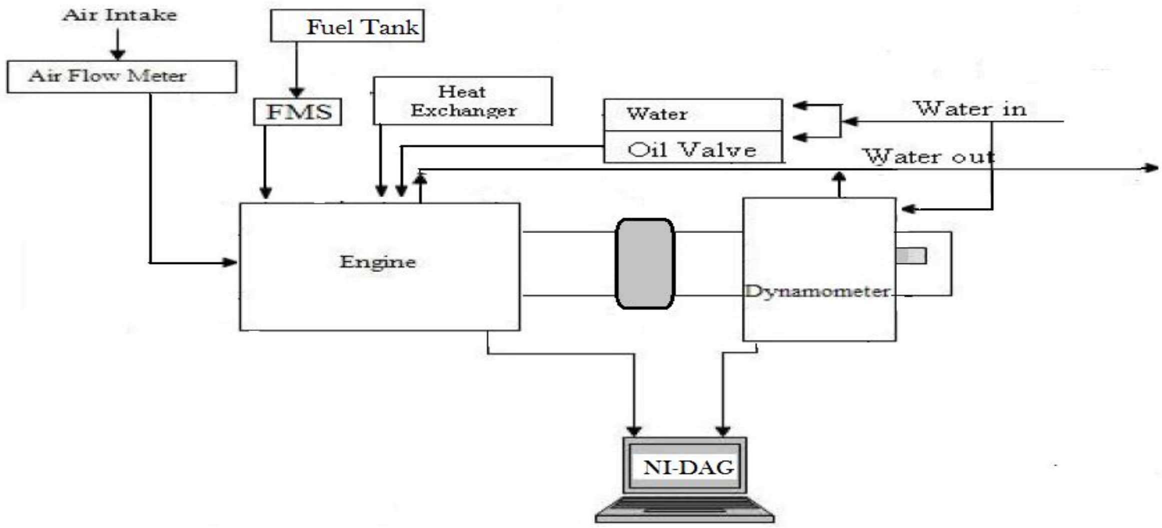


Figure 3.2: Schematic of the test cell for the experimental setup

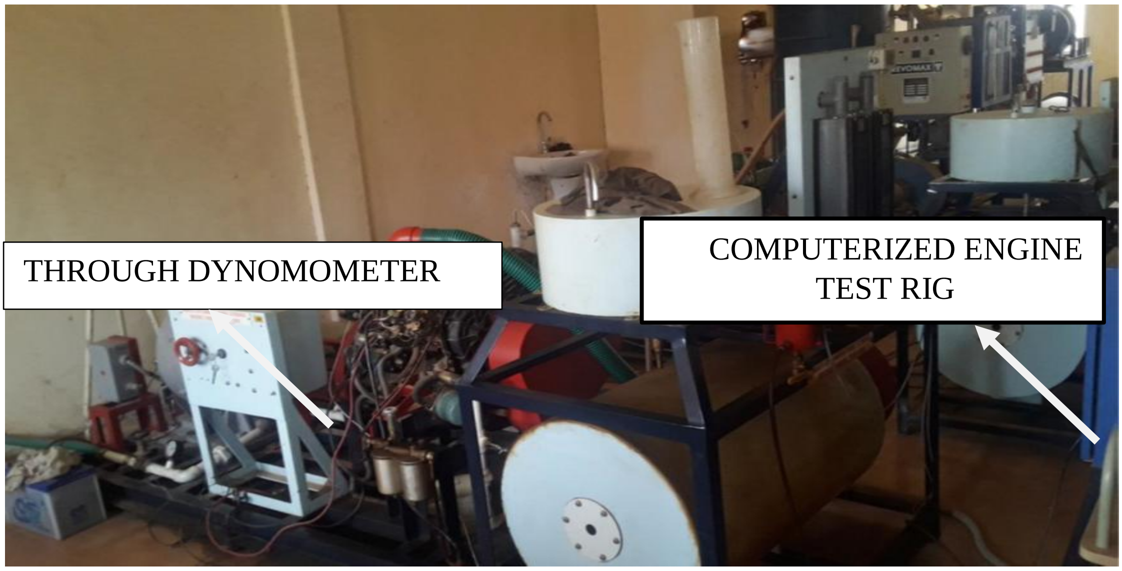


Figure 3.3: Engine test rig

3.5 Engine setup description:

Present setup was four cylinder, four strokes, vertical, water cooled diesel engine. Flow rate of water to engine jacket and to exhaust gas calorimeter is measured with the help of individual Rotameter. Test rig is also supplied with air intake tank and fuel supply tank. Proper instrumentation had been done to measure temperatures and flow wherever required. Engine is connected with dynamometer (Eddy Current Type) with Load sensor. Detail description of the test engine setup is presented in Table 3.5.

A combustion pressure sensor is mounted on the cylinder to detect the pressure. Output shaft of the engine is coupled with crank angle sensor for detecting crank angle and(R.P.M) of the shaft. With the combination of pressure sensor and crank angle sensor, pressure inside the cylinder at different angles of crank can be detected and pressure versus crank angle and pressure versus cylinder volume can be calculated to plot P-V and P-θ diagrams. The whole assembly is fixed on a rigid channel frame. The real time data acquisition can be done by interfacing the set up with computer using software. The software is capable to tabulate the sample readings according to the requirement of experiment under study and results obtained can be compared. Software allows the user to have control on data logging, printing stored data, and preparing spread sheet in Excel.

Table 3.5: Specifications of the engine

Item	**Specification**
Type of Engine	4cylinder ,4-Stroke water cooled, Diesel Engine
Make	Hindustan Motor
Bore	84 mm
Stroke	90 mm
Type of loading	With Eddy Current Dynamometer
Air intake measuring system	Air tank fitted with Differential Pressure Transmitte
Combustion Pressure sensor	Piezoelectric Sensor (Quartz), 0-1000 psi
Crank Angle Sensor	Resolution 1 Deg
Torque Measurement	Using Load Cell,0-100 kg
Fuel system	Distribution type jet pump (indirect injection)

3.5.1 Engine dynamometer:

An eddy current dynamometer shown in Figure 3.3 model AG-80; Indian made and can test up to power capacity is utilized to load the engine, this dynamometer is a water cooled type. It consisted of an electromagnetic stator and a rotor disc made of copper or steel. The stator produces electromagnetic field which was controlled by NI-DAQ software.

Figure 3.4: Test engine rig eddy current dynamometer

3.5.2 Engine and dynamometer cooling systems:

There are two cooling systems in the engine test cell provided to cool the engine parts in addition to the instrumentation part itself, including the engine cooling system and the dynamometer cooling system. The engine cooling system shown in Figure 3.4 the water circulation between the engine and the heat exchanger .During water circulation the cold water is pumped into the engine and it absorbs the heat produced from the combustion. The cooling water flow rate is measured using a vertical Rotmeter as shown in Figure 3.5 that is device control the amount of water entering the engine. The second part of the engine cooling system is the dynamometer cooling tower. The function of the cooling tower, which is apart from the engine cooling system, is to extract the heat during the cooling process. The concept function of dynamometer that loads the engine during braking requires more cooling water to dissipate the heat from the friction between the dynamometer parts.

Figure 3.5: Water cooling system

Figure 3.6: Rotameter

3.5.3 Basic measurements:

The basic measurements to be taken to evaluate the performance of an engine on almost all tests are the following:

(a) Speed.

(b) Fuel consumption.

(c) Air consumption.

(d) Brake mean effective pressure.

(e)Volumetric efficiency.

(f) Indicated mean effective pressure.

3.5.4 Engine performance characteristics:

3.5.4.1 Brake power (BP):

The experimental data are used to indicate the engine performance for different fuels, which are represented by the maximum engine power. Brake power is the function of the engine torque and engine speed. The engine brake torque is recorded directly from the dynamometer controller as the engine output. According to the output torque, the engine brake power is computed as Eq. (3.1) [2]:

$$\boldsymbol{BP = \frac{2\pi NT}{60}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \quad (\mathbf{3.1})$$

Where: ($\boldsymbol{BP}$) is the engine brake power (**kW**)

($\boldsymbol{T}$) is the engine brake torque (**N.m**)

($\boldsymbol{N}$) is the engine speed (**rpm**)

3.5.4.2 Brake specific fuel consumption (BSFC):

Brake specific fuel consumption is one of the important parameters when the engine is working with different fuels, which exhibits the performance of fuels. It is an indicator of how efficiently the engine is producing work with different fuels. Brake specific fuel consumption describes the engine fuel consumption relative to the output power from the engine. It is the ratio of the amount of the engine fuel consumption to the rate of the engine output power using certain fuel. The fuel mass flow rate consumed by the engine is measured by the fuel flow meter per unit time.

According to the engine brake power, the brake specific fuel consumption is computed as Eq. (3.2) [2].

$$BSFC = \frac{m_f}{BP} \ \frac{kg}{kws} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \textbf{(3.2)}$$

Where m_f: Flow rate of fuel consumed by engine, *kg/s*.

3.5.4.3 Brake Thermal Efficiency (τ_{bt}):

Brake thermal efficiency represents one of the crucial characteristics for the engine which describes the engine performance with different test fuels. It is a function of the engine output work to the heat input. It is affected by many parameters regarding various test fuels with different properties. The brake thermal efficiency is computed as in Eq. (3.3) ([2]

$$\tau_{bt} = \frac{BP}{m_f \times CV} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{3.3})$$

Where: CV = Calorific value of fuel in *kJ/kg*.

3.5.4.4 Indicated power (IP):

Beside the measured engine torque, which depends on the engine size, the indicated mean effective pressure (IMEP) is another more useful relative engine performance indicator. This parameter is used to compare between the different engines performance. The indicated power is computed as in Eq. (3.4; 3.5) [2]:

$$\text{IMEP} = \left[\frac{\text{Area of PV diagram,mm} \times \text{Scale of the diagram,bar/mm 2}}{\text{length of diagram,mm}}\right] \ldots\ldots (3.4)$$

$$\text{IP} = \frac{imep \times A \times L \times N \times N_C}{2 \times 60 \times 1000} \ (\text{KW}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.5)$$

3.6 Test procedure:

The engine fuel tests were conducted at variable speed and variable load with increasing engine speed from 1250 rpm to 2000 rpm at increment interval of 250.The engine starts with diesel fuel at the beginning of each test, and then it is switched to the tested blends. The engine performance parameters were collected for each speed after the engine reached the steady state operation conditions, then the speed was increased to the new value and the data were collected taken to develop various engine parameters for each fuel during the test such as the load acting on dynamometer (kg), torque and fuel flow rate. For the starting of the engine test, the engine was operated in idling conditions for about 20 minutes to ensure that the engine operated at steady state conditions and constant engine cooling water temperature. Furthermore, the engine fuel tests were repeated three times for each fuel at the specified operation conditions to ensure accurate and reliable measurements. Before running the experiment, several precautions have to be taken into consideration:

- To ensure that engine is filled with SAE 20W40 oil up to required level with help of Dip Stick
- Tank is filled with diesel fuel and all connections lines are fitted to the engine and opened.
- The panel/interfacing unit is connected with the computer by data cable provided.
- The open is continuous cold water supply to the engine jacket and calorimeter.
- The Set is flow rate of water through engine jacket and calorimeter using Rotameter.
- The Open is water supply through pump, for cooling of dynamometer.
- Insert the ignition key and turn it in the clockwise direction to ignition on position, which is indicated by an indicator lamp. Turn the ignition switch key further clockwise against the spring pressure to start the engine. As soon as the engine starts, leave the ignition key and let it run for 2 minutes under no load condition.
- When engine start running smoothly, firstly load the engine slightly and then gradually increase the load.
- Run the engine for 2 minutes so that it can stabilize.
- Note the flow rate of water to Engine jacket and Calorimeter with the help Rotameter provided.

CHAPTER 4
RESULTS AND DISCUSSION

This chapter presents the property results of the effect of blended fuel, engine speed, and engine load on the engine performance. It aims to give clear understanding of the engine performance in the presence of fuel blends at different speed and different load. The tested engine performance include the following: brake power, brake specific fuel consumption, brake thermal efficiency, indicated power, indicated specific fuel consumption, indicated thermal efficiency and mechanical efficiency. The experimental tests for the engine performance analysis were conducted for biodiesel (D70BJ30, D35BJ35) and blended fuel D70BJ30+*DMBA*, D65BJ35+*DMBA* and D60BJ40+*DMBA*. All tests were conducted at variable loads ranging from 25 to 100% with an increment of 25% and variable speeds ranging from 1250 to 2000 rpm with increment 250 rpm. The observation tables for torque, Load acting on dynamometer, Volume of fuel consumed, Time taken to consumed X ml of fuel, air flow rate, flow rate of cooling water to engine and flow rate of cooling water to calorimeter for different blends are shown in Appendix A. Moreover, Appendix B shows sample calculation and the results of the engine performance.

4.1Brake power:

4.1.1 Effect of jatropha bio-diesel blends and antioxidant addition on brake power (*BP*) as a function of engine speed:

Figure 4.1 shows the effect of engine speed and the fuel blends on the brake power(*BP*) at fixed load of (10%). The maximum brake power with blended fuel and blended fuel add antioxidant was observed at engine speed of 2000 rpm. However, the maximum brake power achieved for blend fuel is higher than that of fuel blend add antioxidant. This difference is due to the higher viscosity and lower heating value of blended fuel adds antioxidant compared to the blended fuel.

In general, the brake power increases with the increasing engine speed for all the tested fuels and the maximum brake power achieved at 2000rpm. The figure shows that the uses of antioxidant additive slightly reduce the blended fuel brake power at all tested speed.

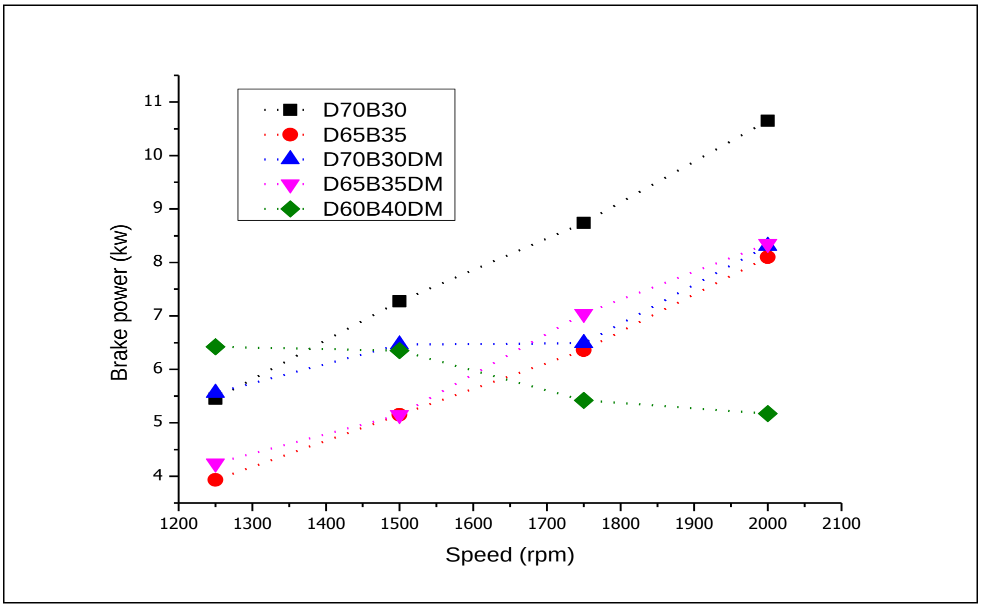


Figure 4.1 – Brake power versus speed engine (*N*)

4.1.2 Effect of jatropha bio-diesel blends and antioxidant additive on brake power (*BP*) as a function of engine load:

The effect of engine loads with five different types of fuel blends on the brake power (*BP)* is shown in Figure 4.2 at fixed speed of (500rpm).

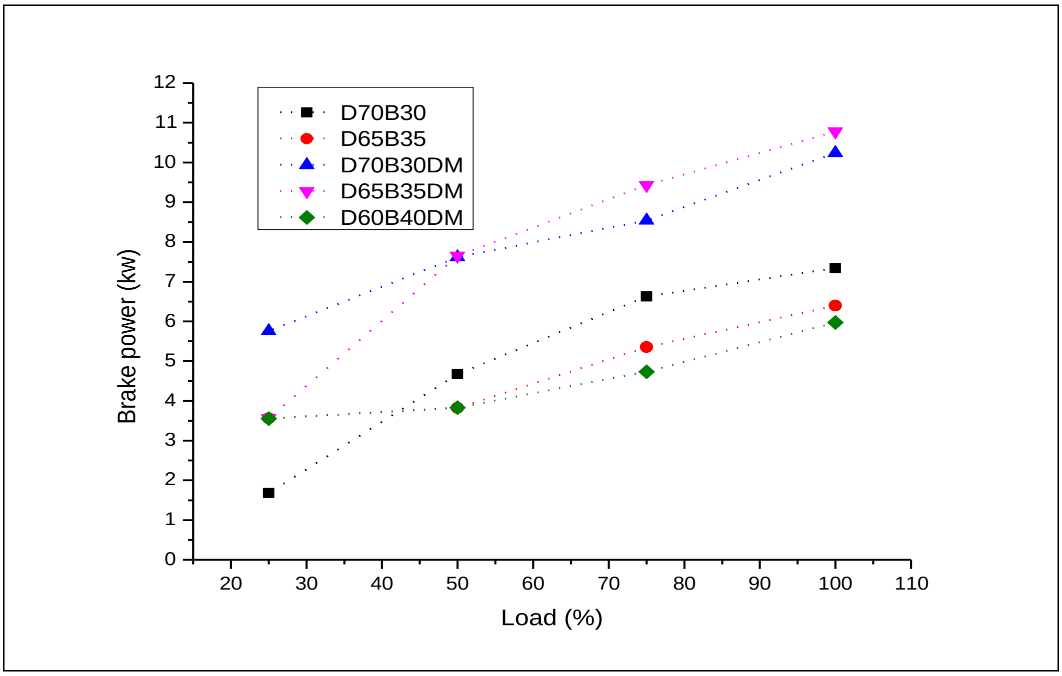


Figure 4.2 – Brake power (*BP*) versus load of engine (%).

Figure 4.2: shows that blending fuel with jatropha bio-diesel additive antioxidant increases the brake power slightly compared to the brake power output from engine

when using bio-diesel. For bio-diesel and all fuel blends additive antioxidant the brake power increased with an increasing in the engine load. Figure 4.2 also shows that the brake power increased with an increasing jatropha bio-diesel ratio in the fuel blend. The highest brake power was obtained by the fuel blend (D65BJ35DM) at load 100%.

4.2 Brake specific fuel consumption:

4.2.1 Effect of jatropha bio-diesel blends and antioxidant additive on brake specific fuel consumption (BSFC) as a function of engine speed:

Figure 4.3 shows the effect of changing engine speed and the fuel blend on the brake specific fuel consumption (BSFC) at fixed load of (10%).

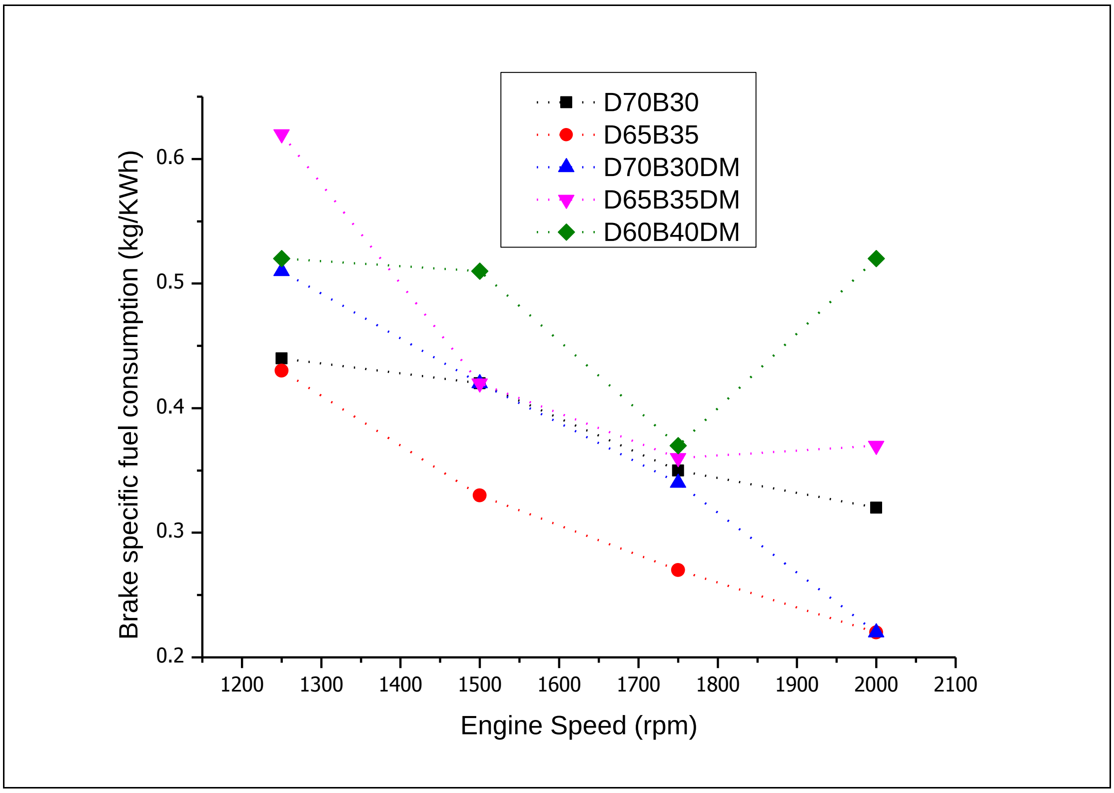


Figure 4.3: Brake specific fuel consumption (*BSFC*) versus speed of engine (*N*)

The brake specific fuel consumption (*BSFC*) is defined as the fuel flow rate per unit power output. It can be considered as a measure of the engine efficiency in using the supplied fuel to produce work. The *BSFC* is one of the most important parameters to evaluate engine performance with various fuels and it can be calculated based on the engine brake power and fuel mass flow rate for each speed. In general, the trend of the *(BSFC)* varies for different engines according to the engine performance curve. The test results show that the lower (*BSFC*) was obtained by the fuel blend (D65B35DM) at speed 2000 rpm. The (*BSFC*) of the blended fuels at constant antioxidant percentages is comparable to that of bio diesel over the whole engine speeds with a slight difference. This difference is due to the reduction in the fuel calorific value and the effect of additive on fuel density.

4.2.2Effect of jatropha bio-diesel bleneds and antioxidant additive on brake specific fuel consumption (*BSFC*) as a function of engine load:

The effect of different engine loads and five different types of fuel blend on the brake specific fuel consumption (*BSFC*) at constant speed of (500rpm) is shown in Figure 4.4.

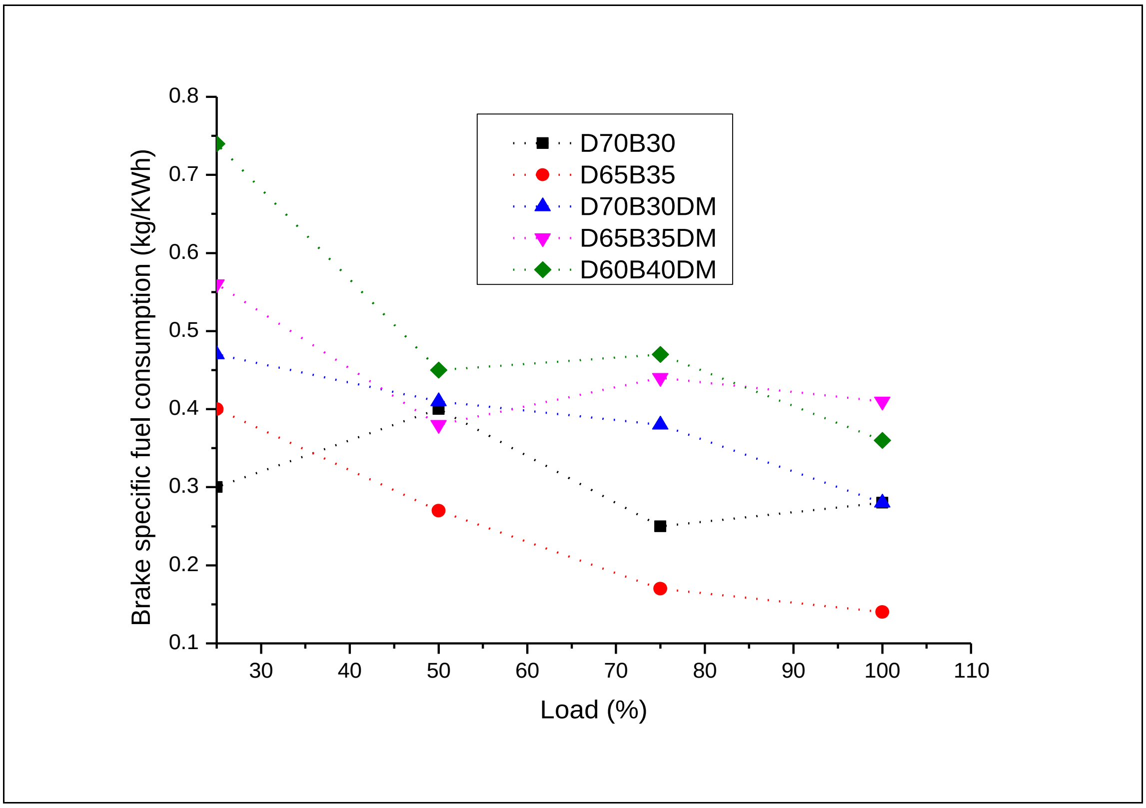


Figure 4.4: Brake specific fuel consumption (*BSFC*) versus load of engine (*%*)

The results of brake specific fuel consumption (*BSFC*) related to engine load are presented in Figure.4.4. The brake specific fuel consumption is greater at smaller loads, but it decreases at medium and higher loads. It was expected from the heating value of various blends, the (*BSFC*) increases with increasing oxygenate content. The sequence is (D70B30), (D70B30DM), (D65B35DM) and (D60B40DM) being the same at all engine loads, maintain the increasing sequence of biofuel content. The increase is higher at small loads, the highest variation is found for (D60B40DM) at medium load. At high load the values are comparable with that of D70B30.

4.3 Brake thermal efficiency:

4.3.1 Effect of jatropha bio-diesel blends and antioxidant additive on brake thermal efficiency (τ_{bth}) as a function of engine speed:

Figure 4.5 shows the effect of changing engine speed and the fuel blend on the brake thermal efficiency (*BTE*) at fixed load of (10%).

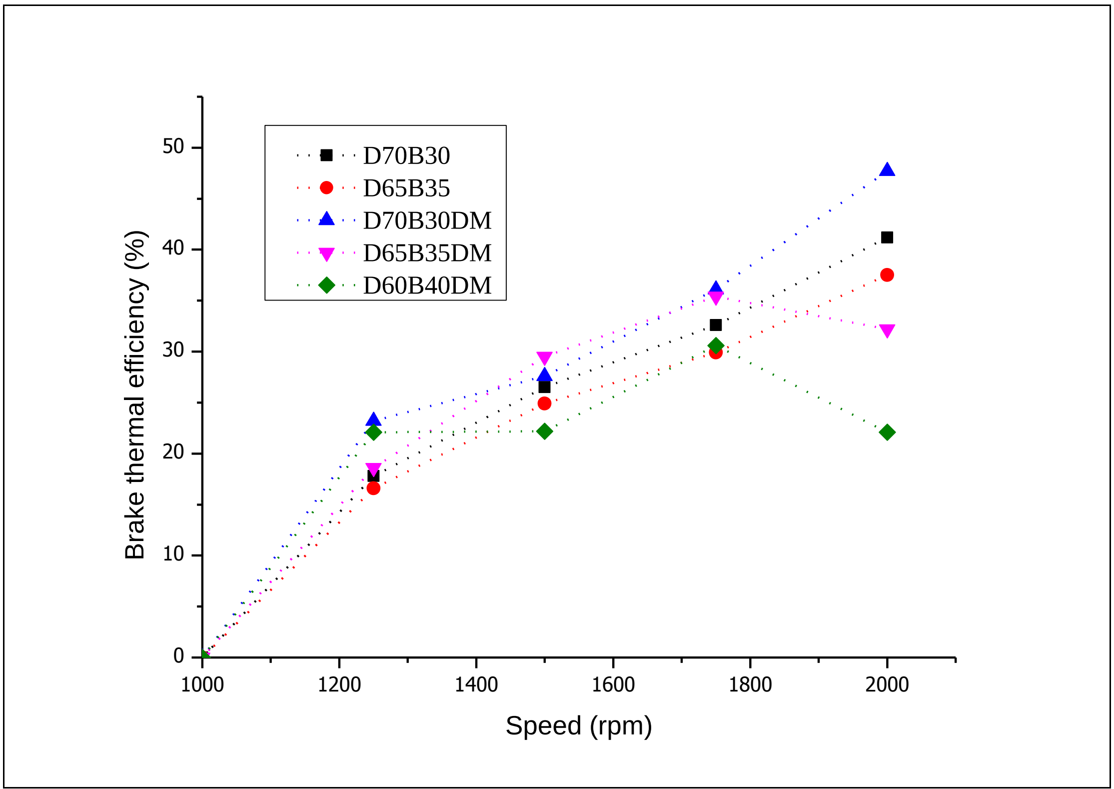


Figure 4.5: Brake thermal efficiency (τ_{bth}) versus speed of engine (*N*)

The brake thermal efficiency (*BTE*) is the ratio of the thermal power available in the fuel to the power that the engine delivers to the crankshaft. It is an indicator for the operation with the test fuel. This parameter is more appropriate than fuel consumption to evaluate the performance of different fuels, besides their heating value. Since the thermal efficiency is normalized with the fuel heating value, it is greatly dependent on the manner in which the energy is converted. The brake thermal efficiency is determined based on the calculated brake power at a certain speed and the measured calorific value for the tested fuel. The test results reveal that the brake thermal efficiency increases with the increasing engine speed up to 1750 rpm. The (*BTE*) of the blended fuel (D70B30DM), at 1750 rpm, is (36.1%) which is slightly higher than that of the D70B30 (32.6%). This difference may be attributed to the high oxygen content of blended fuel additive antioxidant compared to bio diesel.

Figure 4.5 shows that bio diesel with jatropha bio-diesel additive antioxidant improve The brake thermal efficiency compared to the brake thermal efficiency when using bio diesel fuel within speed limits from 1250 rpm to 1750 rpm, but above engine speed of 1750 rpm the brake thermal efficiency still higher for blends (D70B30DM) compared to the brake thermal efficiency when using bio diesel fuel. The maximum efficiency was obtained at engine speed of 2000 rpm; and that when using (D70B30DM) blend (47.97%).

4.3.2 Effect of jatropha bio-diesel blends and antioxidant additive on brake thermal efficiency (τ_{bth}) as a function of engine load:

The effect of different engine loads and five different types of fuel blend on the brake thermal efficiency (*BTE*) at constant speed of (500rpm) is presented in Figure 4.6.

Figure 4.6 shows that blending bio diesel with jatropha bio-diesel addtive antioxidant improve the brake thermal efficiency compared to the brake thermal efficiency when using biodiesel fuel within load limits from 25% to 100%.The maximum efficiency was obtained at engine load of 100%; and that when using (D70B30DM) blend (47.7%).

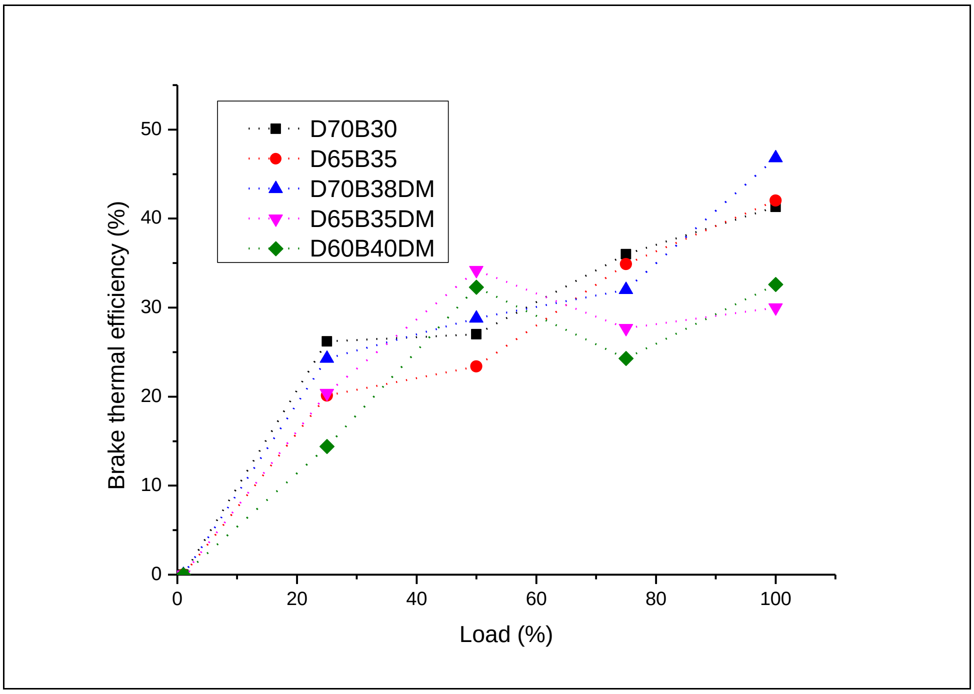


Figure 4.6: Brake thermal efficiency (τ_{bth}) versus load of engine (%)

4.4 Indicated power:

4.4.1 Effect of jatropha bio-diesel blends and antioxidant additive on indicated power (*IP*) as a function of function speed:

Figure 4.7 shows the effect of changing engine speed and the fuel blend on the indicated power (*IP*) at fixed load of (10%).

The maximum indicated power with biodiesel and blended fuel additive antioxidant was observed at 2000 rpm engine speed. The maximum indicated power achieved for biodiesel fuel is higher than that of fuel blends additives antioxidant. This difference is due to the lower heating value of blended fuel additive antioxidant compared to the biodiesel fuel. In general the indicated power increased with increasing in engine speed for biodiesel and fuel blends additive antioxidant.

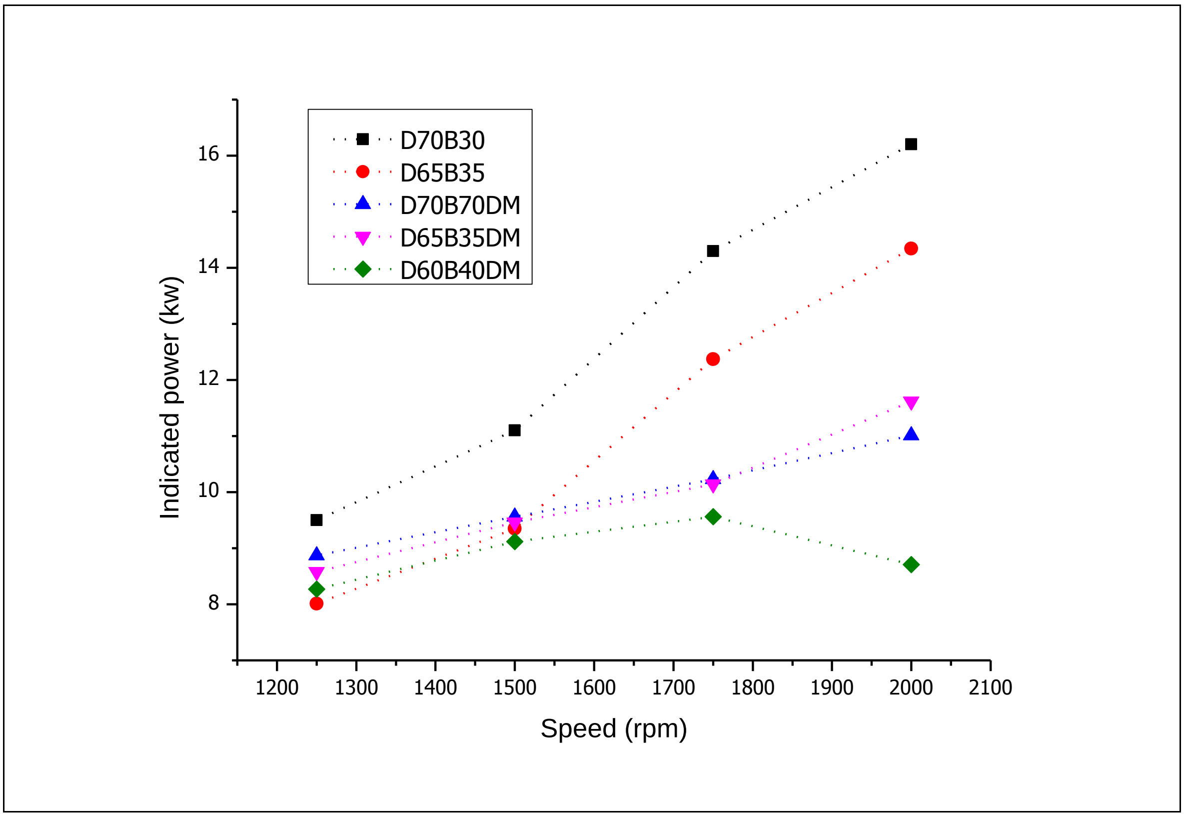


Figure 4.7: indicated power (*IP*) versus speed of engine (*N*)

4.4.2 Effect of jatropha bio-diesel blends and antioxidant additive on indicated power (*IP*) as function of engine load:

Figure 4.8 shows the indicated power (*IP*) with five different engine loads and with five different types of fuel at constant speed of (500rpm).

The maximum indicated power with bio diesel and blended fuel additive antioxidant were observed at 100% engine load. However, the maximum indicated power achieved for fuel blends added antioxidant is higher than that of biodiesel fuel from limit load 25% to 75%.

In general, the indicated power increases with the increasing engine load for tested fuels (D70B30DM). Furthermore, fuel blends additive antioxidant has the maximum indicated power at loads (25%, 50%, 75%) compared to the biodiesel fuel.

The blend (D70B30DM) gives the highest indicated power at half load compared to the other fuel samples.

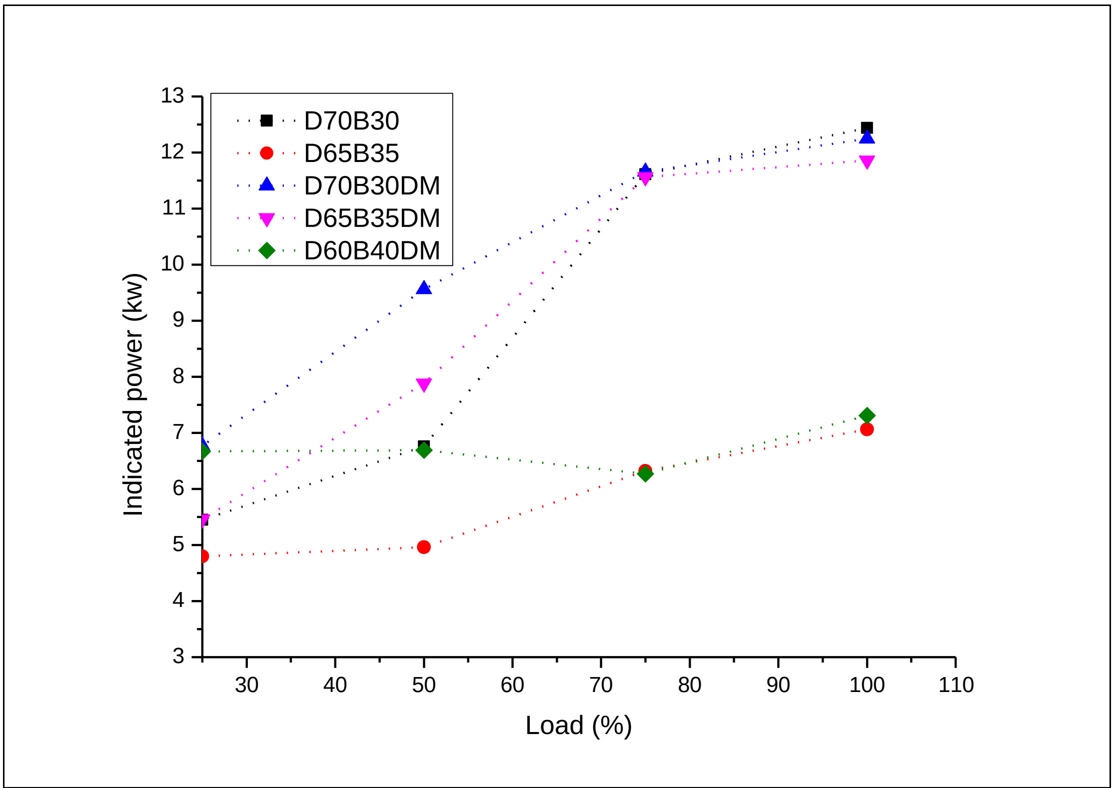


Figure 4.8: indicated power (*IP*)versus load of enginE

4.5 Indicated specific fuel consumption:

4.5.1 Effect of jatropha bio-diesel blends and antioxidant additive on indicated specific fuel consumption (*ISFC*) as a function of engine speed:

Figure 4.9 shows the indicated specific fuel consumption (*ISFC*) with five different engine speeds and with five different types of fuel at fixed load of (10%).

The indicated specific fuel consumption (*ISFC*) is defined as the fuel flow rate per unit indicated power. The test results show that fuel blends added antioxidant has the lowest (*ISFC*) from engine speed 1250 rpm to 1500 rpm.

but above engine speed of 1500 rpm the indicated specific fuel consumption increase fuel blend D70B30DM and D65B35DM compared to the indicated specific fuel consumption when using biodiesel fuel.

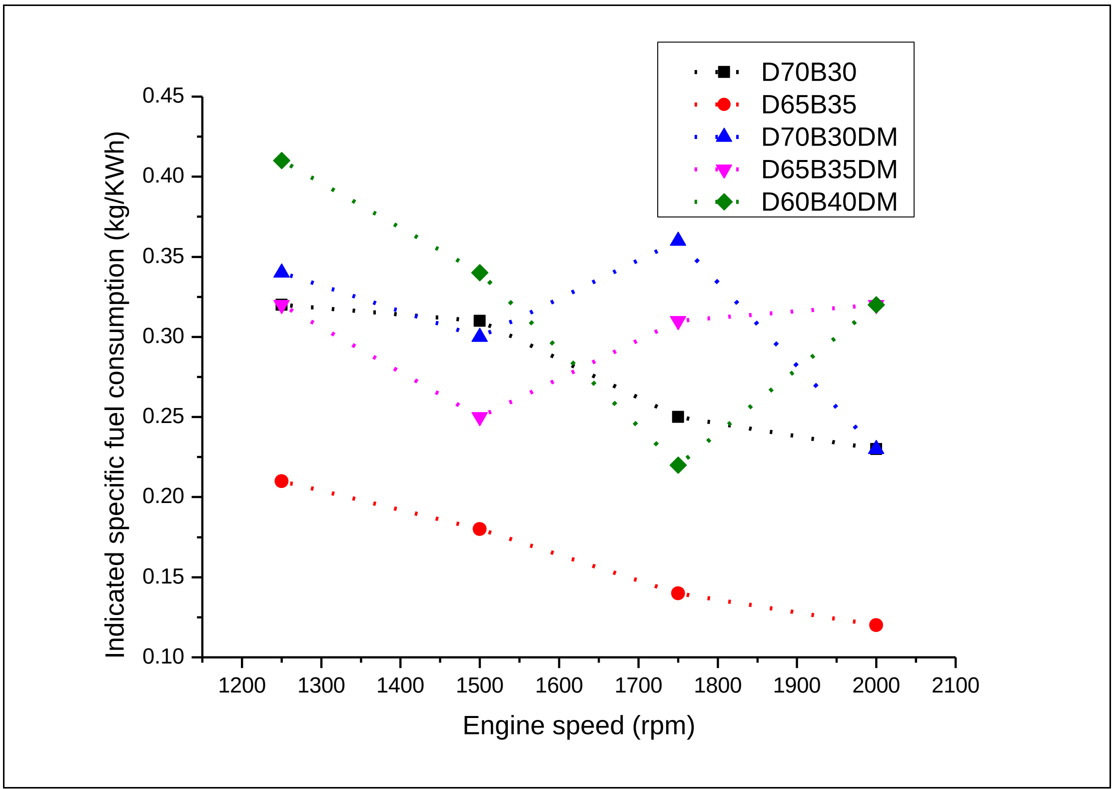
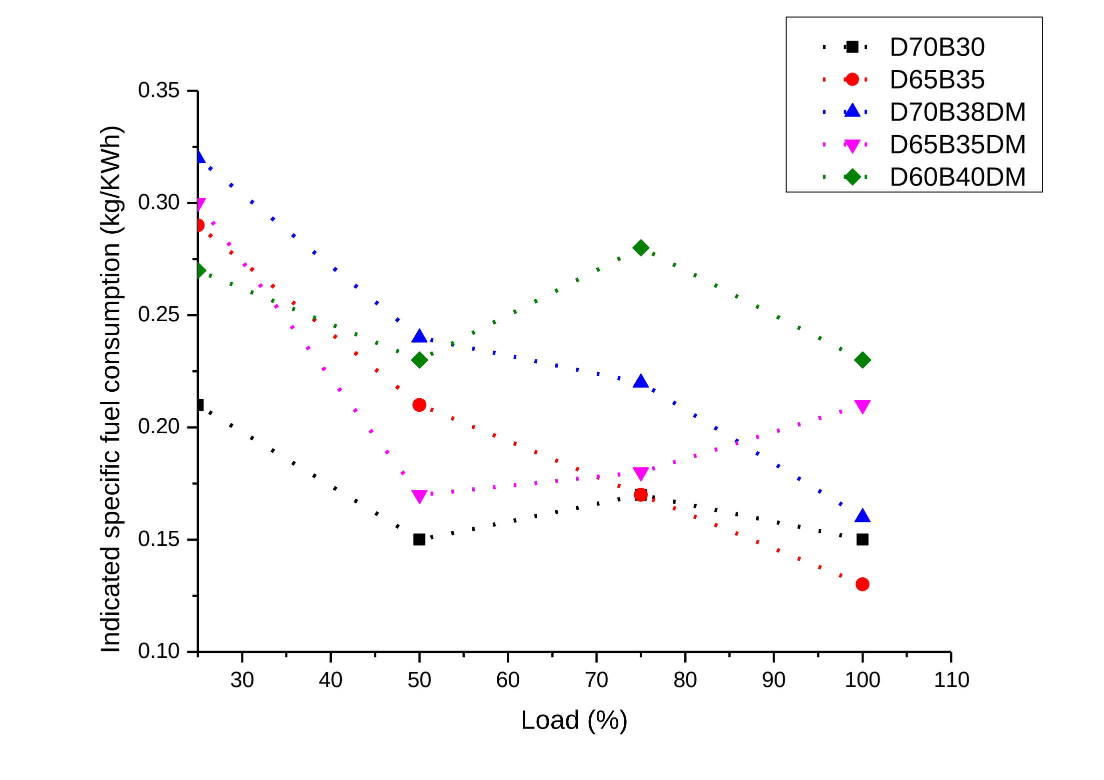


Figure 4.9: indicated specific fuel consumption (*ISFC*) versus speed of engine (N)

4.5.2 Effect of jatropha bio-diesel and antioxidant additive blend on indicated specific fuel consumption (*ISFC*) as a function engine load:

Figure 4.10 show the indicated specific fuel consumption (*ISFC*) with five different engine loads and with five different types of fuel at constant speed of (500rpm).

Figure 4.10 shows that bio diesel with jatropha bio-fuel added antioxidant decreases the indicated specific fuel consumption relatively compared to the indicated specific fuel consumption when using biodiesel fuel within loads (50 % and 100%).



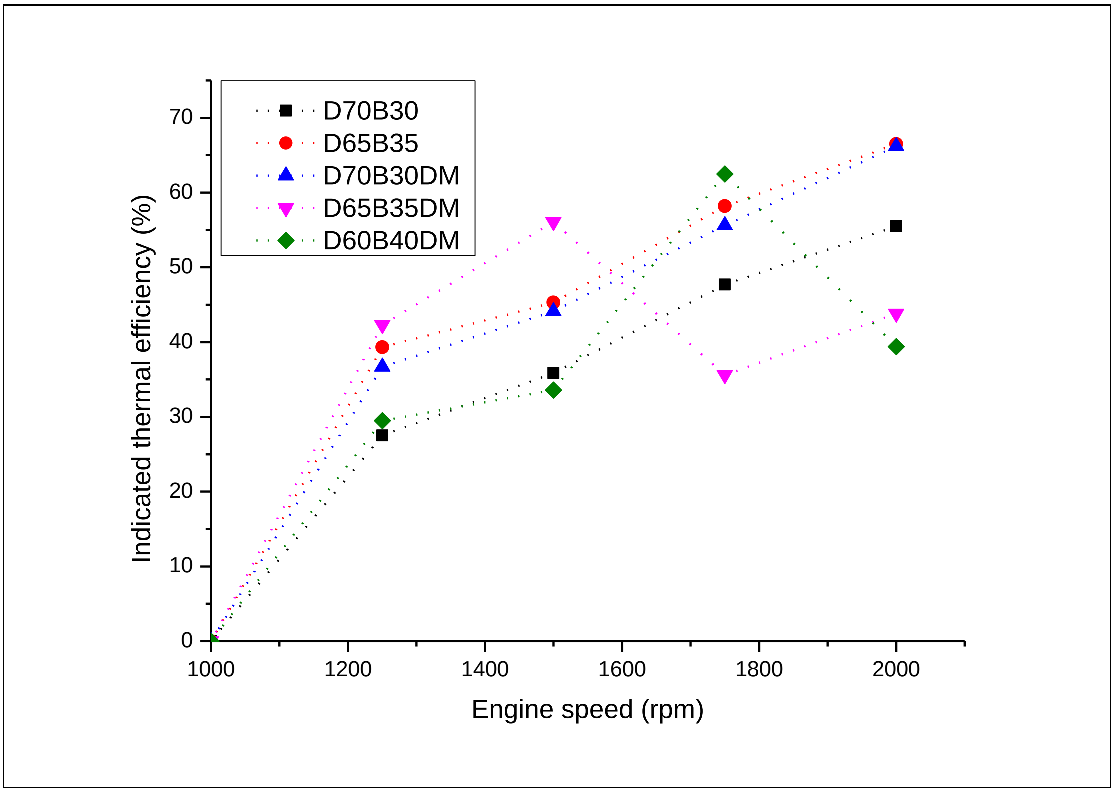
4.10: indicated specific fuel consumption (*ISFC*) versus load of engine (*%*)

4.6 Indicated thermal efficiency:

4.6.1Effect of jatropha bio-diesel blends and antioxidant additive on indicated thermal efficiency (τ_{ith}) as a function of engine speed:

Figure 4.11 show the indicated thermal efficiency (τ_{ith}) with five different engine speeds and with five different types of fuel at fixed load (10%).

Figure 4.11 shows that bio diesel with jatropha bio-diesel added antioxidant improves the indicated thermal efficiency. It is relatively high with the blends (D70B30DM) compared to the indicated thermal efficiency when using biodiesel fuel within speed limits from 1250 rpm to 2000 rpm.



4.11: indicated thermal efficiency (τ_{ith}) versus speed of engine (*N*)

4.6.2 Effect of jatropha bio-diesel blends and antioxidant additive on indicated thermal efficiency (τ_{ith}) as a function of engine load:

Figure 4.12 show the indicated thermal efficiency (τ_{ith}) with five different engine loads and with five different types of fuel at constant speed of (500rpm).

Generally adding jatropha biodiesel and antioxidant to the diesel fuel tends to decrease the indicated thermal efficiency, this due to the reduction in indicated power. The maximum efficiency was obtained at engine load of 100**%**; and that when using (D70B30) blend and (D65B35).

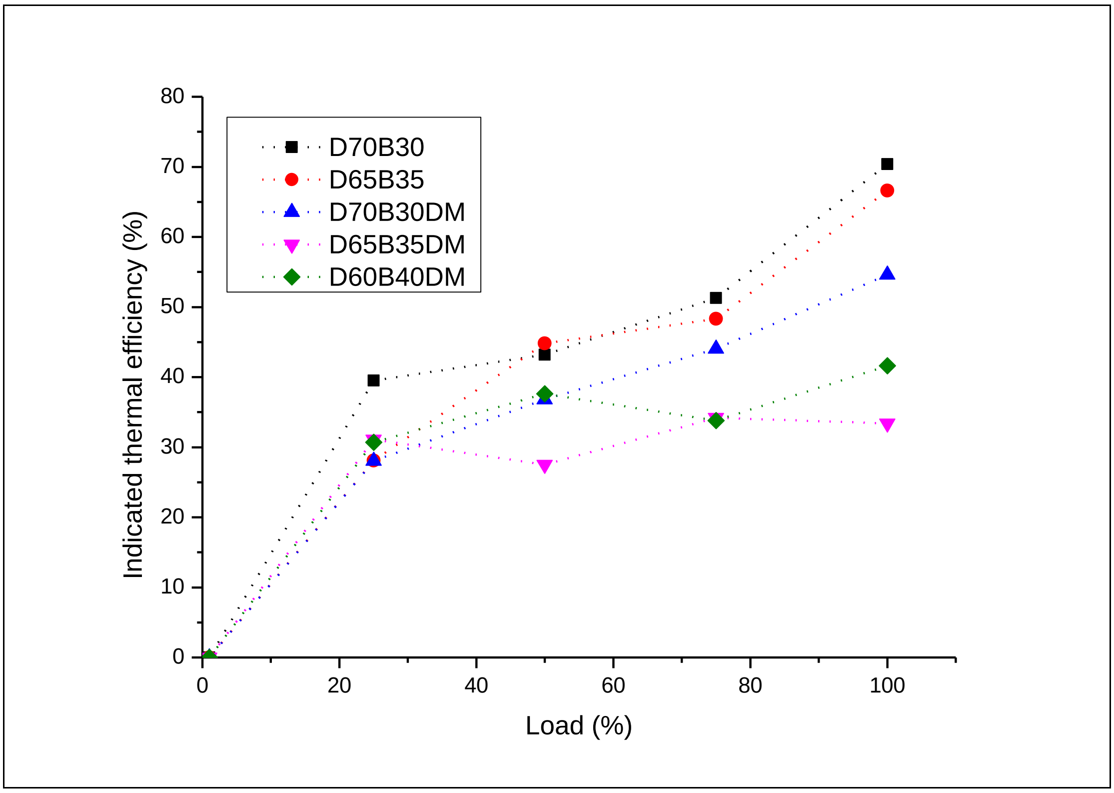


Figure 4.12: indicated thermal efficiency (τ_{ith}) versus load of engine (%)

4.7 Mechanical efficiency:

4.7.1Effect of jatropha bio-diesel blends and antioxidant additive on mechanical efficiency (τ_m) as a function of engine speed:

Figure 4.13 show the mechanical efficiency (τ_m) with four different engine speeds and with five different types of fuel at fixed load (10%).

Mixing jatropha bio-diesel and added antioxidant increased the mechanical efficiency at high speed as shown in Figure 4.13. The mechanical efficiency slightly high when using biodiesel compared to that obtained with the blended fuel added antioxidant at low speed. The highest mechanical efficiency was achieved with the fuel blend D65B35DM at speed 1750 rpm.

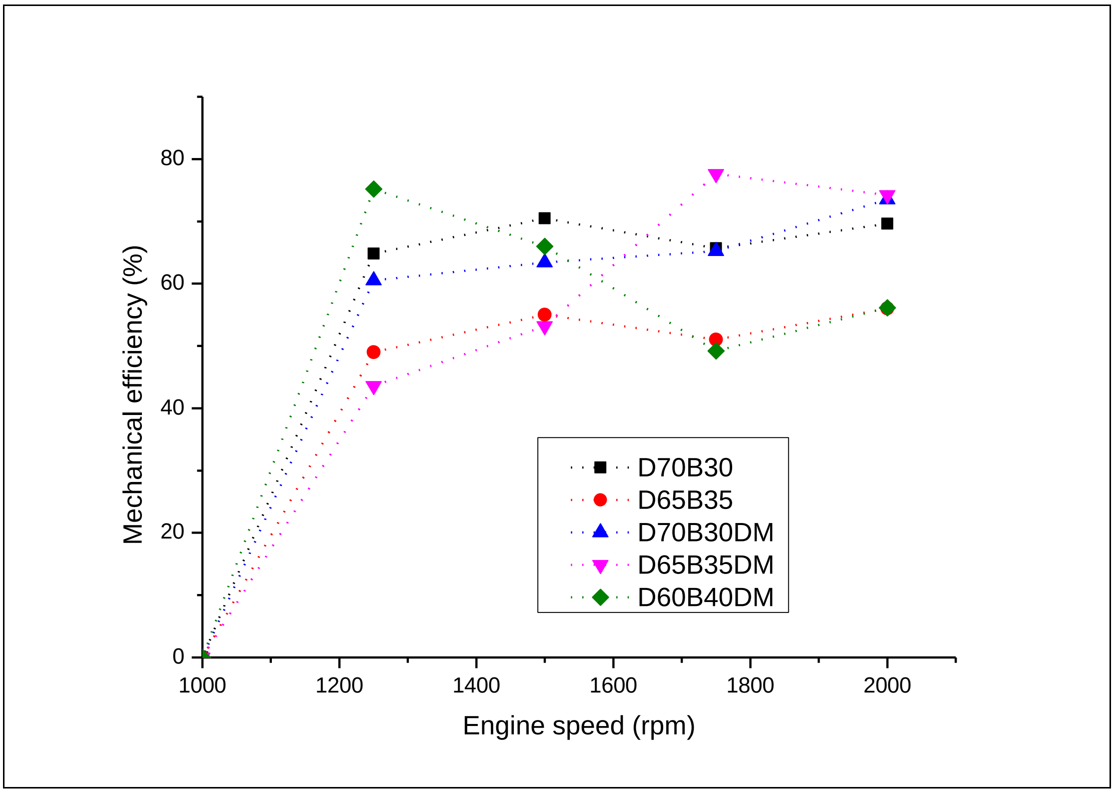


Figure 4.13: mechanical efficiency (τ_m) versus speed of engine (N)

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4.7.2 Effect of jatropha bio-diesel and antioxidant additive blend on mechanical efficiency (τ_m) as a function engine load:

Figure 4.14 show the mechanical efficiency with four different loads and with five different types of fuel at constant speed (500rpm).

The mechanical efficiency is slightly high with the blends (D65B35DM) compared to the mechanical efficiency when using biodiesel fuel with load 50% and 100%. In general mechanical efficiency increased with load to a certain limit then start to decrease again.

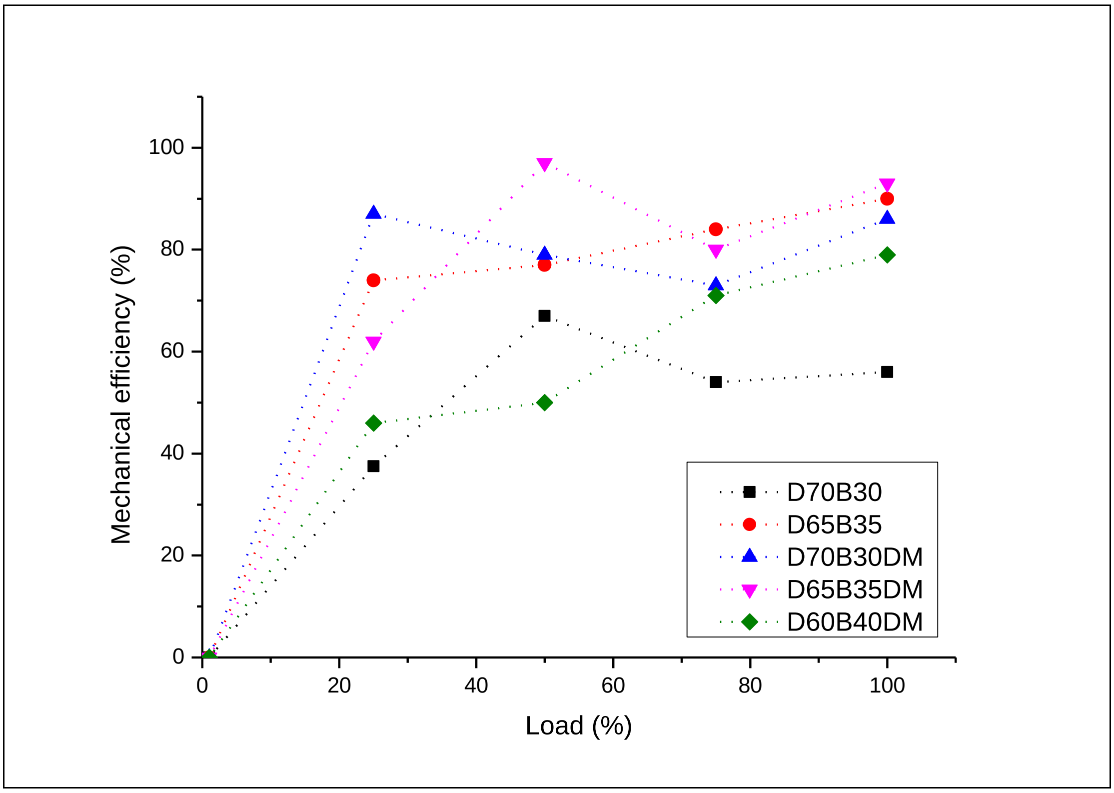

Figure 4.14: mechanical efficiency (τ_m) versus load of engine (%)

CHAPTER 5
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The objective of this study was to investigate the effects of feedstocks blending and antioxidants addition on fuel properties on the engine performance. This chapter presents the summary of the main findings from the work carried out in this research. It also proposes recommendations for future development in each of the areas covered during this research.

Tests were conducted on a diesel engine using jatropha bio-fuel and antioxidant blends to obtain the performance criteria. The results obtained through this research can be classified into two groups as follows:

5.1.1Fuel properties characterization:

The aim of the fuel properties characterization was to perform a diagnostic study for assessing the influence of different chemical additives on the engine performance. The properties of blended fuel were evaluated by investigating the effect of increasing the biodiesel blending and antioxidant ratio with biodiesel on blended fuel properties.

5.1.2 Engine performance:

Tests were conducted on a diesel engine using biodiesel fuel and antioxidant added blends to obtain the performance criteria. The performance criteria include brake power, brake specific fuel consumption, brake thermal efficiency, indicated power, indicated specific fuel consumption, indicated thermal efficiency and mechanical efficiency. The results show that the following engine performance:

i. Antioxidant added blends increases the brake power slightly by load compared to the brake power output from engine when using biodiesel fuel, more precisely the blend (D65B35DM) gives the highest brake power compared to the other fuel samples.

ii. Antioxidant blends decreases the brake specific fuel consumption relatively compared to the brake specific fuel consumption when using biodiesel fuel, more precisely the blends (D70B30DM) gives the lowest brake specific fuel consumption at engine speed of 1750 rpm .

iii. Antioxidant blends improve the brake thermal efficiency relatively high slightly compared to the brake thermal efficiency when using biodiesel fuel, more precisely the maximum efficiency was obtained at engine speed of 2000 rpm; and that when using (D70B30DM) blend (47.7%)

iv. Antioxidant blends increases the indicated power slightly by half load (50%) compared to the indicated power output from engine when using biodiesel fuel, more precisely the blend (D70B30DM) gives the highest indicated power at load (50%) compared to the other fuel samples.

v. Antioxidant blends decreases the indicated specific fuel consumption relatively compared to the indicated specific fuel consumption when using biodiesel fuel.

vi. Antioxidant blends improve the indicated thermal efficiency relatively high slightly compared to the indicated thermal efficiency when using biodiesel fuel, more precisely the maximum efficiency was obtained at engine speed of 2000 rpm; and that when using (D70B30DM) blend (54.6%).

5.3 Recommendations:

Based on the results that have been reached through experiments, the following are recommend:

1. Studying the effect of changing antioxidant ratio on blended biodiesel-diesel fuel properties and engine performance.

2. Conduct experiments on the engine using jatropha bio-fuel and antioxidant additive to investigate the exhaust emissions.

3. Apply response surface methodology (RSM) in order to investigate the combustion performance of blends and carry out the optimum response.

APPENDIX A
The Observation Tables for blends

Table B.1: Observation table for (D70BJ30) :(by speed)

Engine speed (rpm)	**1250**	**1500**	**1750**	**2000**
Torque (Nm)	41.67	50.58	53.16	58.524
Load acting On Dynamometer, m (kg)	20.757	24.945	26.198	28.307
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	190.14	185.20	175	170
Air Flow Rate, Q_a (m^3 / sec)	0.0078	0.024	0.024	0.025
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW (LPH)	200	200	200	200

Table B.2: Observation table for (D70BJ30) :(by load)

Load (%)	**25**	**50**	**75**	**100**
Torque (Nm)	12.84	31.84	46.42	51.41
Load acting On Dynamometer, m (kg)	6.72	13.849	22.743	25.403
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	908.2	393.2	545.8	743
Air Flow Rate, Qa (m^3 / sec)	0.0084	0.0047	0.00807	0.00772
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW (LPH)	200	200	200	200

Table B.3: Observation table for (D65BJ35) :(by speed)

Engine speed (rpm)	**1200**	**1400**	**1600**	**1800**
Torque (Nm)	31.29	35.17	37.96	42.99
Load acting On Dynamometer, m (kg)	15.12	16.99	18.34	20.77
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	264	260.4	253.2	249.6
Air Flow Rate, Q_a (m^3 / sec)	0.0078	0.0019	0.0079	0.0019
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW (LPH)	200	200	200	200

Table B.4: Observation table for (D65BJ35) :(by load)

***Load* (%)**	**25**	**50**	**75**	**100**
Torque (Nm)	33.99	36.48	51.12	61.15
Load acting On Dynamometer, m (kg)	16.423	17.623	24.696	29.543
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	314.4	431.4	488.4	507.6
Air Flow Rate, Qa (m3 / sec)	0.0011	0.0010	0.00103	0.0019

	5			
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW (LPH)	200	200	200	200

Table B.5: Observation table for (D70BJ30+DMBA) :(by speed)

Engine speed (rpm)	**1250**	**1500**	**1750**	**2000**
Torque (Nm)	38.11	38.38	36.26	39.73
Load acting On Dynamometer, m (kg)	18.826	19.011	17.878	19.659
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	235.5	265	314.2	390
Air Flow Rate, Q_a (m3 / sec)	0.0063	0.0074	0.00752	0.0072
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water toCalorimeter,WCCW (LPH)	200	200	200	200

Table B.6: Observation table for (D70BJ30+DMBA) :(by load)

Load (%)	**25**	**50**	**75**	**100**
Torque (Nm)	40.78	54.62	63.11	77.67
Load acting On Dynamometer, m (kg)	20.261	27.746	30.426	38.182
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	245	216.6	211.2	249.1
Air Flow Rate, Q_a (m3 / sec)	0.0102	0.0091	0.00384	0.00872
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW(LPH)	200	200	200	200

Table B.7: Observation table for (D65BJ35+DMBA) :(by speed)

Engine speed (rpm)	**1250**	**1500**	**1750**	**2000**
Torque (Nm)	27.47	31.23	38.13	42.57
Load acting On Dynamometer, m (kg)	13.743	15.541	18.763	21.351
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	263.5	317.3	272	196.7
Air Flow Rate, Q_a (m3 / sec)	0.0011	0.00532	0.00801	0.00810
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW(LPH)	200	200	200	200

Table B.8: Observation table for (D65BJ35+DMBA) :(by load)

Load (%)	**25**	**50**	**75**	**100**
Torque (Nm)	40.53	54.42	62.01	77.52
Load acting On Dynamometer, m (kg)	20.261	26.746	30.424	38.103

Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	244	215.7	210.5	249.1
Air Flow Rate, Qa (m3 / sec)	0.0102	0.0081	0.0052	0.00851
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW(LPH)	200	200	200	200

Table B.9: Observation table for (D60BJ40+DMBA) :(by speed)

Engine speed (rpm)	**1200**	**1400**	**1600**	**1800**
Torque (Nm)	45.31	37.4	26.26	24.17
Load acting On Dynamometer, m (kg)	22.352	18.345	13.162	12.115
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, T (sec)	199.5	209.7	368.1	254.1
Air Flow Rate, Q_a (m3 / sec)	0.0016	0.0084	0.00801	0.0075
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW(LPH)	200	200	200	200

Table B.10: Observation table for (D60BJ40+DMBA) :(by load)

Load (%)	**25**	**50**	**75**	**100**
Torque (Nm)	21.21	23.32	30.64	40.51
Load acting On Dynamometer, m (kg)	10.712	11.628	15.478	20.022
Volume of Fuel Consumed, X (ml)	150	150	150	150
Time taken to consumed X ml of Fuel, t (sec)	334.5	274	326.1	335.3
Air Flow Rate, Qa (m3 / sec)	0.0011	0.0081	0.00722	0.00721
Flow rate of cooling Water to Engine, WECW (LPH)	200	200	200	200
Flow rate of cooling Water to Calorimeter, WCCW(LPH)	200	200	200	200

APPENDIX B1
CALCULATION SAMPLE

(BY SPEED 1250):

The corresponding values for the speed of 1250 rpm for pure diesel were taken for this calculation sample.

Brake power (BP):

$$BP = \frac{2\pi NT}{60\times 1000} = \frac{2\pi\times 1250\times 41.67}{60\times 1000} = 5.45\ \text{KW}$$

Fuel consumption (m_f):

$$m_f = \frac{x\times \rho_f}{t\times 10^6} = \frac{150\times 850}{190.14\times 10^6} = 6.7\times 10^{-4}\ kg/s$$

Brakespecificfuelconsumption (BSFC):

$$\text{BSFC} = \frac{m_f\times 3600}{BP} = \frac{6.7\times 10^{-4}\times 3600}{5.45} = 0.44\ \text{kg/KWh}$$

Brakethermalefficiency (τ_{bth}):

$$\tau_{bth} = \frac{BP}{m_f\times CV} = \frac{5.45}{6.7\times 10^{-4}\times 45625}\times 100 = 17.8\%$$

Where (CV) is heating value of diesel fuel

Indicatedpower (IP):

$$IMEP = \left[\frac{Area\ of\ PV\ diagram, mm\ \times Scale\ of\ the\ diagram, bar/mm\ 2}{length\ of\ diagram, mm}\right]$$

$$IMEP = \frac{2119\times 1}{498.76} = 4.248\ bar$$

$$IP = \frac{imep\times A\times L\times N\times N_c}{n\times 1000\times 60}$$

$$= \frac{4.248\times 10^5\times 5.542\times 10^{-3}\times 0.09\times 4\times 1200}{2\times 1000\times 60} = 8.4\ KW$$

Indicatedspecificconsumption (ISFC):

$$ISFC = \frac{m_f\times 3600}{IP} = \frac{6.7\times 10^{-4}\times 3600}{8.4} = 0.28\ kg/KWh$$

Indicatedthermalefficiency (τ_{ith}):

$$\tau_{ith} = \frac{IP}{m_f\times CV} = \frac{8.4}{6.7\times 10^{-4}\times 45625}\times 100 = 27.5\%$$

Mechanicalefficiency (τ_m):

$$\tau_m = \frac{BP}{IP} \times 100 = \frac{5.45}{8.4} = 64.8\%$$

(BY load):

The corresponding values for the load 25% for pure diesel were taken for this calculation sample.

Brake power (BP):

$$BP = \frac{2\pi NT}{60\times1000} = \frac{2\pi\times1250\times12.84}{60\times1000} = 1.68 \text{ KW}$$

Fuel consumption (m_f):

$$m_f = \frac{x \times \rho_f}{t \times 10^6} = \frac{150 \times 850}{908.2 \times 10^6} = 1.404 \times 10^{-4}\ kg/s$$

Brake specific fuel consumption (BSFC):

$$BSFC = \frac{m_f\times3600}{BP} = \frac{1.404\times10^{-4}\times3600}{1.68} = 0.3\ kg/KWh$$

Brake thermal efficiency (τ_{bth}):

$$\tau_{bth} = \frac{BP}{m_f\times CV} = \frac{1.68}{1.404\times10^{-4}\times45625} \times 100 = 26.2\%$$

Indicated power (IP):

$$IMEP = \left[\frac{Area\ of\ PV\ diagram, mm \times Scale\ of\ the\ diagram, bar/mm\ 2}{length\ of\ diagram, mm}\right]$$

$$IMEP = \frac{1120 \times 1}{498.76} = 2.245\ bar$$

$$IP = \frac{imep \times A \times L \times N \times N_c}{n \times 1000 \times 60}$$

$$= \frac{2.245 \times 10^5 \times 5.542 \times 10^{-3} \times 0.09 \times 4 \times 1200}{2 \times 1000 \times 60} = 4.48\ KW$$

Indicated specific consumption (ISFC):

$$ISFC = \frac{m_f\times3600}{IP} = \frac{1.404\times10^{-4}\times3600}{4.48} = 0.22\ kg/KWh$$

Indicated thermal efficiency (τ_{ith}):

$$\tau_{th} = \frac{IP}{m_f\times CV} = \frac{4.48}{1.404\times10^{-4}\times45625} \times 100 = 39.5\%$$

Mechanical efficiency (τ_m):

$$\tau_m = \frac{BP}{IP} \times 100 = \frac{1.68}{4.48} = 37.5\%$$

APPENDIX B2
RESULT OF ENGINE PERFORMANCE

(BY SPEED):

Table C.1: Brake power (BP) [kW]:

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40****+DMBA*
1250	5.45	3.93	5.56	4.24	6.42
1500	7.27	5.15	6.46	5.15	6.35
1750	8.74	6.36	6.49	7.04	5.42
2000	10.65	8.1	8.31	8.35	5.17

Table C.2: Brake specific fuel consumption (BSFC) [kg/kW.h]

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40****+DMBA*
1250	0.44	0.43	0.51	0.62	0.52
1500	0.42	0.33	0.42	0.42	0.51
1750	0.35	0.27	0.34	0.36	0.37
2000	0.32	0.22	0.22	0.37	0.52

Table C.3: Brake thermal efficiency (τ_{bth}) [%])

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40****+DMBA*
1250	17.8	16.6	23.2	18.6	22.1
1500	26.5	24.9	27.6	29.5	22.2
1750	32.6	29.9	36.1	35.4	30.6
2000	41.2	37.5	47.7	32.2	22.1

Table C.4: Indicated power, IP [KW]

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40****+DMBA*
1250	9.5	8.01	8.87	8.58	8.27
1500	11.1	9.35	9.56	9.46	9.12
1750	14.3	12.37	10.23	10.14	9.56
2000	16.2	14.34	11.01	11.62	8.71

Table C.5: Indicated specific fuel consumption (ISFC) [kg/kW. h]

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
1250	0.32	0.21	0.34	0.32	0.41
1500	0.31	0.18	0.30	0.25	0.34
1750	0.25	0.14	0.36	0.31	0.22
2000	0.23	0.12	0.23	0.32	0.32

Table C.6: Indicated thermal efficiency (τ_{ith}) [%]

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
1250	27.5	39.3	36.7	42.3	29.5
1500	35.85	45.3	44.1	56.1	33.6
1750	47.7	58.2	55.6	35.6	62.5
2000	55.5	66.5	66.2	43.8	39.4

Table C.7: Mechanical efficiency (τ_m) [%]

		Fuel sample			
Engine speed(rpm)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
1250	64.8	49	60.5	43.6	75.2
1500	70.5	55	63.4	53.2	66
1750	65.7	51	65.2	77.6	49.2
2000	69.6	56	73.5	74.2	56.1

(BY load):

Table C.8: Brake power (BP) [kW]

		Fuel sample			
Load (%)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
25	1.68	3.56	5.76	3.56	3.55
50	4.67	3.82	7.62	7.65	3.83
75	6.63	5.35	8.54	9.43	4.73
100	7.34	6.4	10.24	10.78	5.97

Table C.9: Brake specific fuel consumption (BSFC) [kg/kW.h]

		Fuel sample			
Load (%)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
25	0.3	0.40	0.47	0.56	0.74
50	0.40	0.27	0.41	0.38	0.45
75	0.25	0.17	0.38	0.44	0.45
100	0.28	0.14	0.28	0.41	0.36

Table C.10: Brake thermal efficiency (τ_{bth}) [%])

		Fuel sample			
Load (%)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40****+DMBA*
25	26.2	20.1	24.3	20.4	14.4
50	27	23.4	28.8	34.2	32.3
75	36	34.9	32.01	27.7	24.3
100	41.3	42.01	46.8	30	32.6

Table C.11: Indicated power, IP [KW]

		Fuel sample			
Load (%)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
25	5.45	4.8	6.77	5.46	6.67
50	6.76	4.96	9.56	7.88	6.69
75	11.61	6.32	11.66	11.56	6.27
100	12.44	7.06	12.25	11.86	7.31

Table C.12: Indicated specific fuel consumption (ISFC) [kg/kW. h]

		Fuel sample			
Load (%)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
25	0.21	0.29	0.32	0.3	0.27
50	0.15	0.21	0.24	0.17	0.23
75	0.17	0.17	0.22	0.18	0.28
100	0.15	0.13	0.16	0.21	0.23

Table C.13: Indicated thermal efficiency (τ_{ith}) [%]

		Fuel sample			
Load (%)	***D70BJ30***	***D65BJ35***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
25	39.5	28.08	28.03	31.1	30.7
50	43.2	44.8	36.8	27.5	37.6
75	51.3	48.3	44.04	34.2	33.8
100	70.4	66.6	54.6	33.4	41.6

Table C.14: Mechanical efficiency (τ_m) [%]

		Fuel sample			
Load (%)	***D70BJ30***	***D5BJ356***	***D70BJ30****+DMBA*	***D65BJ35****+DMBA*	***D60BJ40*** *+DMBA*
25	37.5	74	87	62	46
50	67	77	79	97	50
75	54	84	73	80	71
100	56	90	86	93	79

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