THE STUDY OF PHYSIOCHEMICAL PROPERTIES AND SPRAYING CHARACTERISTICS OF HYBRID BIOFUEL FOR COMPRESSION IGNITION (CI) ENGINE APPLICATION

By:

MOHAMMAD AZHAR BIN FADZIL

(Matrix No. : 127201)

Supervisor:

DR. YUSOF IDROAS

MAY 2018

This dissertation is submitted to

Universiti Sains Malaysia

As partial fulfilment of the requirement to graduate with honors degree in

BACHELOR OF ENGINEERING (MECHANICAL ENGINEERING)

School of Mechanical Engineering

Engineering Campus

Universiti Sains Malaysia

DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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AKNOWLEDGEMENT

Thanks to God for His Blessing and Governess for giving me a chance and strength to complete my thesis writing successfully. First of all, I would like to thank my final year project supervisor, Dr Mohamad Yusof Idroas for his valuable guidance through the course of this work, and continuous encouragement for me to finish up this project. Thanks also to Dr Mohamad Ikhwan Zaini Ridzwan, for his role as final year project coordinator who provide information and conduct several seminar on technical report writing.

Furthermore, I would like to thank my parents Mr. Fadzil Tahir and Mrs. Saroja Madi for their continual support and love. I am grateful for my family members that always believing in me and have stood by my side. I am thankful for them for bringing me to this point in my life. Special thanks also to Mr. Sharzali Che Mat for his valuable guidance for me to complete this project.

I would like thank to my fellow friends, Qayum Sani, Fairuz Rahman, and Azfar Razin who have aspired along similar paths as I have. They were never too busy to help me and listen to my ideas. Many of the ideas come out from their general feedback to me.

Last but not least, appreciation is owed to all technician in School of Mechanical Engineering, USM especially Mr. Zalmi, Mr. Latif, and Mr. Norijas for their help to me understand in detail about my final year project.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

NOMENCLATURE

ASTM : AMERICAN SOCIETY FOR TESTING AND MATERIALS

ISO : INTERNATIONAL ORGANIZATION FOR STANDARDIZATION

CI : COMPRESSION IGNITION

SVO : STRAIGHT VEGETABLE OIL

RPO : REFINED PALM OIL

BUT : BUTANOL

PEN : PENTANOL

CV : CALORIFIC VALUE

ASOI : AFTER START OF INJECTION

ABSTRAK

Minyak sayuran bio bahan api adalah salah satu daripada alternatif kepada bahan api diesel petroleum yang berpotensi kerana sifat fizikalnya yang setara dengan bahan api diesel petroleum. Walaubagaimanapun, kelikatan yang tinggi dan ketumpatan SVO mengehadkan aplikasi langsung mereka dalam enjin pencucuhan mampatan. Oleh itu, untuk menyelesaikan masalah ini, hibrid bio-bahan api diperkenalkan untuk mengurangkan kelikatan dan ketumpatan SVO. Dalam kajian ini, salah satu bio-bahan api, alkohol berantai yang lebih tinggi (butanol dan pentanol) telah diadun bersama dengan Minyak Kelapa Sawit (RPO). Sebanyak lima campuran dengan nisbah peratusan sebanyak 10%, 20%, 30%, 40% dan 50% alkohol disediakan. Ciri-ciri utama bahan api seperti kelikatan kinematik, nilai kalori dan ketumpatan gabungan diukur dan ditanda aras terhadap piawaian biodiesel berdasarkan ASTM D6751. Telah didapati bahawa kelikatan, ketumpatan dan nilai kalori campuran ini menurun dengan peningkatan pecahan alkohol. Campuran optimum iaitu 50BUT:50RPO dan 53PEN:47RPO mempunyai sifat fisiokimia yang setanding dengan bahan api diesel tersebut. Campuran yang optimum telah dikaji dari segi ciri penyemburan mereka dalam sistem suntikan kereta biasa. Ciri semburan adunan yang optimum telah dianalisa dan diukur. Kedua-dua campuran mempunyai panjang semburan setanding pada tekanan suntikan 1000 bar. Sementara itu, sudut semburan dan lebar campuran adalah lebih kecil berbanding dengan bahan api berasaskan diesel. Secara keseluruhannya, kedua-dua 50BUT:50RPO dan 53PEN:47RPO mempunyai ciri-ciri fisiokimia dan semburan yang standing dengan bahan api berasaskan diesel. Secara rumus, kedua-dua campuran hibrid bio-bahan api boleh digunakan untuk aplikasi enjin pencucuhan mampatan.

ABSTRACT

Straight vegetable oil (SVO) biofuels is one of potentially alternative petroleum diesel fuel due to its comparable physical properties to that petroleum diesel fuel. However, the high viscosity and density of SVO limits their direct application in a CI engine. Therefore, to solve this problem, hybrid biofuels were introduced to reduce the viscosity and density of SVO. In this study, biofuel of higher chain alcohol (butanol and pentanol) was blended together with Refined Palm Oil (RPO). A total of five blends with the mixing ratios of 10%, 20%, 30%, 40% and 50% of both alcohols were prepared. Key properties of the fuel such as kinematic viscosity, calorific value and density of the blends were measured and benchmarked against the biodiesel standards based on ASTM D6751. It was found that viscosity, density and calorific value of the blends decreased with the increase of alcohols fraction. Optimized blends which were 50BUT50RPO and 53PEN47RPO have a comparable physiochemical properties to that diesel fuel. The optimized blends were studied in term of their spraying characteristic in a common rail injection system. The spray characteristics of optimized blends were captured and measured. Both blends have a comparable spray penetration at 1000 bar injection pressure. Meanwhile, the spray angle and width of optimized blends were smaller in comparison with diesel-based fuel. This is due to the comparatively higher viscosity and surface tension of hybrid biofuel blends, which enhanced the friction effect between fuel and the injector nozzle surface and inhibited the breakup of the liquid jet. Overall, both 50BUT:50RPO and 53PEN:47RPO have a comparable physiochemical properties and spraying characteristic in comparison with diesel-based fuel. Hence both hybrid biofuel blends can be used for a compression ignition (CI) engine application.

CHAPTER 1: INTRODUCTION

1.1 Introduction.

Diesel engine is an internal combustion engines which converts chemical energy contained in the fuel into mechanical power. Diesel fuel is a mixture of hydrocarbons which produce only carbon dioxide (CO_2) and water vapor (H_2O) during an ideal combustion process. However, in real process diesel emissions include also pollutants that can have adverse health and environmental effects. Most of these pollutants originate from various non-ideal processes during combustion, such as incomplete combustion of fuel, reactions between mixture components under high temperature and pressure, combustion of engine lubricating oil and oil additives as well as combustion of non-hydrocarbon components of diesel fuel, such as sulfur compounds and fuel additives. Common pollutants include unburned hydrocarbons (HC), carbon monoxide (CO), nitrogen oxides (NOx) or particulate matter (PM).

Diesel fuel is the fuel of choice for transportation and industrial transport vehicles. In the past decades, emission from transportation contribute fair effect towards emission pollution. In US, Greenhouse gas emissions from transportation primarily come from burning fossil fuel from cars, trucks, ships, trains, and planes. Over 90 percent of the fuel used for transportation is petroleum based, which includes gasoline and diesel. Transportation contribute 27 percent of greenhouse gas emission in 2015. In Europe, transportation contribute 23 percent of greenhouse gas emission in 2015. Hence, it is important to study an alternative fuel for diesel fuel which have comparable physiochemical properties and reduce emission pollution [1].

1.2 Introduction to Biodiesel.

Biodiesel is one of the alternative for diesel fuel as the diesel fuel is not a renewable energy. It is an alternative fuel similar to conventional diesel fuel. Biodiesel can be produced from straight vegetable oil, animal oil or fats, tallow and waste cooking oil through transesterification process. There are three basic process path to biodiesel production from oils and fats which are base catalyzed transesterification of the oil, direct acid catalyzed transesterification of the oil and conversion of the oil to its fatty acids and then to biodiesel. The largest possible source of suitable oil comes from oil crops such as rapeseed, palm or soybean. In Malaysia palm oil represents the greatest potential for biodiesel production

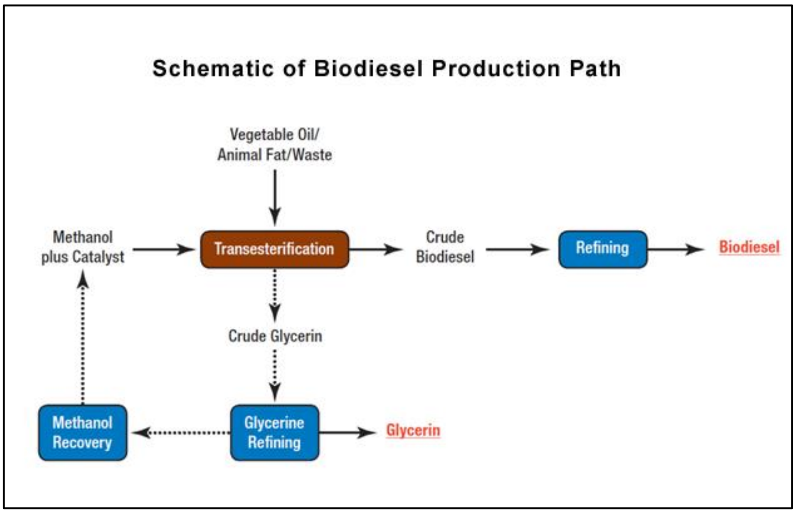

Figure1.2.1: Schematic of biodiesel production process.

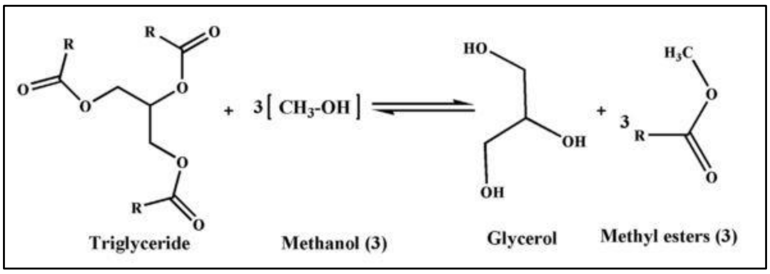

Figure 1.2.2: Transesterification process for producing the biodiesel.

Various methods have been reported for the production of biodiesel from vegetable oils, such as dilution, pyrolysis, and transesterification and supercritical methanol methods Table 1.2 shows comparison of different biodiesel production methods:

Table 1.2: Comparison of biodiesel production methods [2].

Methods	**Dilution**	**Pyrolysis**	**Transesterification**	**Supercritical Methanol**
Advantages	Simple process	Simple process	Fuel properties are closer to diesel	No catalyst
		Non-polluting	High conversion efficiency	Short reaction time
			It is suitable for industrialized production	High conversion
Disadvantages	High viscosity	High temperature is required	Products must be neutralized and washed	Apparatus cost is high
	Bad volatility	Apparatus is expensive	Accompanied by side reactions	High energy consumption
	Bad stability	Low purity	Difficult reaction products separation	

However, high viscosity content in biodiesel affect the performance of diesel engine. Furthermore, the high viscosity may damage the diesel engine due to poor combustion process and high density of biodiesel increase the level of emission of NOx. Moreover, low calorific value of biodiesel results in the increase in specific fuel consumption and decrease in combustion temperature.[3] In term of spray characteristics study, it is found that the spray tip penetration of biodiesel is longer than that of diesel under the same injection condition. This is due to higher liquid phase fraction of biodiesel holds higher momentum, and return increases the spray tip penetration. The spray cone angle for diesel is wider than that for biodiesel under the same injection pressure, because of the high viscosity and surface tension of biodiesel[4].

1.3 Introduction to Biofuels.

Biofuels such as alcohols are less viscous and have lower surface tension compared to biodiesel. Biofuels can be classified into two categories: primary and secondary biofuels. The primary biofuels are directly produced from burning woody or cellulosic plant material and dry animal waste. The secondary biofuels can be classified into three generations that are each indirectly generated from plant and animal material. The first generation of biofuels is ethanol derived from food crops rich in starch or biodiesel taken from waste animal fats such as cooking grease.

The second generation is bioethanol derived from non-food cellulosic biomass and biodiesel taken from oil-rich plant seed such as soybean. The third generation is the biofuels generated from cyanobacterial, microalgae and other microbes, which is the most promising approach to meet the global energy demands [5].

1.3.1 Introduction to Straight Vegetable Oil (SVO).

Diminishing fossil fuel and concern over global environment have led researchers to extensively study vegetable oils as fossil fuel replacement. Its properties are close to diesel, and it is renewable and biodegradable, which makes them a great candidate to replace the current fossil fuel. For the past decade, the effect of using vegetable oils as a direct fuel on engine performance and emissions has been investigated by several researchers.

Straight vegetable oils are mainly composed of triglycerides which contain three fatty acids and one glycerol. Triglyceride contributes to the high viscosity of vegetable oil, compared to fatty acid methyl ester (FAME). Fig. shows the typical structure of a triglyceride molecule. The composition of fatty acids determines the physiochemical properties of vegetable oil. Fatty acid is characterized by the length of carbon chain and numbers of double bonds. Commonly found fatty acids in vegetable oils are palmitic, stearic, oleic, linoleic and linolenic acid.

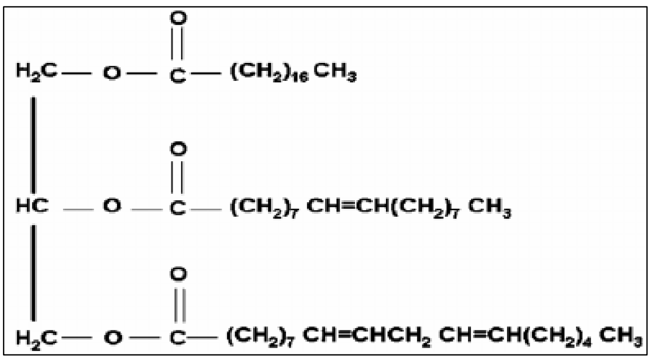

Figure 1.3.1: Typical triglyceride molecule structure [6].

1.3.2 Introduction to Alcohol.

Alcohols are one of biofuel which have low viscosity compared with biodiesel. Alcohol is any organic compound in which the hydroxyl functional group (–OH) is bound to a carbon. In general, the hydroxyl group makes alcohols polar. Those groups can form hydrogen bonds to one another and to most other compounds. Due to the presence of the polar OH alcohols are more water-soluble than simple hydrocarbons. There are six major production process of an alcohol. These process includes Ziegler and Oxo processes, hydration reactions, fermentation, substitution, reduction and hydrolysis.

Alcohol is classified into two major group which is low chain alcohol and high chain alcohol. These term is based on the carbon contained in the compound. Alcohol with carbon number of three and lower is called lower chain alcohol and alcohol with four carbon and higher is called high chain alcohol.

Table: Properties of higher alcohols in comparison with diesel and other lower alcohols [7].

Properties	Diesel	Methanol	Ethanol	Propanol	Butanol	Pentanol	Hexanol	Octanol	Decanol	Phytol
Molecular formula	C_xH_y	CH_3–OH	C_2H_5–OH	C_3H_7–OH	C_4H_9–OH	C_5H_{11}–OH	C_6H_{13}–OH	C_8H_{17}–OH	C_9H_{19}–OH	$C_{20}H_{39}$–OH
Molecular weight (Kg/kmol)	190–211.7	32.04	46.07	60.09	74.12	88.15	102.18	130.23	158.28	296
C (%wt)	86.13	37.48	52.14	59.96	64.82	68.13	70.52	73.72	68.23	81.08
H (%wt)	13.87	12.48	13.02	13.31	13.49	13.61	13.70	13.82	12.64	13.51
O (%wt)	0	49.93	34.73	26.62	21.59	18.15	15.70	12.29	10.11	5.4
Solubility (g/L)	Immiscible	Miscible	Miscible	Miscible	77	22	7.9	4.6	3.7	–
Lubricity (μm corrected wear scar)	315	1100	1057	922	591	670.5	534	404	406	–
Cetane number	52	5	8	12	17	18.2–20	23	39	50	45.9
Self-ignition temperature (°C)	254–300	463	420	350	345	300	285	270	255	–
Density (kg/m^3) at 15°C	835	791.3	789.4	803.7	809.7	814.8	821.8	827	830	850.9
Viscosity at 40 °C (mm/s^2)	2.72	0.58	1.13	1.74	2.22	2.89	5.32	–	6.5	63.54
Lower heating value (MJ/Kg)	42.49	19.58	26.83	30.63	33.09	34.65	39.10	52.94	–	43.6
Latent heat of evaporation (kJ/kg)	270–375	1162.64	918.42	727.88	581.4	308.05	486	–	–	–
Vapor pressure (mmHg)	0.4	127	55	20	7	6	1	0.08	< 0.1	–
CFPP [b] (°C)	−17	< −51	< −51	< −51	< −51	−40	–	–	–	–
Boiling point (°C)	180–360	64.7	78.3	97.1	117.5	137.9	157	195	233	204
Flash point (°C)	> 55	11–12	17	11.7	35–37	49	59	81	108	–

High chain alcohol have several advantages compared to low chain alcohols. High chain alcohol can be blended with diesel, biodiesel and straight vegetable oil without any surfactant. Alcohol molecules contain alkyl and hydroxyl, the more carbon an alcohol molecule contains, the easier the alcohol can be blended. Moreover, higher chain alcohol have more cetane number and calorific value compared to lower chain alcohol. Cetane number is important to control the ignition delay of a CI engine.

Typically the low heating value of alcohol rises with increased carbon atom number. Therefore, the fuel consumption of higher chain alcohols will reduce and a better mileage can be obtained. Lastly, higher alcohols are safer than lower alcohol due to its very low vapor pressure point and a high flash point, hence it is a much safer fuel to use in high temperatures.

1.4 Problem Statement.

Diesel engine vehicles are one of the most preferable transportation in the world. This is due to its high fuel efficiency and high engine performance efficiency. However the major drawback of diesel engine is the high emission level of pollution emitted to the environment. These emission includes HC, NOx and soots. In recent years, the introduction of biodiesel in diesel engine as an alternative to diesel-based fuel proved can reduce soot emissions, but increase NOx emissions slightly. Furthermore, the high viscosity may damage the diesel engine due to poor combustion process and high density of biodiesel increase the level of emission of NOx. Moreover, low calorific value of biodiesel results in the increase in specific fuel consumption and decrease in combustion temperature. Today, the production cost of biodiesel through transesterification is costly and involve a high capital investment. It is reported that the price of biodiesel in today market is one and half more expensive than commercial diesel-based fuel. Lower alcohols blends such as ethanol and methanol in other hand have been studied by several researcher due to its ability to reduced NOx emission and formation of soots. However, lower alcohols have difficulty to be blended with SVO due to limited solubility and phase separation within a short period of time. Therefore, a presence of surfactant is needed to enhance the miscibility and stability of the blend.

The main goal of this project was to reduce viscosity of SVO by blending methods. Refined palm oil will be blended with higher chain alcohols (butanol and pentanol) and the physiochemical properties of the blends will be determined. The optimized blends ratio that have comparable physiochemical properties as diesel-based fuel will be predicted using mathematical model developed from experimental data. Then, the optimized blends and will be further studied in term of their spray characteristics in comparison with diesel-based fuel.

1.5 Research Objectives.

1. To study the methods to reduce viscosity of straight vegetable oil (SVO) where the blending method is the critical process.
2. To formulate the optimized ratio of hybrid biofuel blends which have comparable physiochemical properties to a diesel-based fuel.
3. To determine the key physiochemical properties of hybrid biofuels in term of calorific value, viscosity and density which can be used to determine the performance and emission of the CI engine.
4. To analyze the spraying characteristic of hybrid biofuels in term of spray penetration length, spray angle and spray width.

1.6 Scope of Work.

The project scope include the study of methods to reduce viscosity of straight vegetable oil (SVO) where the blending method is the critical process. The hybrid biofuel blends of refined palm oil (RPO) with butanol and RPO with pentanol will be prepared. The physiochemical properties of hybrid biofuels will be studied and analyzed in term of its kinematic viscosity, density and calorific value. Lastly, an experiment to study the spraying characteristics of hybrid biofuel will be conducted in term of spray penetration length and spray angle.

CHAPTER 2: LITERATURE REVIEW

2.1 Methods of Reducing Viscosity of SVO

Straight vegetable oil (SVO) biofuel is a promising alternative to petroleum diesel fuel primarily due to its comparable physical properties to that of petroleum diesel fuel. However, recent studied have reported that the direct use of SVO in diesel engine will lead to severe carbon deposit, fuel injector clog and rapid wears of fuel pump components. These issues were primarily associated with a high viscosity of SVO that dramatically alters fuel spray characteristics, atomization quality and volatility [8].

There were several methods used to reduce the viscosity of SVO, such as micro-emulsion, preheat, blending, and transesterification method. Among the available methods, transesterification method was the most widely used to reduce the viscosity of SVO and convert triglycerides into fatty acid methyl ester (commonly known as biodiesel) and glycerol. However, transesterification process involved complex yet expensive process where a specific equipment and instrumentation were required. Furthermore, the formation of glycerol as the result from the process requires further expensive purification process to produce pure glycerol which has better value than crude glycerol [9].

Blending of SVO with other lower viscosity fuel was also found to be an effective and economical method to reduce its viscosity. This method has been studied by many researchers. Generally, previous study shown that engine fuelled with this blended fuel has comparable performance characteristics to those of diesel fuel, but with some reduction in brake specific fuel consumption (BSFC). Most of researcher concluded that this is mainly associated with the low calorific value (CV) of the blend, which resulted in the reduction of engine performance and increase in BSFC.

Meanwhile, on the bright side, NOx emission was reported to be slightly lower compared to diesel fuel.

Alcohol is another ingredient that is often used by researchers for blending with vegetable oil. Recently, researchers have studied the blends of longer-chain alcohols like butanol with SVO primarily due to their close properties to those of diesel fuel. Longer-chain alcohols has better CV, flash point, boiling point and cetane number as compared to short-chain alcohols. Moreover, longer-chain alcohol is miscible with SVO thus, no additional surfactant is required to produce a stable blend [8].

2.2 Straight Vegetable Oil as Direct Fuel

In the past decades, many researcher study the potential of straight vegetable oil (SVO) to be used as direct fuel for a compression ignition engine application. Straight vegetable oil is renewable and bio-degradable hence they are great candidate to replaced fossil fuel in the future. Series of studies have been conducted to determine the performance end emission of a CI engine using straight vegetable oil as a fuel.

M.S.Shehata conducted an experiment using neat sunflower oil to investigate their performance and emissions characteristics at different engine loads and different engine speeds. From the study, they found that brake thermal efficiency (BTE) brake power (BP) and torque were lower, while specific fuel consumption (BSFC) was higher compared to diesel fuel. For emission test, the NOx emission was significantly reduced, however CO_2 and CO emissions increased [10].

Recently D. Sonar studied the effect of various injection opening pressure (IOP) on engine performance and emissions characteristic. Preheated and unheated mahua oil were tested on a single cylinder, four stroke direct injection engine at low until full load conditions and at constant engine speed (1500 rpm). They concluded that the BSFC and EGT for those of heated and unheated mahua oil were generally higher than diesel fuel, but preheated oil had slightly lower BSFC and EGT compared to unheated oil. From emission test, study found that NOx emission was lower at low load, but higher at full load, for both heated and unheated of mahua oil. NOx was found to increase as IOP increase. However, slight reduction in CO and HC emissions were observed [11].

P. Ndayishimiye investigated the potential of palm oil as a replacement for diesel fuel on unmodified single cylinder, four stroke CI engine. Preheated palm oil was tested on the engine from low until full load conditions at a constant speed of 1800 rpm where palm oil was heated at three different temperatures, 50°C, 60°C and 70°C. Result shows that all preheated palm oils exhibited high BSFC compared to diesel. BTE was found slightly lower at partial load, however at full load it was comparable with diesel. NOx emissions were higher at medium load, but undergoes reduction at full and high loads. HC emission was immensely reduced between 30°C and 40°C where 50°C temperature gave the highest reduction [12].

Table 2.2: Performance and emission of CI engine fuelled with SVO [10] [11] [12].

Fuel	Fuel Properties			Engine type	Test Condition	Reference Fuel	Emission	Performance
	Calorific Value (MJ/kg)	Density (kg/m^3)	Viscosity (mm^2/s)					
Sunflower Oil	37.7–39.6	925	33.9	Single cylinder, four stroke direct injection diesel engine	constant injection timing, constant start of injection, low load conditions (at 1200 rpm)	Diesel	⇩ Nox ⇧ CO ⇧ CO2	⇧ BSFC ⇩ BTE ⇩ BP ⇩ Torque
Mahua oil	35–41.8	891-960	24–37.6	Single cylinder, four stroke, water cooled direct injection diesel engine	varying injection opening pressure (IOP), Low to Full load conditions (at 1500 rpm	Diesel	⇩ Nox ⇧ CO ⇧ CO2	⇧ BSFC ⇩ BTE ⇩ BP ⇩ Torque
Palm oil	36.9	910	39.6	Single cylinder, four stroke, air cooled direct injection diesel engine	constant injection timing, constant start of injection, low load conditions (at 1200 rpm)	Diesel	⇧ Nox ⇧ CO ⇧ CO2 ⇧ HC	⇧ BSFC ⇩ BTE ⇩ BP ⇩ Torque

Therefore, from past research on the usage of straight vegetable oil in a compression ignition engine, it can be concluded that the BSFC increased while the BP, torque and BTE reduced slightly. The low calorific value (CV) of SVO leads to more fuel needed to combust in order to obtain the same engine performance as diesel fuel. Hence, the BSFC of was higher compared to that diesel fuel. BTE reduction however may be due to the high viscosity of SVO which leads to poor spray characteristic and fuel atomization.

The high viscosity and poor fuel atomization of straight vegetable oil limits the potential of SVO to be a replacement for diesel fuel. On the contrary, the NOx emission level reduced while CO and HC mostly increased. The increased in CO emission maybe due to incomplete combustion while HC produced due to lack of oxygen to react with more fuel injected in the engine cylinder [13].

2.3 Vegetable Oil-Diesel Blends

From the research of usage of straight vegetable oil as direct fuel in a compression ignition engine shows that high viscosity and poor fuel atomizing of straight vegetable oil affect the engine performance and emission. Therefore, to reduce the viscosity of SVO, blending with mineral diesel is one of the solution. Blending method is useful to reduce viscosity of the SVO hence improved their fuel atomization. Studies reported that blends of 20% vegetable oil with 80% diesel can be used directly on diesel engine without any engine modification [13].

Ramadhas classified the physical properties of various rubber seed oil (RSO)-diesel blends and study their effects on engine performance and emissions. The experiments were carried out on a single cylinder, four stroke direct injection, and CI engine at zero until full load conditions. They found that the BSFC and EGT of 20% and 40% RSO blends were almost comparable to those of diesel fuel. However, for 60% and 80% RSO blends, the EGT slightly reduced compared to baseline fuel. BTE was found highest at 80% RSO, while 60% RSO was closer to that of diesel fuel. The smoke density was found highest for 20% RSO, while those of 40% and 60% RSO were convenient to that of baseline fuel [14].

Roy investigated the performance and emission characteristic of canola oil-diesel blends on a four stroke two cylinders CI engine. They found that blends containing less than 10% canola oil had no significant increase in BSFC, however greater percentage of blends increased the BSFC up to 2.3% than neat diesel fuel. Meanwhile, the NOx emission for 5% canola oil blend was almost akin to that of diesel fuel, but higher blends produced slightly increased emissions. CO emission in other hand reduced for all blends at all rpm. A decreased of HC at partial rpm is reported, but increased at high rpm [15].

Recently, Nagaraja analysed the effect of variable compression ratio on engine performance and emissions operating with preheated palm oil-diesel blends. Blends of 5%, 10%, 15% and 20% palm oil were tested on a single cylinder CI engine at full load at constant 1500 rpm. Experimental results reported that for all blends, BP increased with increasing compression ratio. Blends containing 20% palm oil achieved the highest BP compared to other blends and diesel fuel. EGT was found lower than diesel fuel for all blends, however the 5% palm oil blends almost comparable to diesel. From emission test, CO and HC were significantly reduced compared to diesel fuel as the 20% blends gave the highest reduction. Nonetheless, there was significant increase in CO_2 for entire range of test [16].

Table 2.3: Performance and emission of CI engine fuelled with SVO-diesel blends [14] [15] [16].

Fuel	Vegetable oil (%)	Engine type	Test Condition	Reference Fuel	Emission	Performance
Rubber Seed Oil + Diesel	20, 40	Single cylinder, four stroke direct injection diesel engine	No load to full load (at 1500rpm)	Diesel	↓ smoke at high load	↑ BSFC
					↓ smoke at low load	↓ BTE
						↓ BP
						↓ Torque
Canola Oil + Diesel	5	Single cylinder, four stroke, water cooled direct injection diesel engine	10–15% load at 1200–1800 RPM	Diesel	↑ Nox	↑ BSFC
					↑ CO	
					↑ CO2	
Palm oil + Diesel	5, 10, 15, 20	Single cylinder, four stroke, water cooled direct injection diesel engine	Preheated oil at 900C, full load at different compression ratios (CR) (at 1500 RPM	Diesel	↑ HC	↑ BP
					↑ CO	↓ EGR
					↑ CO2	

Therefore, summary from previous study on the usage of SVO-diesel blend shows that blending of mineral diesel with SVO can reduced the viscosity and enhanced fuel atomization of the blends. The study shows that although there was reduction on EGT, some of blends managed to achieve comparable BP to diesel fuel. In term of emission, SVO-diesel blends produce higher CO_2 content compared to diesel fuel however most researcher found that CO and HC emission level of SVO-diesel blends was reduced and comparable to that diesel engine.

2.4 Vegetable Oil-Low Chain Alcohol Blends.

Alcohol is a type of biofuel and a renewable energy as biodiesel. Alcohol itself can be divided into two major type which is lower alcohol and higher alcohol. This classification was based on their carbon chain length. Lower alcohols have difficulty to be blended with SVO due to limited solubility and phase separation within a short period of time. Therefore, a presence of surfactant is needed to enhance the miscibility and stability of the blend. Higher alcohol in other hand can be blends with SVO without any surfactant [13]. The miscibility of higher alcohol with diesel and vegetable oil is higher, thus improving the stability of the blends.

Pinzi studied the exhaust and noise emissions of a diesel engine fueled with oxygenated fuels (short-chain alcohols, i.e. ethanol and propanol) and diesel fuel blends. He found that the sound pressure level increases may be due to low cetane number of the blends. Higher ignition delay results in higher amount of fuel burnt during the premixed phase of combustion, hence a higher combustion noise. For exhaust emissions, study found that a reduction of soot emissions when the portion of alcohol in the blend increases. The increase of oxygen in the fuel lowers the soot emission. Moreover, a notable reduction of NOx emissions has also been observed due to major reduction on the combustion temperature. However, the blends show an increase of HC and CO emissions, as a result of incomplete combustion [17].

B. Prbakaran study the experimental evaluations of performance, combustion and emission characteristics of blends containing non-edible cotton seed oil methyl ester and anhydrous ethanol in a diesel engine at various loads. Blends are made from bio-diesel from cotton seed oil by anhydrous ethanol in various blend percentage ranging from 10% to 50%. Study found that the brake thermal efficiency of the blends is similar to that of diesel. The study reported there was reduction of NOx and smoke. Moreover, slight reduction of CO and HC at higher loads was observed however increase at lower loads [18].

Lower alcohol-vegetable oil blend shows potential in reducing the emission of CI engine based on previous research. However, due to incomplete combustion, the engine performance were affected. Low cetane number of the fuel blend results in higher ignition delay. The low calorific value of the blends also results in high BSFC. However, on positive side, the high oxygen content in alcohol helps to reduce the soot emission. Furthermore, the reduction in combustion temperature also results in reduction of NOx emission.

2.5 Vegetable Oil-High Chain Alcohol Blends.

Higher alcohols, as opposed to lower-chain alcohols (methanol and ethanol) have a promising future for diesel engines. Higher-chain alcohol, has better fuel characteristics and can be made of biomass. Nevertheless, the use of lower alcohols like methanol and ethanol in compression-ignition engines presents certain complications due to their low cetane number, high latent heat of vaporization and high resistance to auto-ignition. Moreover, the less calorific value, poor miscibility with diesel and poor lubricating properties restricts their use in diesel engines [7] . The last decade has witnessed significant amount of research in higher alcohols due to the development of modern fermentation processes using engineered micro-organisms that improved the yield of higher alcohols.

Rakopoulos studied the characteristics of combustion and exhaust emissions of cottonseed oil (CSO) blend with 20% volume of either n-butanol or diethyl ether (DEE). The blends were tested on a single cylinder CI engine operated at various loads. He found that the BSFC and BTE for n-butanol or DEE blends were slightly higher than those of diesel fuel, but lower compared to neat CSO. In term of emission, smoke opacity and NOx were significantly reduced using both blends, with 80CSO20DEE blend exhibiting the lowest reduction. On the contrary, the blends emitted higher CO and HC emissions with respect to diesel fuel [19].

Kumar investigated the effect of 10% and 20% of n-butanol blends with jatropha oil (JO) on engine performance and emissions. They reported that the BTE of the blends were slightly lower than diesel, however increased butanol percentage in the blend caused increase in BTE. On the other hand, the blends exhibited higher smoke and unburned HC emissions compared to diesel fuel. Furthermore, under all load conditions, NOx emission was found to decrease slightly, while CO emission was found to be almost similar to diesel fuel. He concluded that 20% butanol blends showed almost likely performance and emission to diesel fuel [20].

Further, Atmanli studied the engine performance and exhaust emissions of diesel (D)–cotton oil (CNO)–n-butanol (B) on a turbocharged diesel engine. It was found that the BSFC of 70%D-20%CNO-10%B blend was 34.1% higher, while brake torque, brake power, BTE and EGT were lower compared to diesel fuel. BTE and EGT were significantly lower at lower engine speed, however at higher engine speed, the divergence became smaller than those of diesel fuels. CO and CO_2 emissions were found to decrease at low engine speed, while HC and NOx emissions increased compared to diesel fuel [21].

Table 2.5: Performance and emission of CI engine fuelled with alcohols blends. [17] [18] [19] [20] [21]

Fuel	Alcohol %	Engine Type	Test Condition	Reference Fuel	Emission	Performance
Ethanol and propanol + diesel	0 to 12	Nissan YD22, 4-cylinder, 4-stroke, turbocharged, direct injection diesel engine (max	Moderate load at 10,000 rpm	Diesel	↓ Soot	↓ Sound Pressure
					↓ NOx	↑ Ignition delay
					↑ HC	
					↑ CO	
Cotton seed oil methyl ester + anhydrous ethanol	10 to 50	Four stroke, single cylinder, Vertical, direct injection, Air cooled, Compression ignition Engine	Various loads (at 1500 RPM)	Diesel	↓ Soot	BP same
					↓ NOx	↑ Ignition delay
					CO reduced at H load	
					HC reduced at high load	
Cotton Seed + butanol or diethyl ether	20	single-cylinder, four- stroke, water cooled, high-speed direct injection	Various loads (at 2000 RPM)	Diesel	↓ Smoke	↑ BTE
					↓ NOx	↑ BSFC
					↑ HC	
					↑ CO	
n-butanol blends with jatropha oil	10, 20	single cylinder, air cooled, direct injection diesel engine	Various loads (at 1500 RPM)	Diesel	↑ Smoke	↑ BTE
					↓ NOx	
					CO same	
					↑ HC	
Diesel (D)–cotton oil (CNO)–n-butanol (B)	10	Land Rover 110 turbocharged direct injection diesel engine.	full load (at various RPM)	Diesel	Constant NOx at high rpm	↓ BP
					↑ NOx at low n med rpm	↓ BTE
					↑ HC	↑ BSFC
						↓ Torque

Overall, from the previous study of the usage of SVO-higher alcohol blends in a compression ignition engine indicated that the SVO-higher alcohol blends successfully reduced the NOx emission. This is probably due to higher oxygen content in alcohol improved the combustion process of the engine. Therefore, the combustion temperature reduced hence leads to reduction of EGT. Moreover the soot formation also reduced slightly. Most of alcohols blend suffer from low calorific value. Thus, the BSFC, brake power, BTE of the engine is higher compared to those diesel fuel.

2.6 Macroscopic Spray Characteristic Study.

Soots and NOx were the two main emissions from modern diesel engines, are mainly influenced by mixture quality of air and fuel and largely governed by fuel atomization and spray characteristics of the fuel. In a spray characteristics study, the concerned parameter that have been studied by researcher in the past were included spray penetration, spray cone angle and spray width. These parameters were important to determine the atomization quality of the fuel. Atomization of fuel generally influenced by the physiochemical properties of the fuel itself. The viscosity, surface tension and density of the fuel plays major role in determined the atomization quality and spray characteristic of the fuel. Studies have shown that those fuels with higher viscosities can lead to reduced spray atomization quality. Consequently, the average droplet diameter of the spray and the breakup time is increased [22]. This leads to incomplete combustion and carbon deposits on the cylinder walls. The spraying characteristic parameter can be determined as the figure:

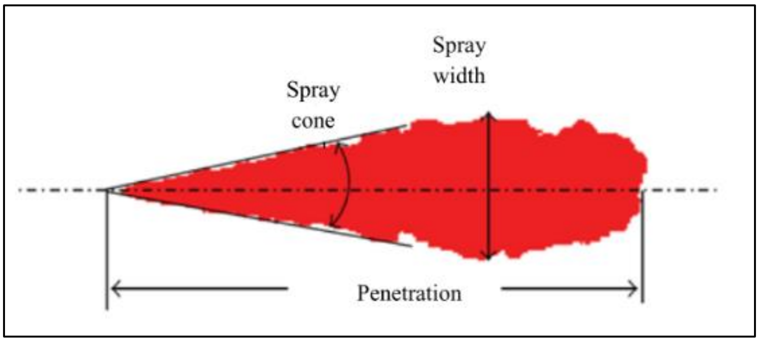

Figure 2.6: Definition of spray parameter [22].

2.6.1 Spray Characteristic of Biodiesel.

The variation of fuel properties of biodiesel, such as viscosity, cetane number, surface tension, density and calorific value can influenced the spray and combustion characteristics and therefore the change the corresponding exhaust gas composition. Biodiesel have been an alternative for diesel fuel for past few years due to its comparable physiochemical properties with diesel fuel. However, biodiesel produce high emission level of soot and NOx. Hence series of studies in term of spraying characteristic of biodiesel were conducted to determine the relationship between their spraying characteristic and performance and emission of biodiesel fuel.

Lee have experimentally investigated the effect of biodiesel-blend ratio on spray atomization and combustion characteristics. They found that increased viscosity of biodiesel is the main reason for reduction in fuel injection velocity of biodiesels, leading to relatively poorer atomization. It is reported that Sauter Mean Diameter (SMD) of biodiesel was higher due to its higher surface tension. However, they also reported that this had only marginal influence on fuel's spray tip penetration [23].

Battistoni studied the internal flow in injector and spray behaviours by using fossil fuels and biodiesel fuels with different geometry orifices respectively. Results show that, in comparison with biodiesel, the Sauter mean diameter (SMD) of biodiesel also is smaller and the penetration of biodiesel is longer compared to diesel fuel [24].

Su conducted an experimental research on the impact of cavitation characteristics on the spray behaviours of biodiesel and diesel. He reported that the cavitation in the injector orifice can enhance downstream atomization quality for both fuels, and the cavitation flow rate of diesel is higher than that of biodiesel. He also compared spray behaviours between two fuels: ethanol-blended biodiesel and blended fuel of diesel and biodiesel and found that the spray quality of biodiesel can be improved by adding ethanol. This is probably due to addition of ethanol which reduced the viscosity of the biodiesel hence improved its spray quality [25].

Mohan investigated the macroscopic spray behaviours for biodiesel and its blends. The results demonstrated that biodiesel holds the longest spray tip penetration and the highest spray velocity among other blends, while the difference in penetration and velocity between B20 (the blended fuel of 20% biodiesel:80% diesel) and diesel fuel is smaller under high ambient pressure. Furthermore, the spray cone angle for biodiesel is narrower than its blends, and the volume of spray for biodiesel is smaller than B20 and diesel, which indicated that the air-fuel mixture quality is poor for biodiesel [26].

From the literature review on spray characteristic study of biodiesel indicates that significant differences of physical property between diesel and biodiesel fuels, which affect their spray characteristics. Most of authors concluded that the high viscosity of biodiesel lead to longer spray penetration and smaller spray angle. However, it is reported that addition of alcohols in the biodiesel blends improved the spraying characteristic of the blends [26].

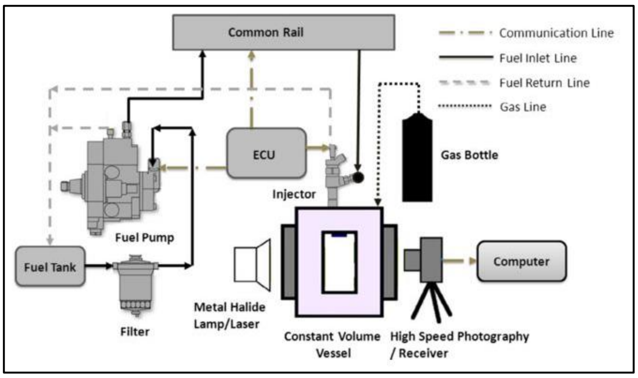

Figure 2.6.1 : Schematic of fuel spray test system [27].

2.6.2 Spray Characteristic of Alcohol Blends

From research conducted by Su, he concluded that the spray quality can be improved by addition of ethanol. Hence, further research were conducted to investigate the effect of alcohol addition in fuels to the spray quality [25]. In general, alcohols were less viscous compared to biodiesel. Furthermore, volatility of alcohols were better than biodiesel. These property of alcohol were essential to improve the spraying characteristic of viscous fuel.

Further, T. Bohl investigated the spray characteristics of diesohol fuel under different fuel injection pressures (Pinj) in a high-pressure common-rail injection system and at various spray ambient pressures (Pamb) in a constant-volume pressure vessel by using high-speed photography technology. The results show differences of the spray tip penetration between the diesohol fuel (E20, E40) and diesel (E0) or ethanol (E100) are very narrow. Moreover, the length of the spray of the diesohol fuel (E20, E40, and E100) slightly decreased. This is may be the result of the volatility of the ethanol. Additionally the differences in the spray cone angle of the diesohol fuel (E20, E40, and E100) are also very narrow. The results suggested that the addition of ethanol has no significant effect on the spray tip penetration, spray cone angle, and spray tip speed [22].

S. H. Park investigate the fuel-atomization, combustion, and exhaust emissions characteristics of dual component fuels. The analysis revealed that the blending of diesel or bioethanol fuel slightly affected the reduction of the spray tip penetration and had little influence on the variation of the spray cone angle. The droplet size of biodiesel fuel was reduced by blending with diesel or bioethanol fuel with low kinematic viscosity and surface tension [4].