EFFECT OF BIODIESEL FUEL ON DIRECT INJECTION DIESEL ENGINE

MONGKON KANANONT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
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ABSTRACT

Due to attention to alternative energy, biodiesel has been one of the potential substitutes that helps reducing the amount of an imported crude oil of the nation dependency. This study discusses the performance, combustion, and emission analysis of direct injection (DI) diesel engine 4 cylinder 4 stoke 3.612 liter, which is normally used as a farm truck in the agricultural activities and fueled with conventional diesel and biodiesel. The results indicate that when the tested engine was fueled with biodiesel, the performance was slightly weakened, but the specific fuel consumption of biodiesel is increased to about 10-15% since the heating value of biodiesel is approximately 10% lower than diesel.. However the thermal efficiency of biodiesel is lower than 5% at all range speeds. The cylinder pressure and heat release rate were slightly changed for biodiesel. For biodiesel fuel, the combustion (i.e. start of combustion : SOC) started earlier than that of diesel fuel about 2 degrees at 1000 rpm and the maximum pressure in the cylinder of biodiesel is higher than that of the diesel fuel at full load condition. However, the heat release rate of biodiesel is lower than diesel. During the test at part load condition, SOC of biodiesel occurs earlier than the diesel fuel. But it is not significant when tested at maximum pressure of both fuels at the same load. In terms of emission analysis, biodiesel can help reducing carbon monoxide (CO), carbon dioxide (CO_2), and unburned total hydrocarbon (THC) emission. Nevertheless oxide of nitrogen (NO_x) increases.

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CHAPTER 1

INTRODUCTION

1.1 Significance and Background

At present, the consumption and prices of petroleum in the world have been increasing continuously. Moreover, a number of emission gases such as NOx, SO2 and CO2 also cause global warming due to the uses of these petroleum products. Biodiesel is one of the alternative fuels used nowadays to decrease the prices of fuel for vehicles and reduce emission gases. Therefore, Thai government (on January 18, 2005, strategy development and promotion of renewable energy in cooperation with Ministry of Energy and Ministry of Agriculture)[1] has encouraged the use of Biodiesel in the diesel engine for transportation and the small diesel engine for agriculture because of Thailand's potential in its production.

There are numerous variants of Biodiesels produced in Thailand such as Biodiesel made from soybean, jatropha seed, animal fats, vegetable oil and palm oil. Palm oil is one of the common alternatives in biodiesel production in Thailand because of its abundance and low price. Used as one of the ingredients of diesel, palm oil is not only a renewable fuel, but its consumption will also increase economic support and activity of local agricultural products. The consequence results into the stimulation of the income distribution in the rural areas in Thailand as well as the reduction of the import of petroleum products.

However, biodiesel still has several limitations in terms of thermal efficiency, fuel consumption rate and long-term use. This thesis, therefore, focuses on the performance of the biodiesel from palm oil used in the direct injection diesel engine, with capacity of 3.612 liters, 4 strokes and 4 cylinders. The maximal torque, maximal pressure in combustion chamber, specific fuel consumption rate, exhaust gases and long-term use of biodiesels were compared with those of commercial diesels in the diesel engine. The results of both biodiesels from palm oil and commercial diesels were analyzed in order to compare their performances. Based on this analysis, the engine will be engineer in according to the results from the study, i.e. in such a way that allows the near-completed combustion of biodiesel as much as possible.

1.2 Objectives

1.2.1 To investigate the performance of direct injection diesel engine when using palm biodiesel fuel and its influence on emission.

1.2.2 To study and compared the characteristics of combustion heat of diesel engine between diesel and palm biodiesel.

1.2.3 To study and compared the emission from diesel engine by using diesel and palm biodiesel.

1.2.4 To study the effect of adjust injection on diesel engine diesel fuelled with and palm biodiesel.

1.2.5 To find solutions the problems and recommendations with guidelines for appropriate use of biodiesel fuel.

1.3 Scopes

1.3.1 To test the performance, rate of fuel consumption, pollution and the combustion characteristics of diesel engines. The different working conditions compared with the oil, palm oil biodiesel to determine the capabilities of both fuels.

1.3.2 To modify the degree of fuel injection of 12 degrees before top dead center to ± 1, ± 2 degrees and tested according to a note to the effect of changes in the use of biodiesel fuel.

1.3.3 To compare and analyze all the results.

1.4 Methodology

1.4.1 To test the performance and emission tests of various types of diesel engines, i.e. diesel and biodiesel.

1.4.2 To adjust the injection timing of the degree diesel engines to use of biodiesel fuel. Then compare the performance difference with the standard diesel engines that use diesel fuel.

1.5Expected Benefits

To understand the behaviour of palm biodiesel in the direct injection diesel engine with adjusting injection timing on full load and partial load

To understand the use of palm biodiesel in the best condition for higher engine performance.

It also reduces the amount of diesel fuel domestic oil and palm supporting farmers and downstream industries. Moreover, biodiesel also helps reducing air pollution from gas combustion.

CHAPTER 2

THEORY AND LITERATURE REVIEWS

2.1 Introduction of Compression-Ignition Engine

The principle of combustion engine for compression-ignition engine is that during the final stage of compression, the fuel will be injected into combustion chamber meanwhile the piston is close to the Top Dead Center (TDC) position. The injected fuel will have very high pressure while passing through the end of the injector, then will be atomized into the combustion chamber and rapidly vaporized, mixing with the high temperature and high pressure air within the cylinder. Subsequently the auto-ignition of fuel-air mix with the proper ratio which is flammable is generated. When the combustion started, the pressure and the temperature in the combustion chamber increase which will cause the remaining fuel to vaporize and quickly mix with the air. Therefore, the good combustion is obtained when the w fuel-air is well mixed which depends on the efficiencies of the following processes: the atomization, the vaporization, the fuel-air mixing and the combustion of the injected fuel into the combustion chamber.

The Combustion Effect in Compression Ignition Engine

Heat-Release rate is the important principle in order to explain the combustion effect within the cylinder. This heat-release rate is the chemical energy of the released fuel during the combustion and the heat-release rate procedure, which can be divided into 4 phases. Each phase will be controlled by the different physical and chemical procedures. Although the main variable impacting on each phase is the selective combustion chamber system and the engine operating conditions, each stage will usually occur in the compression ignition engine.

In direct injection engine, the following Figure 2-1 indicating heat-release rate which explains the process as;

- **Ignition Delay Phase, a-b** is the length of time since the start of fuel injection into combustion chamber until the fuel ignition.
- **Premixed Combustion Phase, b-c** is the duration of premixed fuel combustion after ignition delay phase which will initiate the rapid auto-ignition and increase the heat-release rate.
- **Diesel Fuel Performance Mixing Combustion Phase, c-d** occurs when the premixed fuel is completely burned. The combustion rate will be controlled by the formation rate of the mixture between fuel and air that is ready to be burned.
- **Late Combustion Phase, d-e** is the period that the heat-release rate is low during the exhaust stroke. It is the combustion of the rest of the fuel and the carbon residue which previously generated from the rich mixture.

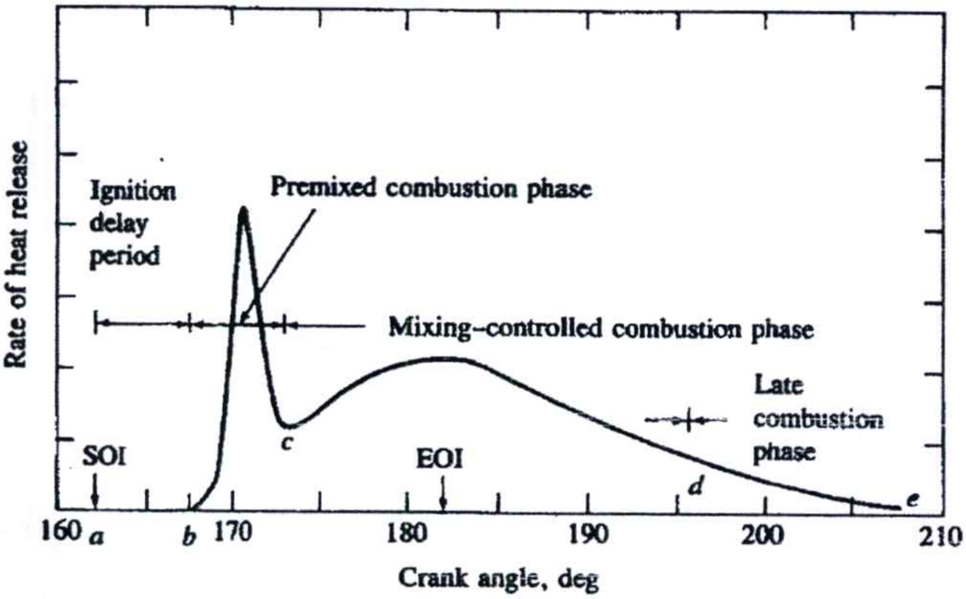


Figure 2-1 heat-release rate of diesel engine using direct injection system with each combustion phase (SOI: Start of injection, EOI: End of injection) [2]

2.2 Fuel quality

The fuel quality and its effect to the performance and the operating system of diesel engine are comprised of;

2.2.1 Cetane Number

Cetane number is a measurement of the combustion quality of diesel fuel during compression ignition. The cetane value is defined by the mixture of pure hydrocarbon fuel which refers to two types; cetane (n-hexadecane) and isocetane (or heptamethyle nonane). The cetane that has a high ignition quality will have a cetane number of 100. Besides, the isocetane that has a low ignition quality will have a cetane number of 15 according to the ASTM D613 standard.

$$\text{Cetane number} = \%\ \text{n-cetane} + 0.15\ (\%\ \text{heptamethyl nonane}) \qquad (2\text{-}1)$$

This cetane number has an impact on the fuel qualities, which are the starting engine quality, the amount of emitted pollution, the compression ability in combustion chamber and the produced engine sound. The advantage of the fuel having higher cetane number is the higher performance engine including the increase of the starting engine quality while it is cooled, the decrease of black smoke during engine warming up, the reduction of loud noise, the reduction of the pollution and the consumption rate of fuel. However, to determine the cetane number of the fuel requires high expense, the calculation of cetane index therefore is used instead in order to evaluate the ignition quality. According to ASTM D976 standard, API gravity value and mid-boiling temperature (50% evaporated) are used in the calculation.

2.2.2 Density

The diesel fuel density is used to indicate the component and the relevant characteristics to the performance such as the ignition quality, the power, the fuel saving, the quality at low temperature and the tendency of smoke produced. Occasionally, density shows as specific gravity or API gravity. The fuel density from distillation processes can be exhibited as below;

Straight-run distilled	805-807 kg/m3
Hydro cracked gas oil	815-840 kg/m3
Thermally cracked gas oil	835-875 kg/m3
Catalytically cracked gas oil	930-965 kg/m3

2.2.3 Viscosity

Viscosity is a measure of the resistance of a fluid which is the important quality of diesel fuel since it has influence on fuel injection equipment performance especially at low temperature. The more the viscosity increases, the lower the cone angle of spray nozzle is. The fuel expansion and spray penetration also decrease, meanwhile a fuel droplet is larger. Hence the viscosity has an effect on the injection timing and the appropriate injector nozzle with each fuel injection pressure, and also has an influence on the injected fuel quantity.

For the diesel fuel, it often considers the upper bound quality of the viscosity to ensure that there is enough fuel circulation in order to start up the cold-engine. The least viscosity is considered upon the prevention of the power loss at the high temperature. If the fuel has too low viscosity rate, the penetration spray will take too long which will wet the combustion chamber wall and finally result in the loss of engine power.

As the matter of fact that the crude palm oil has very high viscosity rate, therefore when mixing crude palm oil with diesel fuel, palm-diesel fuel mixture will have higher viscosity than diesel fuel.

2.2.4 Lubricity Quality

Lubricity of diesel fuel is tested by the high frequency reciprocating rig (HFRR) method according to CEC F-06-A-96 standard which test the oil viscosity in order to decrease the wear-and tear of parts that have direct contact to the fuel.

2.2.5 Quality at low temperature of diesel fuel

Diesel fuel may be consisted of heavy paraffinic hydrocarbons which are able to dissolve in fuel. Paraffin will be gathered up and turned into wax at cold temperature which will cause operating problems to the fuel system of vehicle, the impaction within the fuel system for example.

2.2.6 Flash Point

Flash point is measured at the lowest temperature at which fuel becomes flammable from ignition source under the standard operating lab circumstance. This flash point will have an impact on fuel in order to consider of transportation, storage format, and maintenance.

2.2.7 Palm Oil

Palm Oil is extracted from mesocarp of Elaeis Guineensis which can be divided into two types; palm oil for consumption and for Industry. Palm oil for consumption also can be subdivided into 2 types; virgin oil and refined oil.

Virgin oil is defined as the consumable palm oil whose processed of making the virgin oil are squeezing or compressing with heat , cleansed off by washing and leaving until the oil precipitates, then filtering and centrifuging. On the other hand, refined oil is as well defined as the consumable palm oil, however must have been processed by acid removal method. Palm oil used in this research is the virgin oil or the crude palm oil which is extracted from fibers of fresh fruit bunches. The extracted oil will be oil concentrates and has opaque orange color at normal temperature. The oil will turn into clear reddish orange when being warmed up with heat.

Contaminants found in palm oil are separated into two main groups which are;

1. Hydrolytic contaminants, which compose of humidity, dirt, free fatty acid, glyceride and various enzymes.
2. Oxidative contaminants, which compose of metal debris, oxidation compounds, Tocopherols pigment and Phosphatide

2.3 Research on Application of Vegetable Oil with Diesel Engines

Using vegetable oil as alternative fuel for diesel oil is getting well-known presently according to less quantity but higher price of diesel oil. There are many methods on using vegetable oil, but there are 4 main methods stated by *Yusuf Ali & Hanna [3]* that are straight vegetable oil, decreasing the viscosity of vegetable oil to allow for proper atomization of the fuel by mixing solvent such as alcohol and ethanol (Micro-emulsification), trans-esterification, cracking or pyrolysis. Vegetable oil could be entirely used for diesel oil or blending with Diesel. Generally types of plant oils being used in research vary from characteristics of industrial crops which are plant oils of each locality and region for instance using Soybean oil in the United States of America as in the research of *Pryor et al. [4],* it has been testing performance both for short term and long term of small diesel engine by using 100% Soybean Oil. It is also using Rapeseed oil in European countries as referred in the research of *Norbert Hemmerlein et al. [5].* 100% Rapeseed Oil is used in six diesel engines vary from types and sizes in order to do a research of performance, pollution and durability. While in tropical countries including Thailand prefer to use Palm Oil and Coconut Oil in the study. Besides, in the state of Alaska, animal oil such as fish oil is used for blending with 50% of diesel oil. Wasted oil that is discarded from a restaurant also can be used according to Yu CW, Bari S, Ameen A. *[6]*, for example in Japan, used oil from the instant noodle factory has brought to use in diesel engine directly without any adaptable or additional procedure.

The simple method to use vegetable oil with diesel engine is to use 100% of vegetable oil. Yet there are some problems found by *Sam Jones and Charles L. [7]*.For example the incomplete combustion would cause particulate matter and impaction at the injector nozzle. The piston ring sticks due to wax and gum. The valve seat has much residual carbon, which would cause the valve leakage, thus leading to the decreased compression engine problem The oil stains resulting from the oxidation also cause the damages to the engine.

The use of vegetable oil blended with diesel oil in appropriate ratio as stated in the research of *Mariuse Ziejewski and Hans J. [8]* is to bring 25% of high oleic sunflower oil, blend with 75% of diesel oil using in Direct-Injection-Petter AC2 Engine. The durability has been tested according to EMA standard for the period of two hundred hours in order to compare residual carbon quantity after testing period. During the whole durability testing, the increasing in pollution rate and the significant difference of residual carbon found in engine were not observed. In the research of *Engelman et al. [9]* 10% up to 50% of Soybean oil is used to extend with diesel oil. After fifty hours of testing, a small amount of residual carbon found in the combustion chamber, BSFC value and power from using 100% of diesel oil is also just a small amount. It is found that when blending more than 60% of Soybean oil, the testing engine will be stumbled resulting from impaction at the fuel filter. From the report of *Sam Jones and Charles L. [7]* can be concluded that, most of the researches, blending vegetable oil with diesel oil in high volume will cause the problem during long term testing period. It is still found that blending less than 20% of vegetable oil is applicable to use in engine without causing problem while testing in long term period.

However, the use of Crude Palm Oil has been growing in Malaysia. In the year 2001, there is a research report of using Crude Palm Oil blended with Kerosene in Malaysia by *T.H Lim [10]*. The research is to use 90% of Crude Palm Oil blended with 10% of Kerosene to reduce the viscosity rate of fuel by blending Kerosene with Crude Palm Oil, which was warmed up at the temperature of 60°C to dissolve small solid particles in Crude Palm Oil. As a result of the research, it is found that the extended oil has the similar performance to diesel oil, but still having more Carbon Monoxide than diesel oil for 43%, with higher Nitric Oxide than diesel oil for 7%. Moreover, it is also found that the extended oil has lower fuel consumption rate and higher performance than pure Crude Palm Oil. The pollution released rate is also better by having lower Carbon Monoxide than 19% with lower Nitric Oxide than 19%. In addition, *S. Bati, T.H. Lim and C.W. Yu [11]* has done experiment by warming up blended Crude Palm Oil at the temperature of 100°C to prevent the impaction problem at the fuel supply system. By warming up Crude Palm Oil at the mentioned temperature, researchers report that there is no effect to the fuel system of engine and not making better engine efficiency but to help the better oil flow when warming up at 60°C upward but not higher than 97°C which is the point fuel generates air bubbles. The researchers continue to study by running engine for 500 hours using Crude Palm Oil fuel which was warmed at 92°C. It is tested with Yanmar engine L60AE-D and found that, after the testing, the maximum power value of engine is decreased to 20% and fuel consumption rate is increased to 26%.

CHAPTER 3

EXPERIMENTAL PROCEDURES

3.1 Tested Fuels

In this experiment, palm biodiesel and base diesel is used as the tested fuels to measure and test. The palm biodiesel was produced by Werasuwan Co., Ltd. The required properties as shown in Table 3.1 follow the standard of the Department of Energy Business, Ministry of Energy, Thailand. (According to the nature and the quality of the Biodiesel methyl esters of fatty acids, 2552), the base diesel, which was supplied by PTT Co., ltd, contained 2 percent of bio-diesel (B2). Consequently, the results of the tested fuels were used to analyze in various physical and chemical properties as well as access the performances and emissions of the direct injection diesel engine.The testing standard of physical and chemical properties is illustrated in Table 3.1.

Table 3.1: Properties of biodiesel fuel

Properties	**Methods**	**Results**	**Units**
1.Water Content	ASTM D6304	335.45	ppm
2.Acid Value	ASTM D 664	0.27	mg KOH/g
3.Oxidation Stability	EN 14112	11.01	Hour
4.Carbon Residue	ASTM D 4530	0.01	%wt
5.Gross Heat	ASTM D 240	38.20	MJ/kg
6.Density	ASTM D 4052	0.85	g/cm^3
7.ASTM Color	ASTM D 1500/156	0.8	-
8.Pour Point	ASTM D 97	18	°C
9.Flash Point	ASTM D 93	165	°C
10.Kinematic viscosity at 40 °C	ASTM D 445	4.52	mm^2/sec

3.2 Tested Engine

In this study, the new YUNNEI brand model 4100QB-2, 3.612 liters and 4 cylinders (Figure 3.1) was chosen as the direct inject diesel engine in this experiment. It was selected because this engine type was very famous in the pickup-trucked market sector, with a large number of sales in Thailand.The tested engine consists of simple mechanical devices such as the inline pump and the standard injector. Table 3.2 shows the specifications of the tested engine.

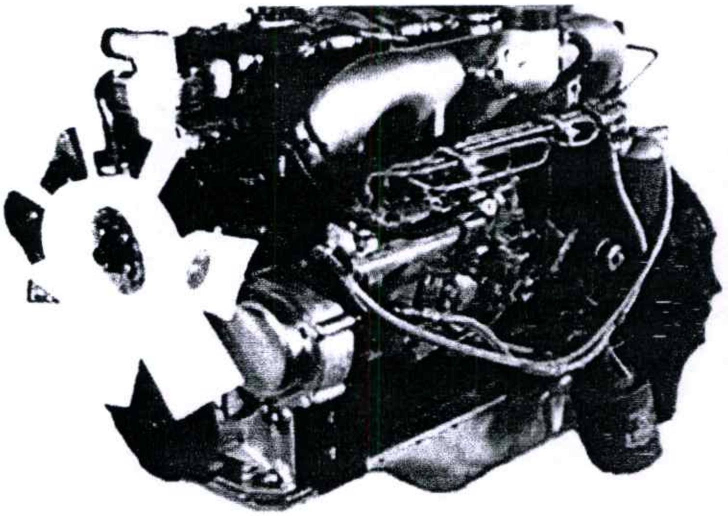


Figure 3.1 Direct injection diesel engine model 4100QB-2

Table 3.2: Tested engine specification

Type	4-stroke, vertical engine
Bore x Stroke	100 x 115 mm.
Number of Cylinder	4
Cylinder Type	Waterish type
Combustion Type	Direct injection ω type
Displacement	3.612 liters
Idle Speed	750 rpm
Compression Ratio	17.5:1
Firing Order	1-3-4-2
Rated Power	66.2/3200 kW-hr
Max Torque	230/2000-2200 N.m/rpm
Fuel Consumption	≤238 g/kW-hr
Net weight	320 kg
Injection timing/pressure	12°/19.1±0.49MPa

3.3 Apparatus

3.3.1. Equipment for Engine Test

The performance and emission testing system were comprised of (1) the direct injection diesel engine, (2) a 150 kW eddy current dynamometer model ED-150 of Tokyo Plant with (3) a mass fuel consumption meter and (4) a computer controller with a "P.Drive" software version 1.57, (5) an exhausted gas analyzer of Horiba model MEXA-1600D with a "MEXA-1600D" software version 1.0.9.0, and (6) various resistance temperature difference (RTD) sensors including a transited box.

The schematic diagram of experimental set up was shown in Figure 3.2. Figure 3.3 and 3.4 show the components of equipment and the print screen samples of the software respectively.

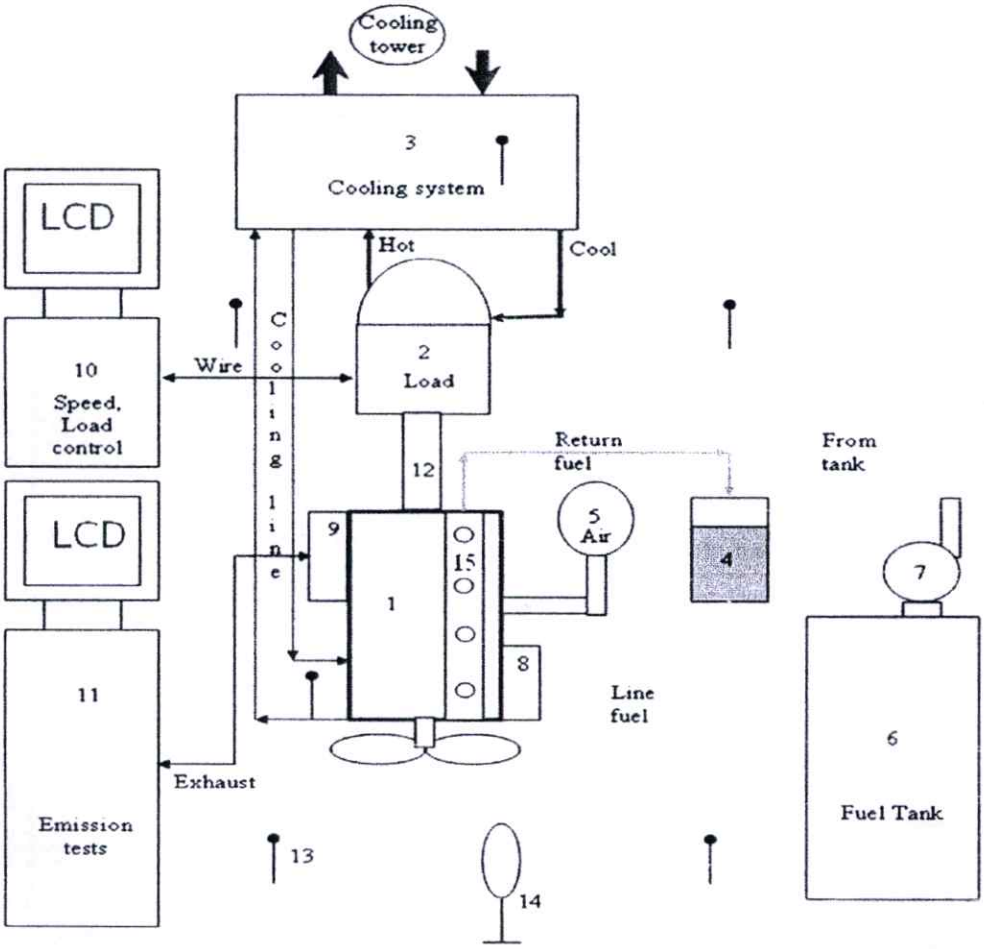
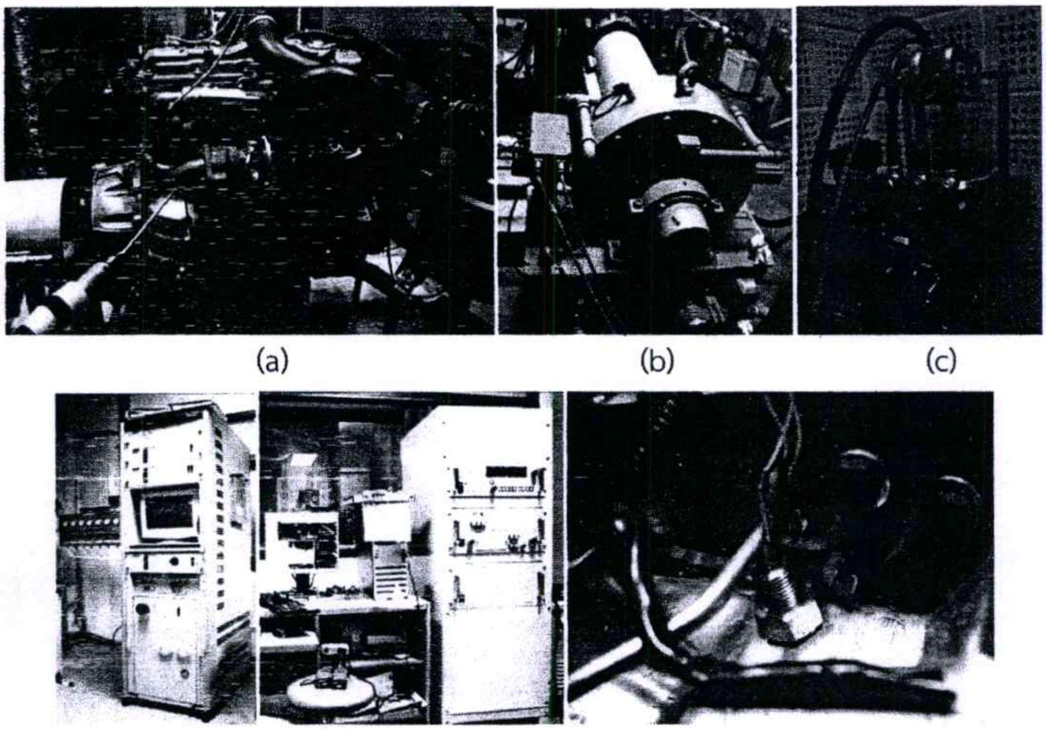
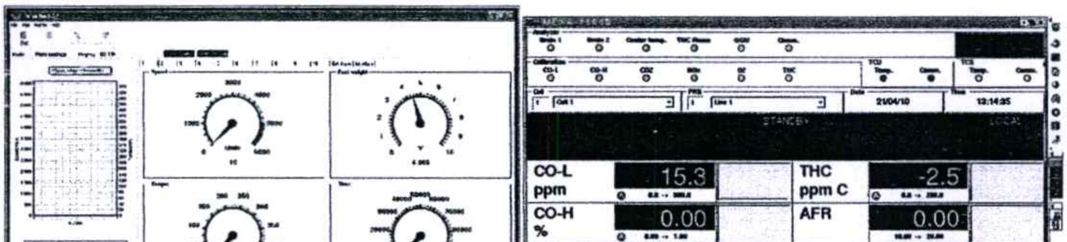


Figure 3.2 The schematic diagram of engine test system


(a) (b) (c)

(d) (e) (f)

Figure 3.3 (a) direct injection diesel engine, (b) eddy current dynamometer, (c) mass fuel consumption meter (d) exhausted gas analyzer, (e) computer controller, and (f) RTD temperature sensor at intake manifold


CO-L ppm 15.3

THC ppm C -2.5

CO-H % 0.00

AFR 0.00

CO2 % -0.13

Lambda under

NOx ppm -1.7

O2 % 0.08

(a) (b)

Figure 3.4 Print screen of (a) P.Drive and (b) MEXA-1600D software

3.3.2. Devices for the Combustion Analysis

A pressure sensor (Kistler model 6052C) was installed in the 4th cylinder head in order to monitor the differences in the behaviours of the combustion of the diesel and biodiesel fuels. Moreover, a shaft encoder with 360 degrees per revolution (ppr) from Sangchai Co., ltd was attached to measure the degree of TDC and BDC. All information was calculated by using the Dewesoft 6.1 software from Dewetron copperation as shown in figure 3.5.

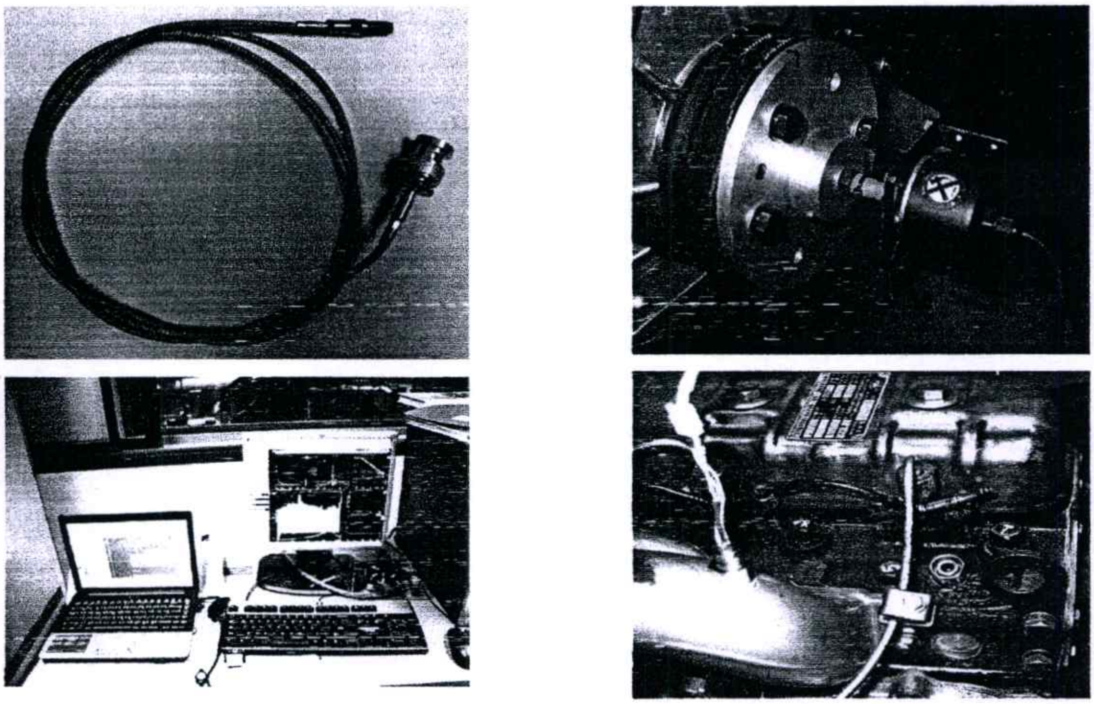


Figure 3.5 Dewesoft 6.1 software from Dewetron

3.3.3. Adjust Injection Timing

Adjust the angle of fuel injection in diesel engines. Adjusted using a set of fuel pumps for Advance or retread equipment, coupled with those injected with Timing light check is converting to a diesel engine (Diesel adaptor) of Sincro Rx3G version 0.01 degrees resolution.

3.3.4. Room testing

This engine test facilities. Rooms are designed to test the engine room to swirl the air in the room air temperature. The air outside was changing all the time. The room will have a series of sensors to detect temperature and humidity inside the room. Check the temperature of the engine operating conditions. The temperature resistance (RTD), as shown in Figure (3.2) the experimental equipment for the software used is shown in Figure (3.5).

3.4 Methodology

In this research, it was divided into two main sections to compare performance. And the amount of pollution emissions of the engine. The effect of adjusting the fuel injection angle of the second part is to compare performance. And the amount of engine exhausts emissions. The test conditions are as follows.

Engine Performance and Emission

1. Install the engine test stand test, engine and the generator parameters.
2. Prepare fuel for the test. (Biodiesel and diesel only)
3. Warm the engine oil temperature at 60 ° C before the test as the initial conditions for the test.
4. Test engine performance and emissions of Full Load Test by adjusting the engine throttle to full speed as the engine is set from the manufacturer. The maximum speed is 3,300 rpm, adjust the meter to increase the load on the engine generator. Next, reduce speed of 200 rpm at low speed until the speed become 1000 rpm at the end. Measured torque is the rate of fuel consumption. Pressure within the cylinder and the exhaust are CO, CO2, NOx, THC, which is from the Gas Analyser.
5. To test engine performance and emissions from the Part Load Test and Load testing will increase the speed of ascending. To remain at the designated location and store performance.And exhaust to compare values between the two fuels.
6. The test is repeated three times and averaged.
7. Compare the performance tests and the amount of emissions. The results obtained from the use of biodiesel and regular diesel fuel.
8. Adjust degrees of fuel injection for diesel fuel in order to find the best performance for the test.

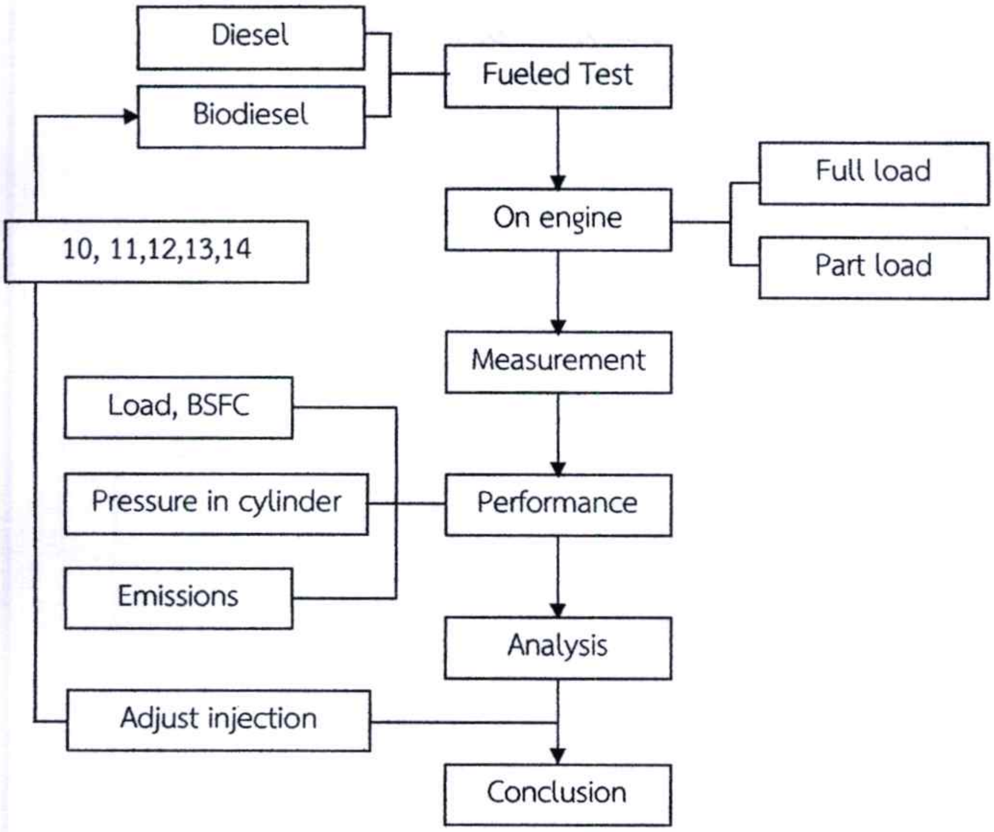


Figure 3.6 Flow chart of performance and emission tests

CHAPTER 4

EFFECT ON ENGINE PERFORMANCE

This chapter is presented with the report on the results of testing Biodiesel in dire injection diesel engine in order to investigate the performance and emission. The test result of diesel fuel is referenced for comparison at the full and part loads in terms of the following parameters.

- Toque and power of the engine
- Break specific fuel consumption
- A/F ratio and Lambda
- Emission such as CO_2, CO, O_2, NO_x and THC
- Temperature of lubricant oil, exhaust gas (air outlet).

4.1 Performance testing

Preliminary study was comparative investigation about engine performance and brake specific fuel consumption (BSFC) from agriculture diesel engine. Different fuel type, diesel and biodiesel were chosen for comparative analysis under full load condition.

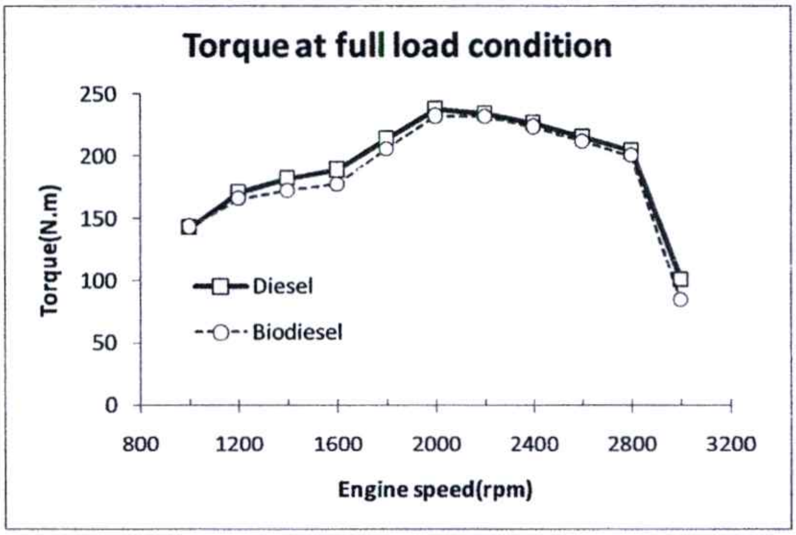


Figure 4.1 (a)

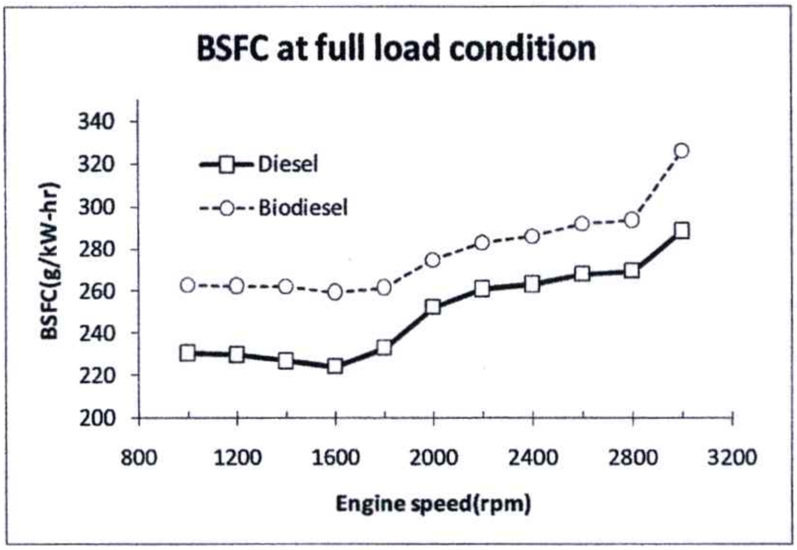


Figure 4.1 (b)

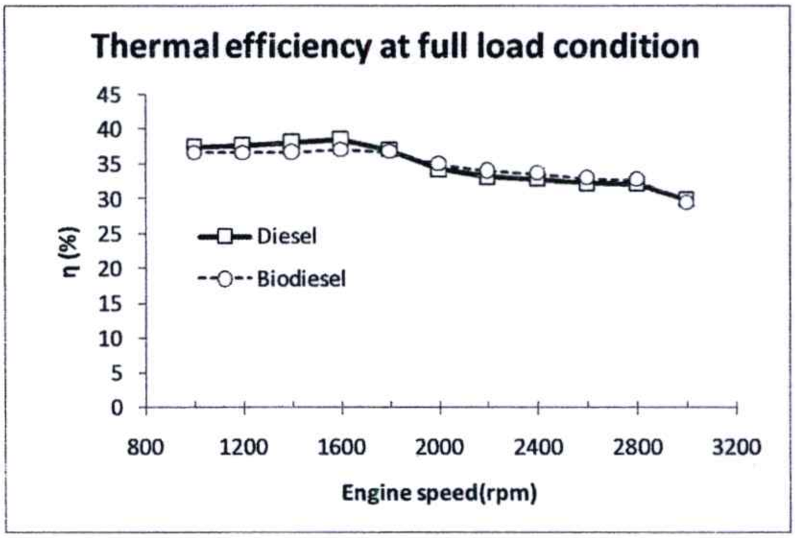


Figure 4.1 (c)

Figure 4.1 (a) : engine torque, (b) BSFC and (c) Thermal efficiency under full load condition.

As show in Figure 4.1 (a) and Figure 4.1(b), result of engine torque under full load condition, it found that engine torque from biodiesel fuel show slightly low value compare with the conventional diesel fuel, especially in low to middle range of engine revolution (1200 – 2000 rpm). Moreover, biodiesel fuels tend to consume more fuel over the whole range of engine speed compare with diesel fuel.

These may cause from different in gross heating value of two types of tested fuels. According to table 2, heating value of diesel fuel is 44.8 MJ/kg while the biodiesel show a little bit less heating value at 38.2 MJ/kg (13.6% less).

If consider in engine torque comparison, at the maximum point of engine torque, 2000 rpm , it found that power band show the same trend both in diesel and biodiesel fuel. However, maximum brake torque of diesel fuel was shown at 237.7 N.m@2000 rpm while biodiesel fuel, maximum brake torque is less than diesel fuel case approximately 2%.

As a result of lower heating value of biodiesel fuel, these can lead the higher BSFC when biodiesel fuels were use. Compare with diesel fuel, BSFC of biodiesel is approximately 10-15% more than conventional diesel fuel.

In Figure 4.1 (b), it can be noticed that under low engine speed condition around 1000-1800 rpm, BSFC value become less when compare to the higher engine speed. The reason for explain these result is the tested engine was designed and mainly focused on agriculture application purpose. The engine speed should not be too high. Form the result, BSFC of diesel engine show the lowest value at 224 g/kW.-hr while BSFC of biodiesel fuel show the lowest value at 259 g/kW-hr. Both minimum values were being observed around 1600 rpm of engine speed.

$$\eta_T=1/(\mathrm{BSFC} \times Q_{LHV} \times \eta_C) \qquad (1)$$

η_T= Thermal effficiency

Q_{LHV} = Heating value (kJ/kg)

η_C = combustion efficiency (0.95-0.98)

Equation for calculate fuel efficiency was shown in equation (1). In this equation, the efficiency was reflex to the capability of fuel that how much it can convert heating value (input) into available work (output). From the result that shown in Figure 4.1 (c), it found that fuel efficiency of both fuel were not significant change, approximately 1-3 %. Furthermore, in low engine speed condition, fuel efficiency was 38%. In the other hand, in high speed condition, fuel efficiency was 33%, less than in low speed around 5%.

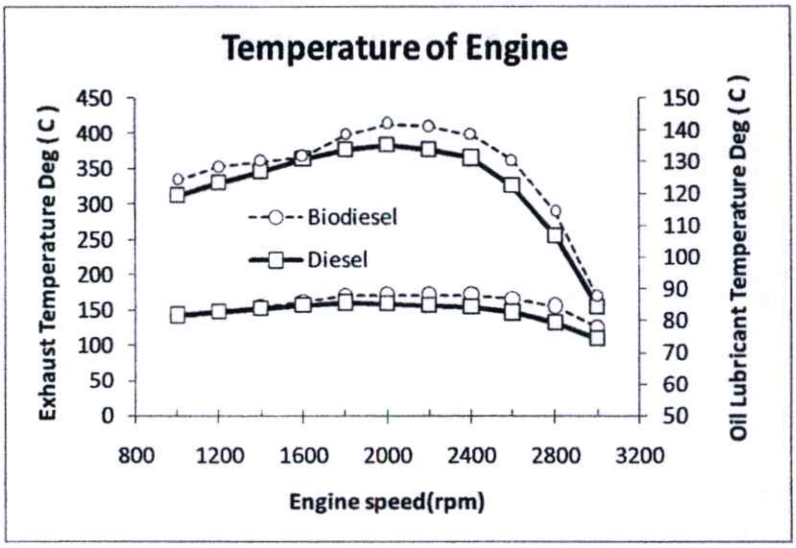


Figure 4.2 Exhaust gas temperature and engine oil temperature under full load condition

Another result relate to the engine reliability is engine temperature. Figure 4.2 show the result of engine oil temperature and exhaust gas temperature. From this result, both engine oil temperature and exhaust gas temperature of biodiesel were a little bit more than that of the diesel fuel. It may be discussed that the biodiesel have less heating value than diesel fuel. Thus, it has to consume more fuel over the tested condition. Another reason can be explain by different in fuel properties, especially, oxygen content. Combustion of biodiesel may dilute much more oxygen during combustion process due to oxygen content with fuel itself and its consequently was let the higher flame temperature. As a result, the engine oil and also the exhaust gas temperature become higher.

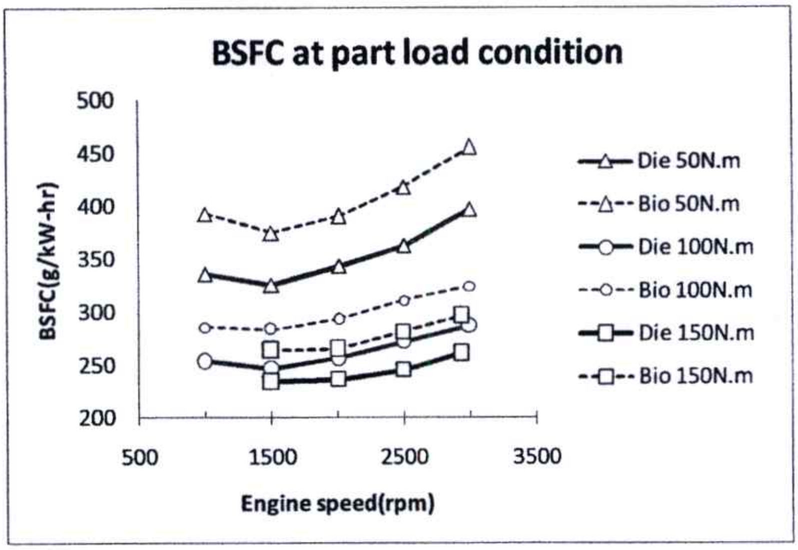


Figure 4.3 (a)

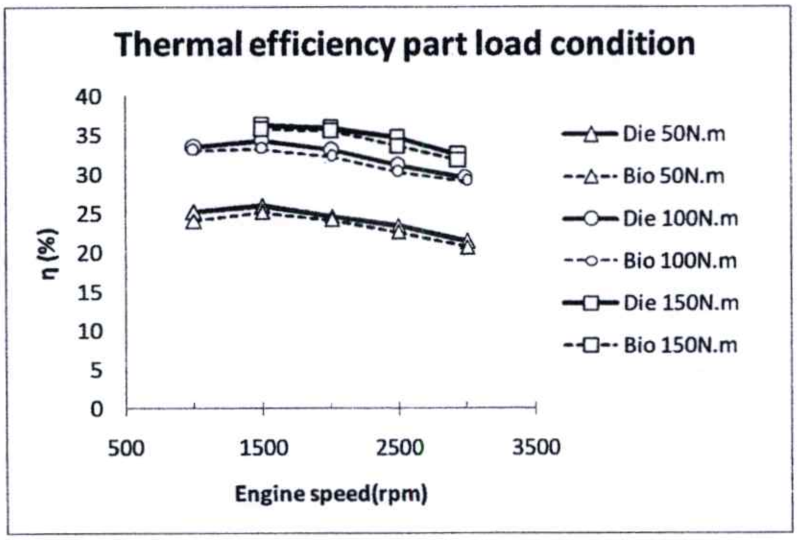


Figure 4.3 (b)

Figure 4.3 (a) BSFC and (b) Thermal efficiency under part load condition.

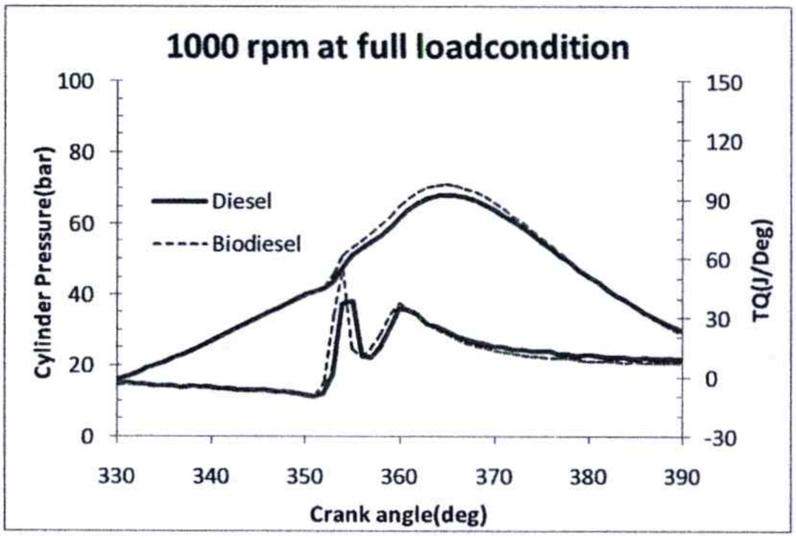
In part load condition, constant brake torque was chosen to examine the fuel efficiency and fuel economy in term of BSFC under various engine speeds. In this study, brake torque or engine load were varied for 3 values, 50 N.m, 100 N.m and 150 N.m, respectively.

From the result of part load condition, show in Figure 4.3 (a) and(b), it found that biodiesel provide the higher value of BSFC in all tested condition compare with base diesel fuel and BSFC of both fuel were decreased when the higher engine load were applied. If consider at constant load, the result also show the same trend in all condition, rpm. As increase the engine revolution, BSFC become higher. In Figure 4.3 (a), BSFC of biodiesel is higher than that of base diesel fuel amount of 12-17% compeer at the same load condition and same engine speed. However, both diesel and biodiesel show the best BSFC at 1500 rpm of engine speed. In Figure 4.3 (b), compare between biodiesel and diesel engine, it has not significant change in thermal efficiency; only 1-3% of higher thermal efficiency can be noticed in diesel fuel case. Moreover, both of tested fuels show the best thermal efficiency at 1500 rpm of engine speed. Diesel can also reach the maximum efficiency at 150 N.m at this point.

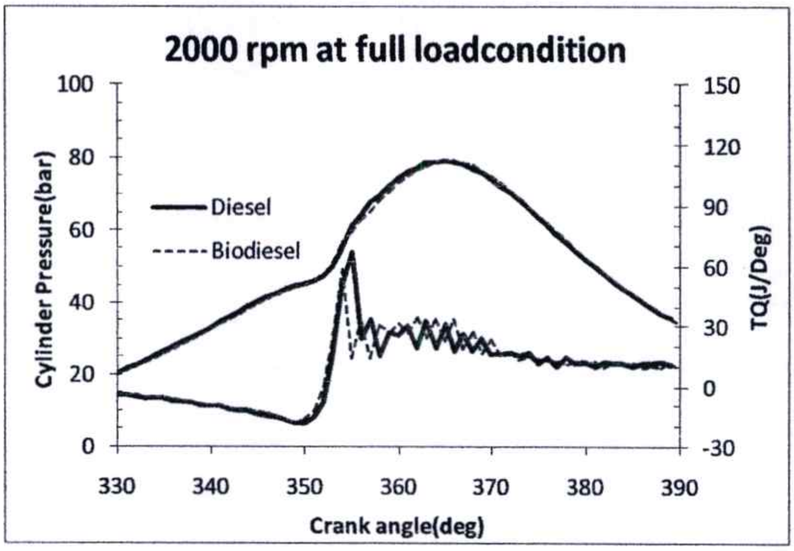
4.2 Result of Combustion efficiency

This section investigates and discusses with phenomena of combustion inside combustion chamber, combustion pressure and heat release rate of combustion by Diesel direct injection. Therefore the result can be effect with possibility of ignition, completely combustion and stability or reliability of the testing engine.

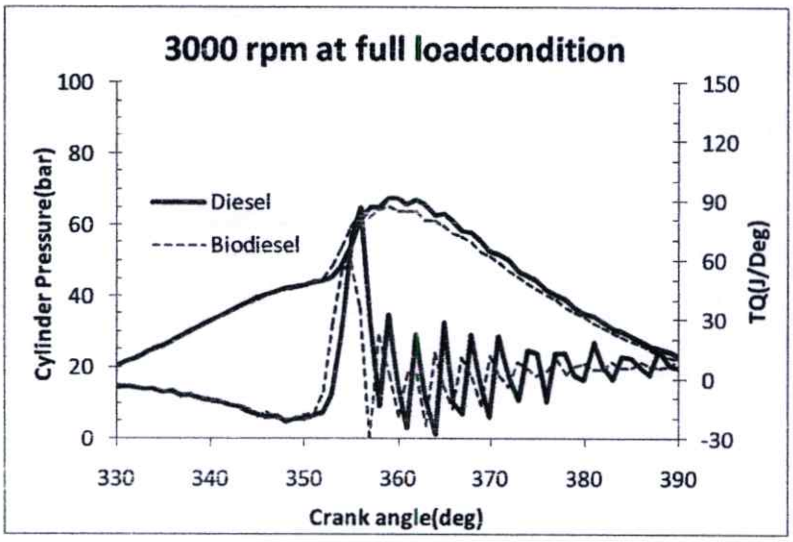
In case of full load condition at speed 1000, 2000 and 3000 RPM – the combustion pressure and heat release rate were correct from diesel and bio-diesel engine direct injection.



(a)



(b)



(c)

Figure 4.4 Combustion pressure and heat release rate in full load condition (a 1000, b 2000 and c 3000 RPM)

At 1000 RPM Combustion of diesel and bio-diesel are quite similar and rarely low combustion pressures. The peak combustion pressure of bio-diesel is 71.1 bar and 4.8% more when compare with diesel. Otherwise the start of combustion (SOC) of bio-diesel starts at 351 degree by fuel injected at 348 degree. Therefore ignition delay time of bio-diesel is 3 degree and 1.7 degree faster than diesel. Bio-diesel can reduce ignition delay time. At 1000 RPM different of ignition delay time is not strongly effect in combustion pressure and heat release rate can explain in term of long combustion period in low engine speed – the small ignition delay time cannot be effective. Bio-diesel can release peak heat release rate at 55 J/deg and higher than diesel.

At 2000 RPM as shown in figure 4.4(b) the increasing rate of combustion pressure is quite similar by peak bio-diesel pressure at 79 bar higher than diesel in 0.3%. The start of combustion of bio-diesel is shorter than diesel by 1 degree at 350 degree of fuel injection. The both of heat release rate fluctuate at during combustion period. The peak heat release rate of bio-diesel is 59.2 J/deg and lower than diesel by 12.3%.

At 3000 RPM as shown in figure 4.4(C) The combustion pressure is quite similar by peak diesel pressure at 67.7 bar higher than bio-diesel in 3.98%. But the start of combustion of bio-diesel is shorter than diesel by 2.1 degree at 351 degree of fuel injection. The both of heat release rate high fluctuate at during combustion period. The peak heat release rate of bio-diesel is 58.8 J/deg and lower than diesel.

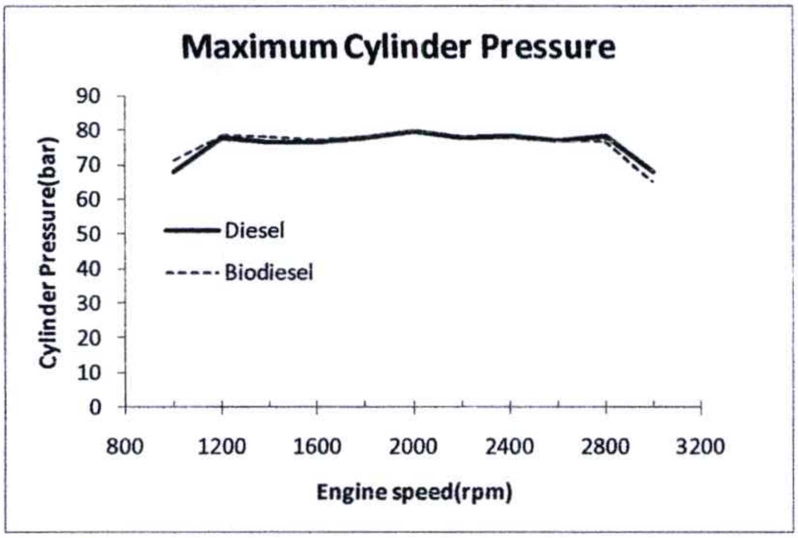
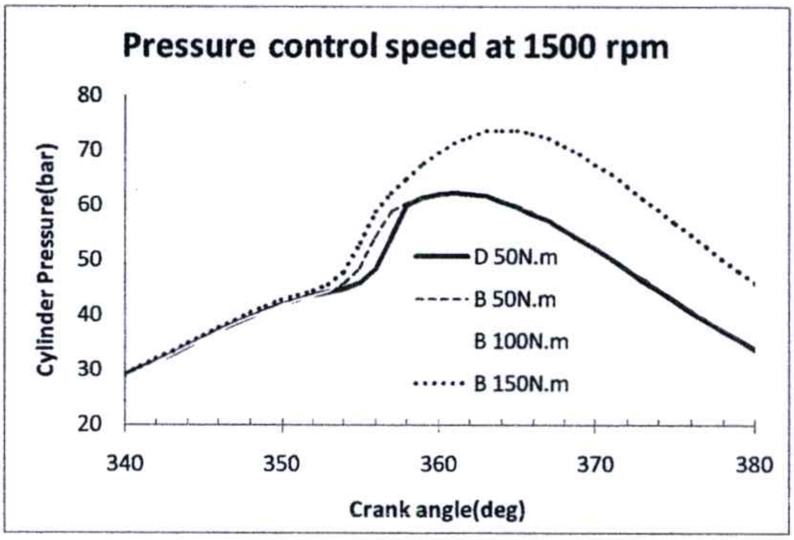


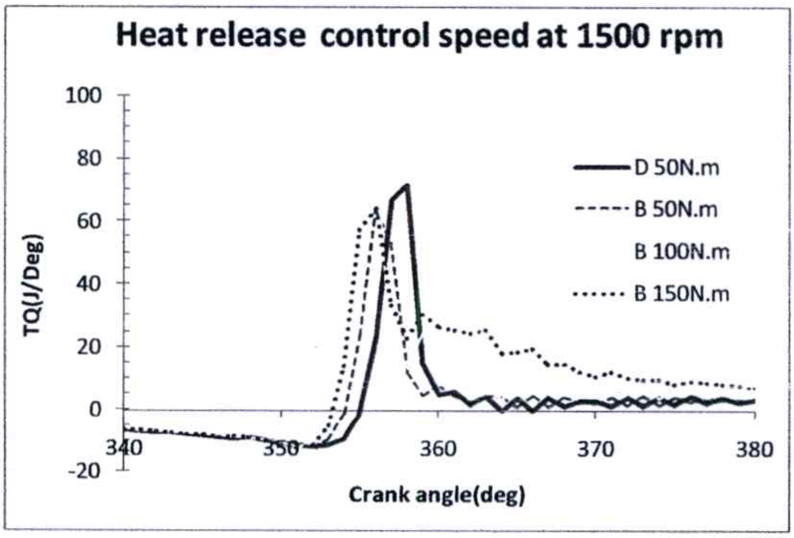
Figure 4.5 Peak of combustion pressure in full load condition

In case of peak pressure at different engine speed – as figure 4.5 shown bio-diesel result is quite better except high engine speed at 2800-3000 RPM might be cause of abnormal working of engine and from BSFC of bio-diesel is higher than diesel at full load condition and include of another reason such as higher cetane number and higher density of bio-diesel is in order to more amount of fuel injection in same injection duration and property of ignition delay time of bio-diesel is shorter than diesel – strongly effect with easier of ignition, flame propagation and strength combustion.

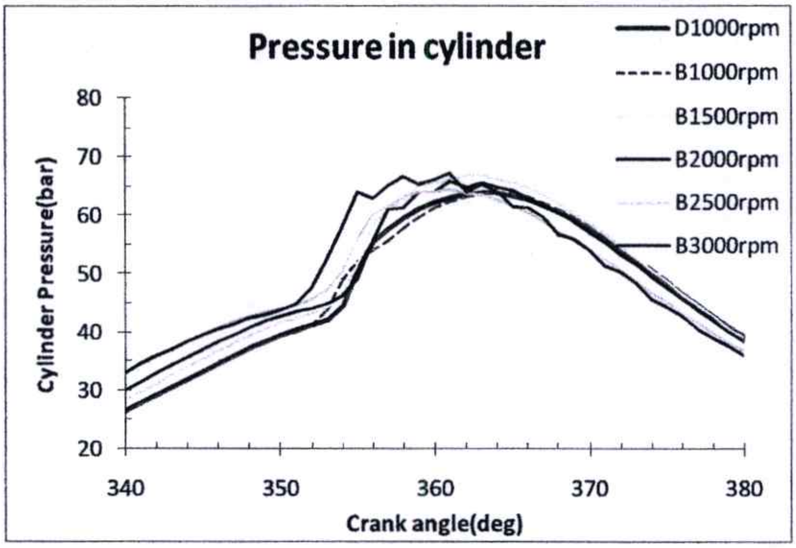
The result of partial load condition for instance combustion pressure and heat release rate of combustion shown in figure 4.6.(a),(b) From the result of combustion pressure and heat release rate at 1500 RPM in 50, 100 and 150 N.m the combustion pressure increases when torque increasing by same type of fuel is same ignition delay result too. Otherwise the heat release rate during combustion interval can extend and rise by related with load condition. Instead of case of higher load – combustion pressure can be extender and longer than lower load.



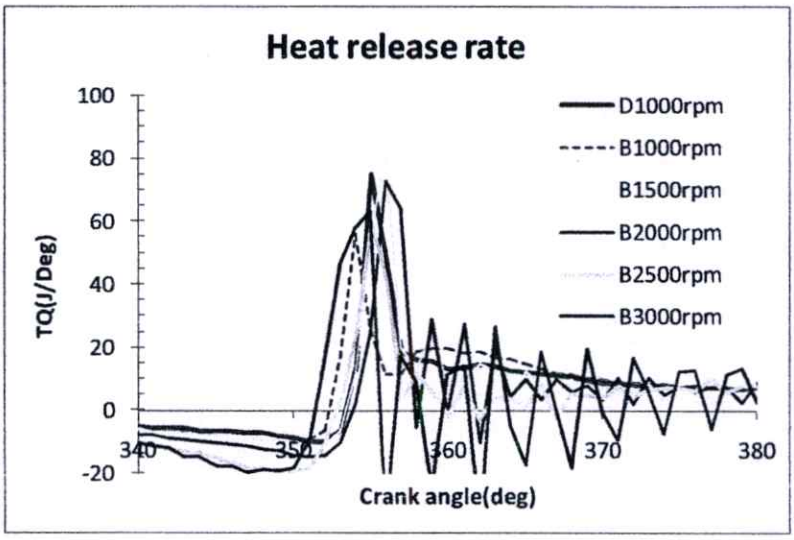
(a)



(b)



(c)



(d)

Figure 4.6 (a) Pressure data at 1500 RPM, (b) Heat release rate at 1500 RPM, (c) Pressure data at 100 Nm and (d) Heat release rate at 100 Nm

At 100 Nm in different engine speed as figure 4.6 (c), (d) shown that the peak pressure have same trend but a little bit difference in start of combustion. That can explain in simple season is fuel supply system can work different in each speed.

4.3 Emission Analysis

Emission analysis of the engine fuelled with diesel and biodiesel was conducted for both full and part loads, as shown in Figure 4.7, 4.8 and 4.9 respectively. THC emission in Figure 4.7(a) signifies the unburned hydrocarbon from the fuel, which could result from incomplete combustion and not having enough time for complete combustion. The higher THC emission for diesel at high engine speed is due to incomplete combustion, as shown by the large amount of CO in Figure 4.7(b). On the other hand, biodiesel at low engine speed with earlier SOC has more time for combustion, and thus shows less unburned hydrocarbon.

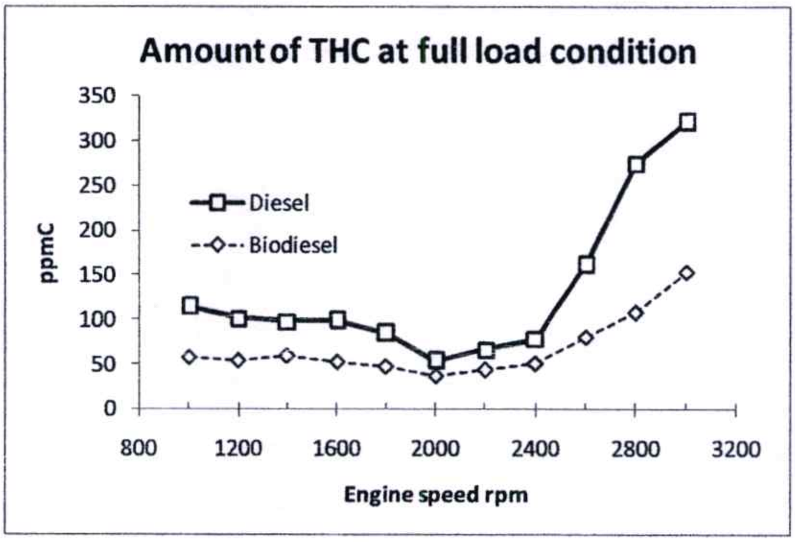


Figure 4.7 (a)

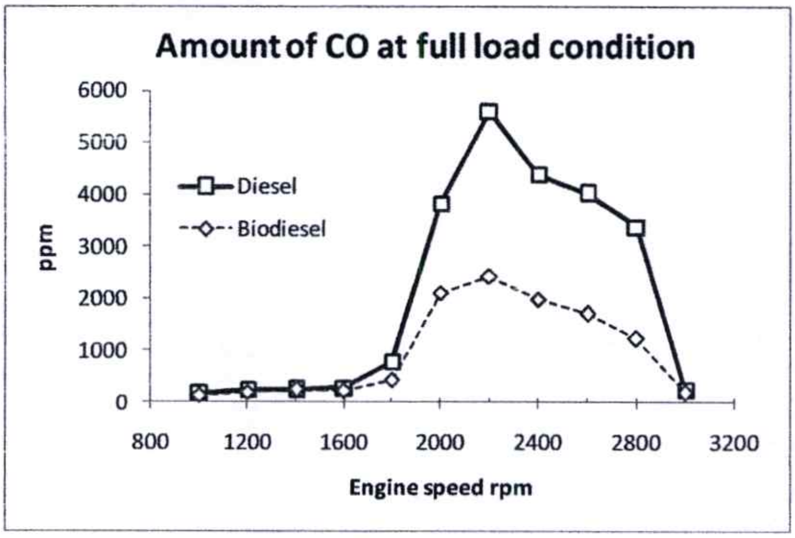


Figure 4.7 (b)

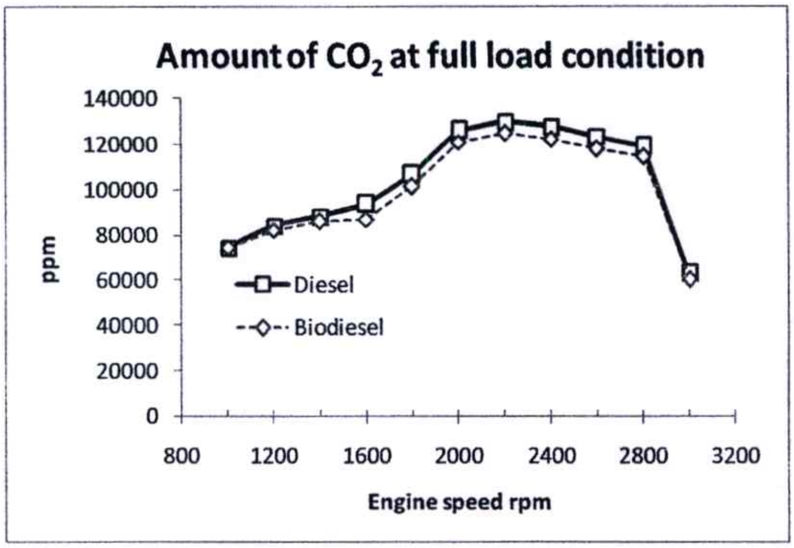


Figure 4.7 (c)

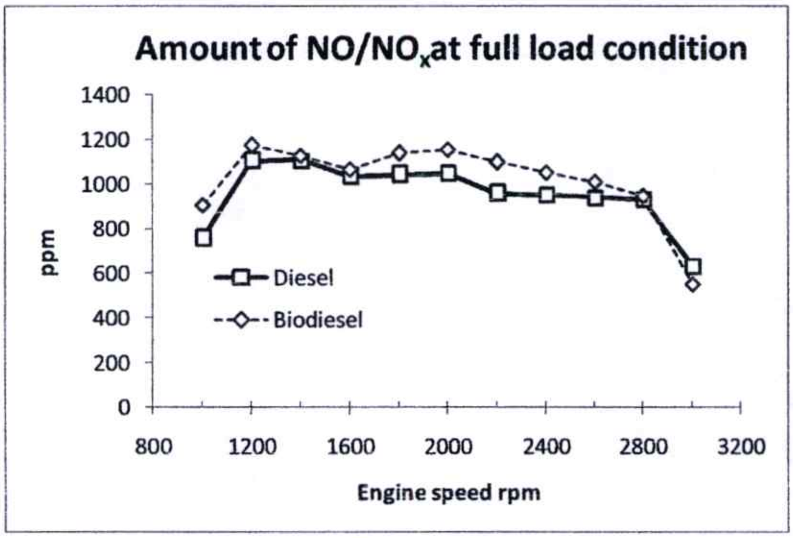


Figure 4.7 (d)

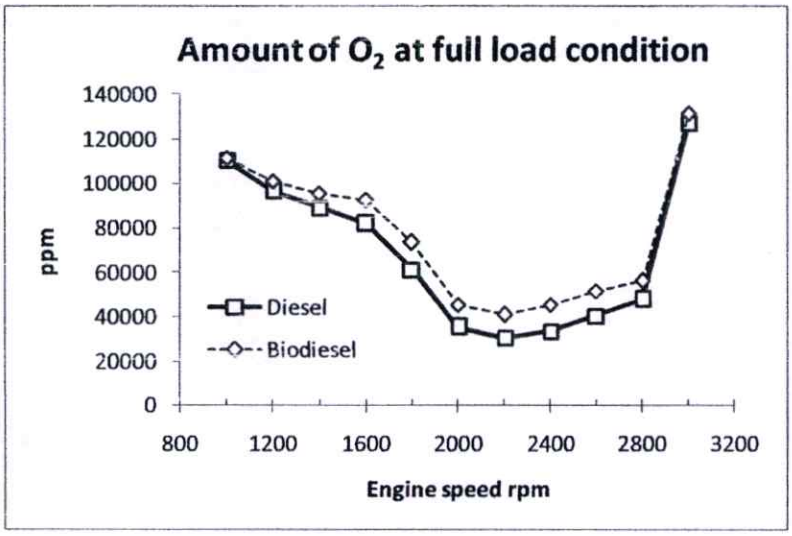


Figure 4.7 (e)

Figure 4.7(b) shows that biodiesel emits similar CO amount for low engine speed (800 - 1600 rpm) but significantly less CO for high engine speed (1800 – 3000 rpm). This implies that it may cause from incomplete combustion at high engine speed range due to pressure wave (fractuation of combustion pressure). The effect on biodiesel CO curve is not much since biodiesel itself contains some oxygen. Consequently, more complete combustion may be obtained and emitted less CO gas also. Figure 4.7(c) shows increasing CO_2 emission with increasing engine speed for both fuels, under low speed condition, the result the similar trend for both fuels. However, biodiesel always emits less CO_2 when the engine speed was greater than 1400 rpm.

For NOx emission, Figure 4.7(d) shows greater NOx emission from biodiesel, as generally explained by the higher combustion temperature from a more complete combustion of oxygenated biodiesel. However, for the engine range 1400 – 2000 rpm, NOx emission from biodiesel is less than diesel, which can be explained by the pressure data in Figure 4.6(c) showing less difference of peak pressure between the two fuels. In accordance with CO_2 behavior, Figure 4.7(e) shows decreasing O_2 emission with increasing engine speed, and biodiesel combustion emits more O_2 than that of diesel. These can imply that oxygen within combustion chamber in case of biodiesel fuel may remained more due to biodiesel didn’t require higher fraction of oxygen for complete combustion as the diesel fuel.

Furthermore, Figure 4.8 shows air-to-fuel ratio (AFR) at full load condition for both fuels. It is clear that higher engine speed requires more fuel, or lower AFR. Since biodiesel contains more oxygen in the molecular structure than diesel, biodiesel requires less air, or lower AFR.

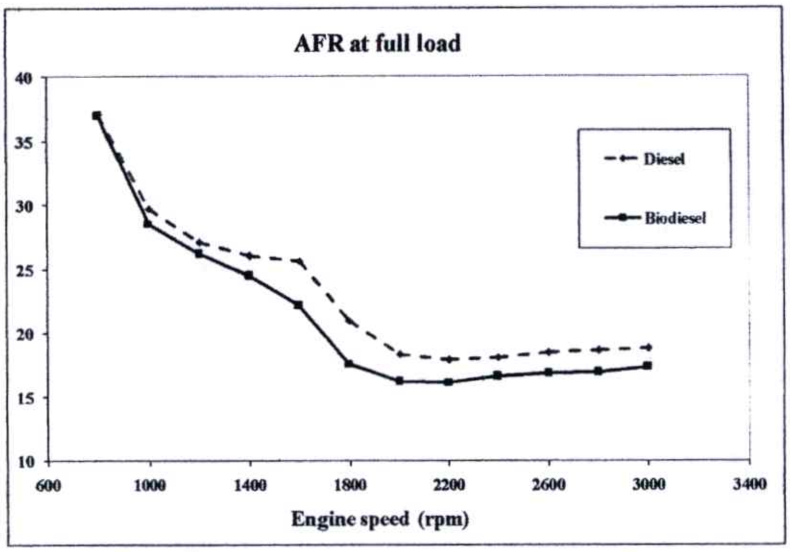


Figure 4.8 Air-fuel ratio at full load condition

For partial load emission data shown in Figure 4.9, only THC and CO are discussed here. Figure 4.9(a) shows greater THC emission at higher engine speed for both fuels. However, biodiesel shows significantly less unburned hydrocarbon for all partial load conditions due to its more complete combustion behavior, as further supported by lower CO emission for biodiesel shown in Figure 4.9(b)

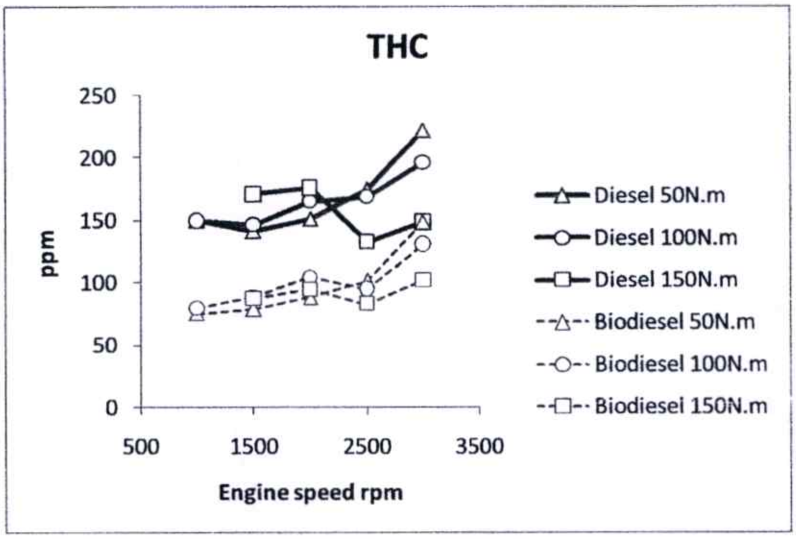


Figure 4.9 (a)

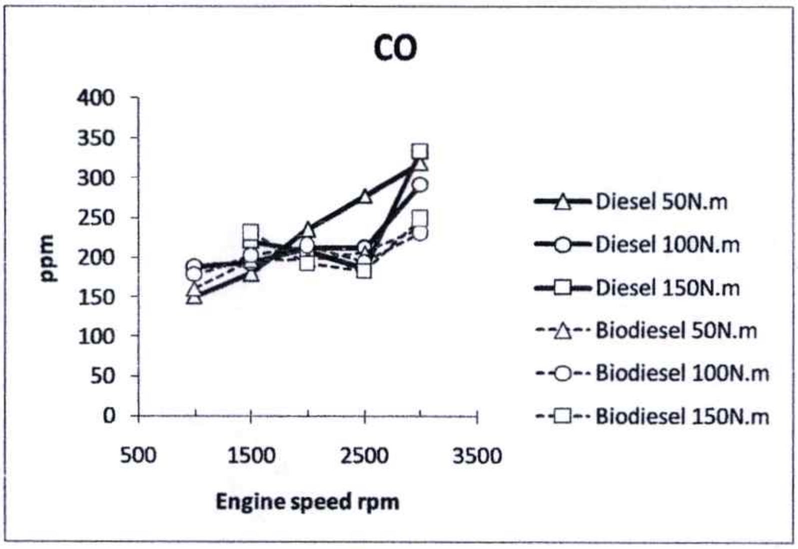


Figure 4.9 (b)

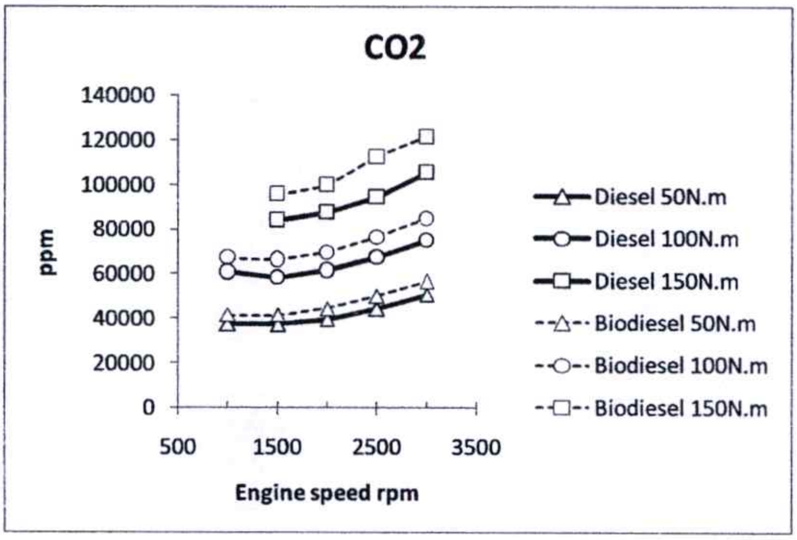


Figure 4.9 (c)

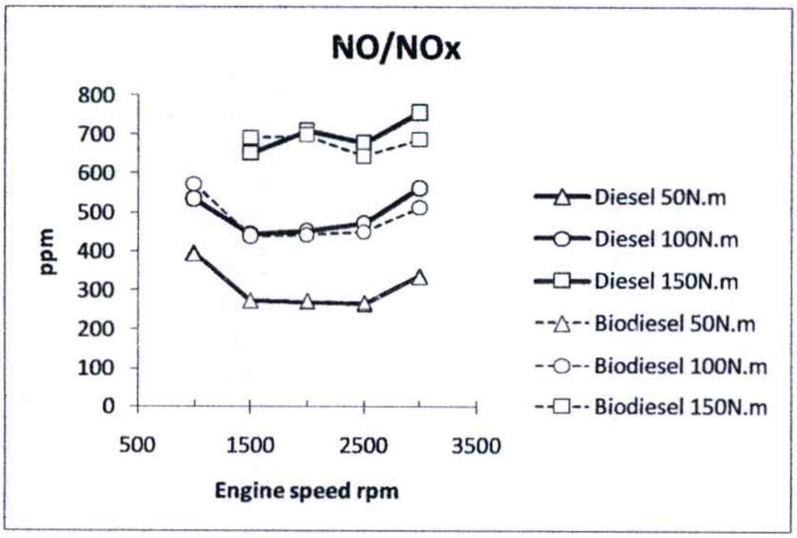


Figure 4.9 (d)

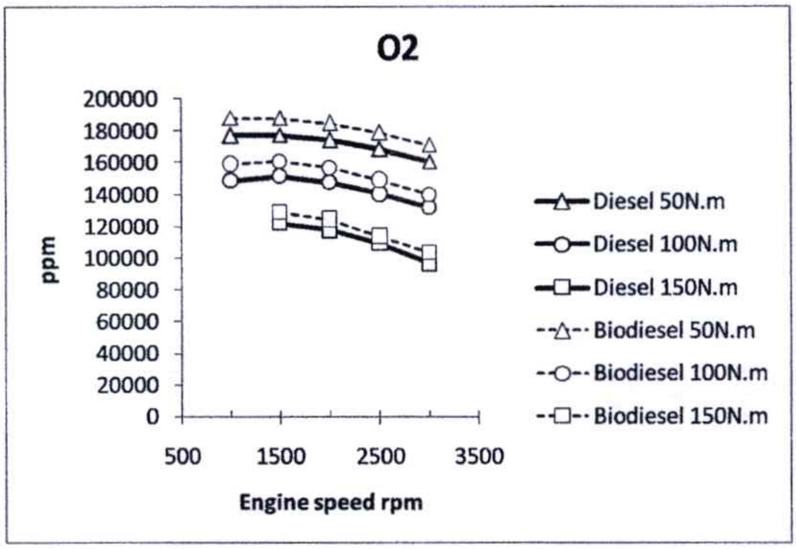


Figure 4.9 (e)

Further supported result for the discussion about THC and CO was shown in Figure 4.9 (c), CO2 emission result. Theoretically, when fuel and air completely combust, CO2 gas might be emitted more. Hence, in this result it can imply that biodiesel can provide more complete combustion than that of diesel fuel as can be seen in higher CO2 emission and lower THC (THC emission may be occurred due to incomplete combustion). However, with the high degree of complete combustion, combustion temperature should be taken into account due to it cause of followed NOx emission. Nevertheless, NOx result show that biodiesel have less significant different when compare with base diesel fuel. Furthermore, biodiesel also show the slightly less value of NOx. These phenomena may discussed that biodiesel operate more complete combustion, then, CO2 gas which have a large number of heat absorption may be generated more within combustion chamber as can be seen in the CO2 emission result in Figure 4.9 (c). Consequently, combustion temperature may be reduced and generated less NOx also. For the result of O2 gas, all over the examine cases, more O2 gas can be observed in the biodiesel due to oxygen from available air remained. These can explained that the biodiesel which is comprise of large fraction of oxygen content required less air for combustion than that of diesel engine at the same engine load and speed, Hence, oxygen may emit more in all cases.

4.4 Adjust injection timing

4.4.1. Performance and consumption

The test results at different injection timings show no significant change in the performance of the engine. Therefore, it could be concluded that adjusting injection timing has no effect on engine torque at full load condition as shown in figure 4.10. This is because of advancing the injection timing which causes the combustion to occur earlier and more severely in the cylinder. However, the heat is also released more quickly. As a result, there is no significant difference in amount of released heat

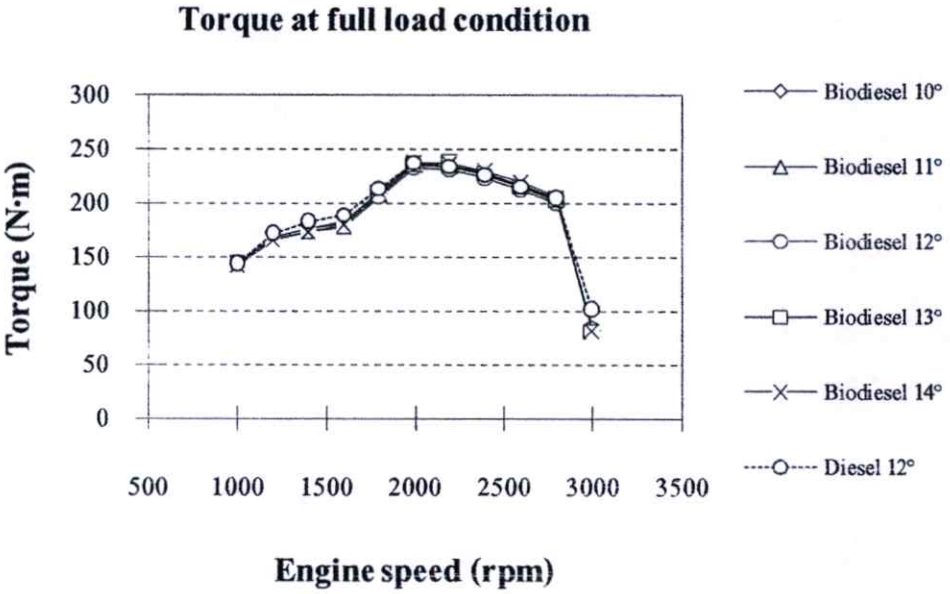


Figure 4.10

As for BSFC, there is no significant change in BSFC at different injection timings as can be seen in figure 4.11, which could be concluded that adjusting the injection timing also has no influence on BSFC.

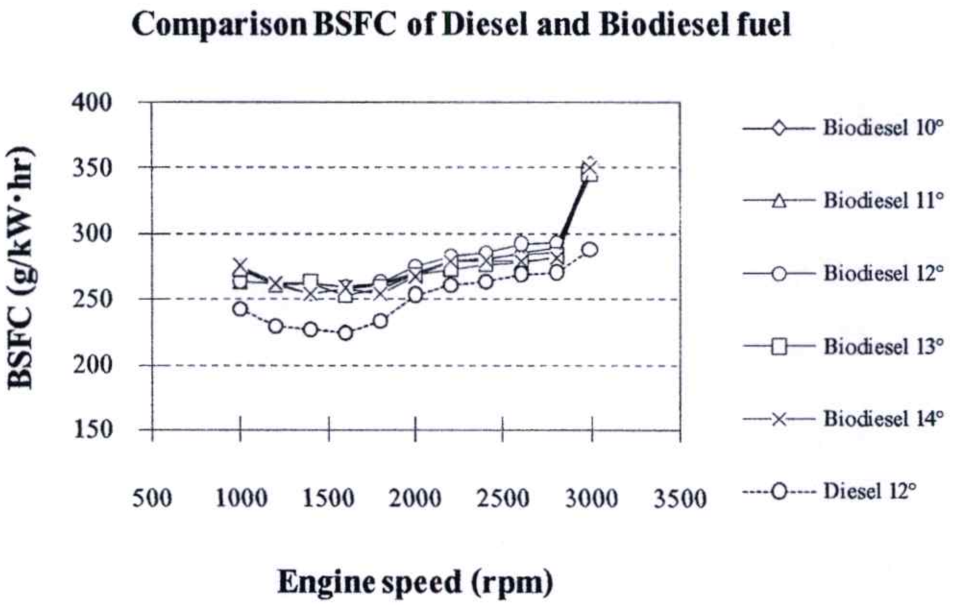


Figure 4.11

4.4.2. Combustion analysis

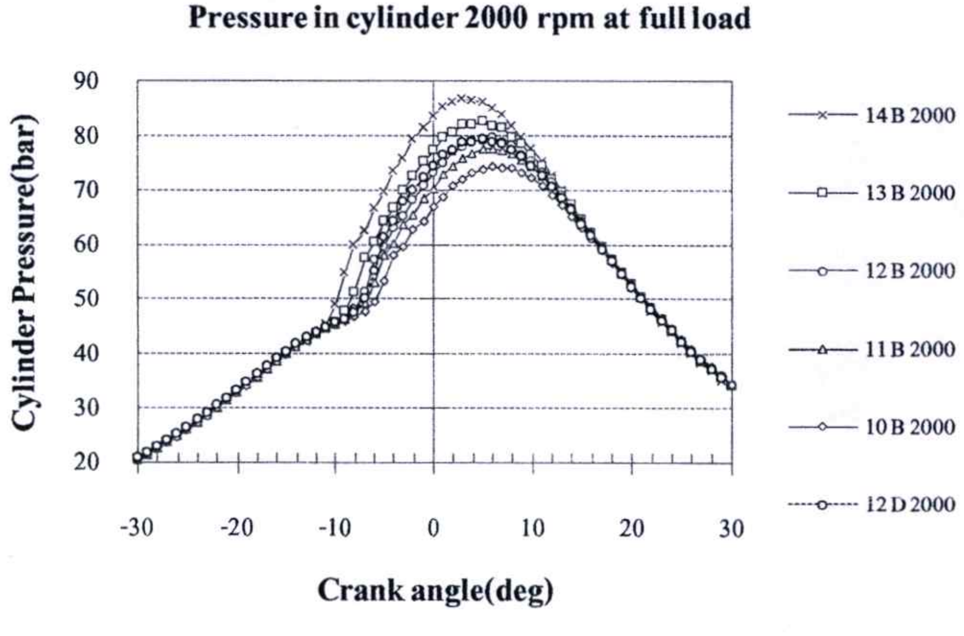


Figure 4.12

Figure 4.12 shows cylinder pressures at different injection timings, it is noticed that the cylinder pressure is varied with injection timing. At 2000 rpm, it is found that for biodiesel at injection timing of 14° and 13° bTDC, the cylinder pressure are more than that of the standard injection timing of diesel at 12° bTDC. Meanwhile, at injection at 11° and 10 bTDC °, the cylinder pressures decreased. It could be concluded that the cylinder pressure increases with advancing of the injection timing.

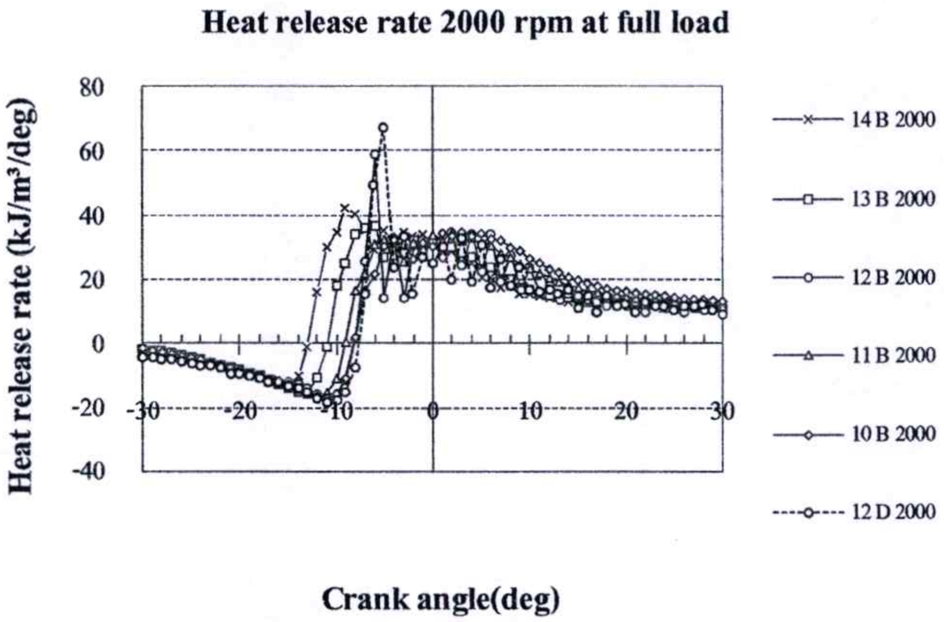


Figure 4.13

Figure 4.13 shows that the heat release rate increases with advancing of injection timing. But the heat release rate is also small in power stroke.

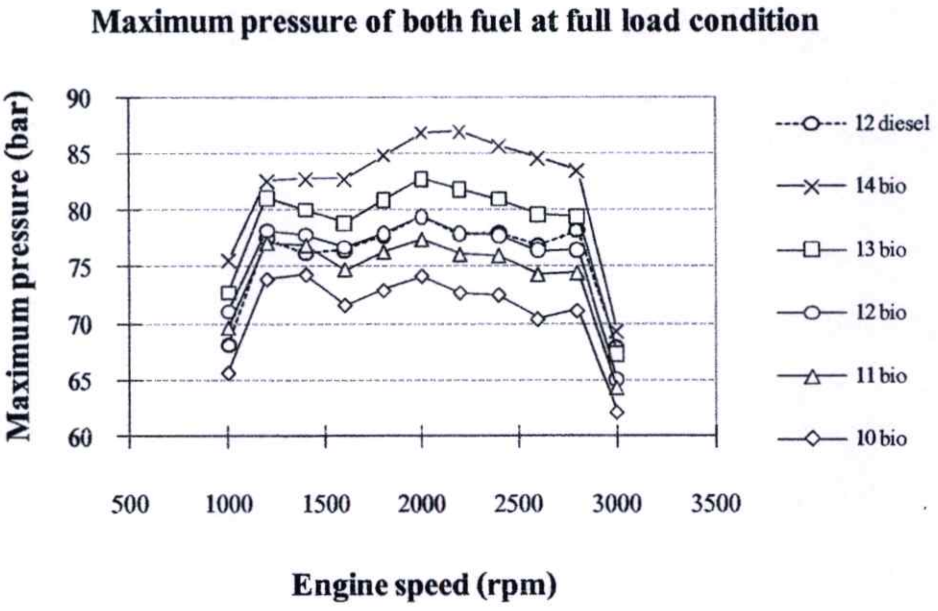


Figure 4.14

The variation of maximum pressure at full load condition at different injection timings is shown in figure 4.14. The results show that the pressure maximum of each injection timing has the similar pattern. At all engine speed, the pressure maximum increases with increasing of the degree of injection and vice versa.

4.4.3. Emission

The test results show that adjusting the injection timing obviously affect the emission of the engine

The amount of CO2 in smoke tends to increase when advancing the injection timing. This is mainly because of the longer combustion duration which results in more complete combustion.

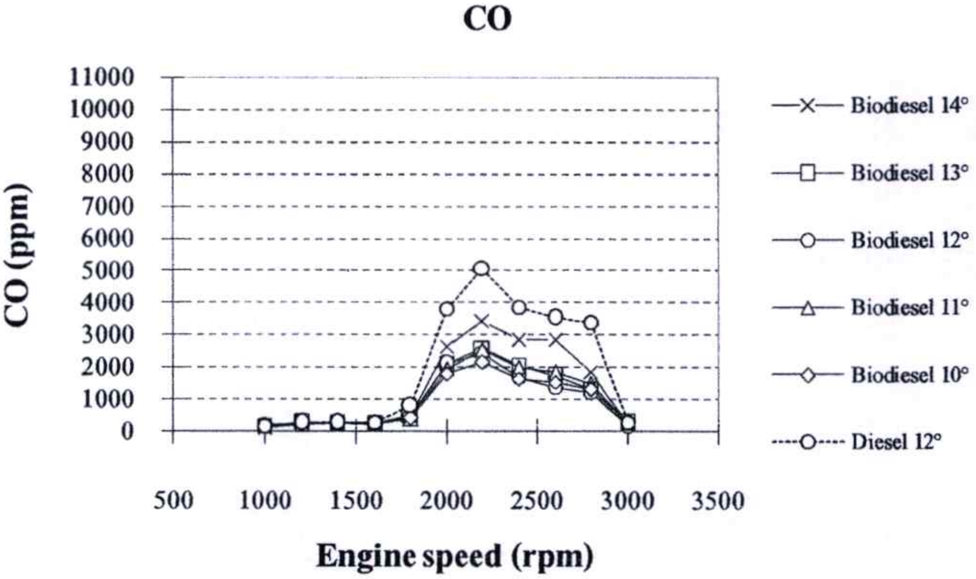


Figure 4.15

The result of adjusting the injection timing at full load condition also reveals that the amount of CO decrease when decreasing the degree of injection before TDC. Since the formation of CO depends on the amount of heat from combustion; the more injection timing is advanced, the more time for combustion which lead to the higher combustion temperature and finally results in higher amount of CO. However, the test results show that the maximum amount of CO occurring from the combustion of biodiesel is still less than the amount of CO occurring from the combustion of diesel.

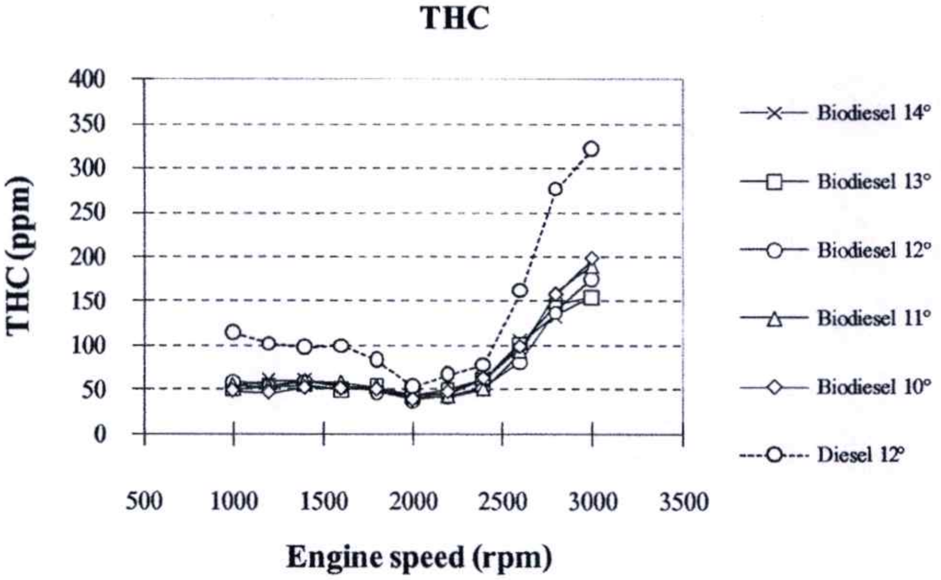


Figure 4.16

The variation of TCH at different injection timings is shown in figure 4.16. It is noticed that THC of biodiesel at all injection timing is less than that of diesel. This is due to oxygen content of biodiesel which results in better combustion in the cylinder. Moreover, biodiesel also has higher cetane number which causes the less than ignition delay and leads to higher heat of combustion. The THC of the biodiesel is thus less than that of the diesel. At 1000-2200 rpm, there is no difference found between the amounts of THC of each injection timing. However, at the higher engine speed, 2400-3000 rpm, THC are found to increase and tend to increase with increasing injection timing.

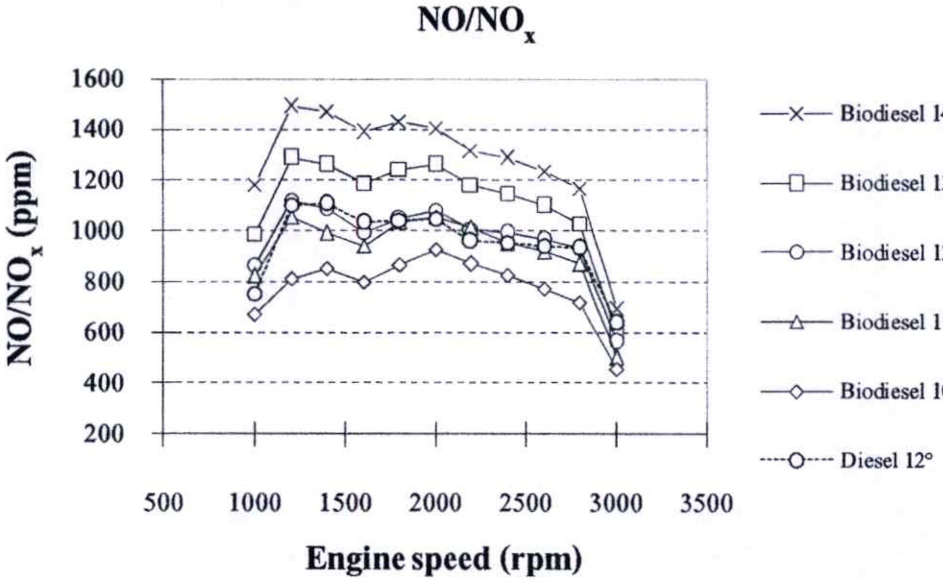


Figure 4.17

The remarkable characteristic of biodiesel is that its combustion is more complete comparing to the combustion of diesel which results in higher released heat. However, more NOx is also released when using biodiesel. Adjusting injection time plays an important role in reducing the amount of NOx. It is found that the amount of NOx decreases when the injection timing is closer to TDC, as can be seen in Figure 4.17. This is because the combustion duration is sufficient, and not too long, which causes the reduction of the formation of NOx.

CHAPTER 5

CONCLUSIONS

The present study has focused on testing of biodiesel for using on dire injection diesel engine to access the limitations of this engine type. The following conclusions and suggestions have drawn.

Conclusions

Systematic engine performance, fuel consumption, combustion behavior and emission analysis were conducted in 4-cylinder DI engine for both commercial available diesel and biodiesel from palm stearin, with important findings as follows.

1. Engine torque of biodiesel was 2-6% lower than that of the conventional diesel. This is because of the lower heating value of biodiesel which also leads to the higher break specific fuel consumption for biodiesel when compared to diesel.

2. There is no significant difference in the thermal efficiency between diesel and biodiesel because biodiesel has the lower heating value but higher BSFC than diesel.

3. At partial load operation, BSFC of biodiesel is higher than that of diesel at the same engine speed and load. However, at the same engine speed BSFC of biodiesel decreased with increasing load.

4. At partial operation, the thermal efficiency of biodiesel is lower than that of diesel at high load condition. However, at low load condition (50Nm) the thermal efficiency of both fuels has no significant difference.

5. As for the pressure and the combustion in the cylinder, when the fuel was injected into the cylinder at 12 before top dead center (BTDC), biodiesel was ignited and burned before diesel. This could be described from the fact that biodiesel has the higher density that diesel; it can overcome the pressure of the spring in the injection pump and the injector faster than diesel. As a result, biodiesel can be injected faster that diesel. Moreover, thanks to the higher value of cetene number (CN) of biodiesel and its oxygen content, the combustion of biodiesel is thus more

complete than that of diesel leading to the higher released heat and pressure than those of diesel.

6. In case of the emission, at the highest load biodiesel can help decrease CO, CO2, THC. But NOx is increased due to the higher temperature of the combustion.

7. Air/Fuel ratio (AFR) is lower for biodiesel since it already contains some oxygen in the molecule. Therefore, less amount of oxygen is required for the combustion.

8. When considering the emission at partial load, it is found that for both fuel the emission increases with increasing of the engine speed at the given load. THC and CO of biodiesel are lower than that of diesel at all load condition since the combustion of biodiesel is more complete. As for CO2, at the same load, biodiesel causes the higher amount of CO2 at all engine speed. This is because of the more complete combustion of biodiesel. It was also found that CO2 increased with increasing load.

As for NOx, at low load (50Nm), there was no difference observed in both fuels at all engine speed. However, at higher load (100-150 Nm) NOx of biodiesel was lower than that of diesel. In general, more NOx occurs at higher temperature. The test result showed that the combustion of biodiesel caused the higher temperature since the combustion is more complete. Meanwhile, more CO2 was also released. CO2 could absorb some heat from combustion so the combustion temperature decreased in partial load. This is the reason why NOx of biosel was lower than that of diesel at partial load.

In additional, since biodiesel has oxygen content in its molecule, it requires less oxygen for combustion. Thus, more O2 remaining after the combustion was found when using biodiesel.

9. The result of adjusting the injection timing shows no significant difference in torque and BSFC. The pressure in the cylinder is higher with advancing of the injection timing from BTDC.

As for the heat release rate, although the combustion occurs earlier at the injection timing of 14 degree bTDC, the heat release also reduces faster. As a result, there is no difference in torque for all injection timing. Adjusting of the injection timing can cause the composition of the emission to change. For example CO2, the test result shows no significant difference at different injection timing. However, the amount of CO2 tended to increase when advancing the injection timing as a result of longer combustion duration.

The amount of CO was lower at the injection timing of 10 degree and can be reduced at higher engine speed (2000-2800 rpm)

However, THC also increased slightly at high engine speed (1800-3000 rpm). It could be concluded that decreasing the injection timing by 10 degree could help reduce the amount of NOx.

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APPENDIX A

Tested Data under Full Load

A-1: Engine Performance, BSFC and Temperature Data

Table A1.1 Diesel results under full load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Full load at 10 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	95.36	288.66	29.96	76.39	173.41
2800	206.92	263.54	60.67	81.48	294.26
2600	217.93	263.77	59.34	83.72	335.17
2400	229.01	259.03	57.56	84.50	367.90
2200	236.97	259.00	54.59	84.29	374.49
2000	239.49	247.54	50.16	84.26	376.72
1800	215.94	231.04	40.70	84.51	364.68
1600	190.12	224.91	31.86	83.54	347.61
1400	182.51	227.59	26.76	82.37	327.91
1200	171.77	229.44	21.58	80.18	295.92
1000	143.12	241.49	14.99	78.31	272.43

Table A1.2 Biodiesel results under full load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Full load at 10 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	81.84	352.95	25.71	74.94	148.24
2800	201.83	288.55	59.18	78.88	233.99
2600	215.36	285.16	58.64	81.28	285.76
2400	226.27	280.03	56.87	82.59	331.40
2200	233.93	278.34	53.89	82.94	348.26
2000	234.57	268.50	49.13	83.43	351.76
1800	208.63	259.86	39.33	83.36	338.17
1600	180.62	258.37	30.26	82.38	317.70
1400	176.91	254.53	25.94	81.16	297.24
1200	168.47	260.41	21.17	79.59	271.72
1000	142.81	273.21	14.96	77.70	248.18

Table A1.3 Diesel results under full load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Full load at 11 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	102.44	281.11	32.18	76.90	181.97
2800	209.58	263.71	61.45	81.64	287.22
2600	219.81	262.32	59.85	83.71	333.56
2400	230.00	259.30	57.81	84.97	370.39
2200	236.94	256.12	54.59	85.36	379.68
2000	239.32	246.53	50.12	85.49	382.39
1800	218.56	227.86	41.20	85.84	371.24
1600	191.81	223.69	32.14	85.00	352.86
1400	184.89	224.45	27.11	83.78	332.61
1200	172.27	225.85	21.65	82.33	309.69
1000	142.80	237.42	14.95	80.29	283.58

Table A1.4 Biodiesel results under full load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Full load at 11 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	83.63	350.36	26.27	74.99	157.64
2800	203.93	285.59	59.80	80.62	268.03
2600	216.83	284.33	59.04	83.10	323.79
2400	227.57	281.82	57.19	83.86	355.42
2200	235.07	278.57	54.16	84.64	370.07
2000	235.42	270.14	49.31	84.73	369.37
1800	207.77	261.16	39.16	84.88	352.80
1600	178.43	259.42	29.90	82.93	316.03
1400	173.67	262.17	25.46	81.49	295.42
1200	166.84	262.40	20.97	79.97	276.34
1000	143.98	263.09	15.08	77.39	252.80

Table A1.5 Diesel results under full load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Full load at 12 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	100.71	288.15	31.64	79.92	173.63
2800	204.19	269.27	59.87	84.66	261.17
2600	215.43	267.70	58.66	86.58	314.07
2400	226.73	263.03	56.98	87.36	343.87
2200	234.80	260.70	54.09	86.78	365.97
2000	237.40	252.11	49.72	87.59	371.18
1800	214.52	233.07	40.44	88.12	364.53
1600	189.12	223.95	31.69	87.63	352.61
1400	181.97	226.55	26.68	86.58	334.07
1200	171.31	229.56	21.53	85.52	318.91
1000	142.76	242.29	14.95	84.11	299.41

Table A1.6 Biodiesel results under full load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Full load at 12 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	84.12	350.80	26.43	77.77	166.88
2800	200.63	293.51	58.83	82.18	262.18
2600	212.13	291.56	57.76	84.88	337.96
2400	223.97	285.59	56.29	85.88	363.86
2200	232.03	282.64	53.46	85.93	372.74
2000	232.57	274.74	48.71	86.00	375.27
1800	205.97	261.54	38.82	85.60	355.56
1600	177.80	259.29	29.79	84.46	334.86
1400	172.72	261.92	25.32	82.99	313.50
1200	165.93	262.13	20.85	81.30	288.70
1000	143.39	262.77	15.02	79.23	266.79

Table A1.7 Diesel results under full load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Full load at 13 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	90.67	293.46	28.48	72.69	139.09
2800	213.36	260.37	62.56	77.91	253.42
2600	224.07	257.79	61.01	81.08	319.19
2400	234.54	258.46	58.95	81.81	345.27
2200	241.17	254.25	55.56	82.28	355.59
2000	243.09	244.99	50.91	82.77	360.98
1800	220.99	228.68	41.66	83.00	348.31
1600	193.92	223.16	32.49	81.77	321.64
1400	186.72	223.18	27.37	80.67	301.97
1200	176.17	225.22	22.14	79.21	279.17
1000	149.33	236.90	15.64	77.23	255.87

Table A1.8 Biodiesel results under full load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Full load at 13 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	81.04	345.33	25.46	73.88	134.20
2800	202.62	282.26	59.41	78.16	226.31
2600	215.82	277.44	58.76	81.17	296.32
2400	228.43	276.07	57.41	82.66	333.88
2200	237.18	272.18	54.64	83.09	346.51
2000	235.63	268.85	49.35	83.52	350.81
1800	210.97	257.33	39.77	83.70	342.30
1600	182.66	252.57	30.60	82.97	324.97
1400	177.01	261.50	25.95	81.77	301.97
1200	168.81	260.85	21.21	79.88	277.28
1000	143.11	272.67	14.99	78.23	258.58

Table A1.9 Diesel results under full load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Full load at 14 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	96.43	290.19	30.30	73.66	148.79
2800	214.89	260.56	63.01	78.50	252.14
2600	225.89	263.19	61.50	81.19	322.72
2400	234.54	258.74	58.95	82.90	353.43
2200	241.14	259.01	55.56	83.60	364.72
2000	242.33	249.77	50.75	83.82	367.98
1800	221.62	228.97	41.77	83.91	358.10
1600	193.71	226.68	32.46	83.00	339.52
1400	185.94	224.18	27.26	81.33	313.29
1200	175.98	229.48	22.11	80.07	293.84
1000	147.00	237.88	15.39	78.54	275.94

Table A1.10 Biodiesel results under full load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Full load at 14 degree BTDC

Engine speed (rpm)	Torque (N·m)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
3000	80.16	350.45	25.18	72.77	129.73
2800	206.68	281.93	60.60	77.43	225.44
2600	220.49	278.79	60.03	79.58	276.61
2400	229.21	278.31	57.61	82.67	338.49
2200	238.04	278.58	54.84	82.99	348.37
2000	237.06	267.61	49.65	83.10	351.69
1800	210.87	254.25	39.75	83.33	343.38
1600	179.14	257.47	30.02	82.82	329.40
1400	174.07	254.23	25.52	81.53	307.09
1200	165.34	261.96	20.78	80.28	286.12
1000	141.92	274.33	14.86	78.68	266.13

A-2: Emission, Air/Fuel Ratio and Lambda Data

Table A2.1 Diesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel

Test condition : Full load at 10 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	287.7952	83878.15	621.0174	129279.6	111.7678	46.66093	29.83093	2.055667
1200	307.81	94607	908.4444	114934.8	89.08726	46.33589	26.6013	1.827333
1400	323.25	100940.7	911.9156	107005.9	90.96911	46.22048	25.06374	1.689667
1600	333.0652	106656.7	845.467	99162.93	88.23556	45.72367	23.77067	1.603333
1800	763.8552	126666.3	900.8444	72889.67	74.37359	45.46619	20.2197	1.351333
2000	3872.233	151715.2	912.7378	37033.89	33.04563	45.39826	16.77133	1.127333
2200	4872.833	155024.1	858.1548	36527.48	40.61859	45.77411	16.63922	1.119667
2400	3824.3	151688.9	817.4685	40442.3	50.56607	45.85344	16.99089	1.146667
2600	3314.022	145406.3	798.7274	50518.22	101.9116	45.53407	17.794	1.191
2800	3090.9	140139.6	783.5681	58381.07	147.3959	45.63922	18.46878	1.245
3000	360.6356	71035.63	544.7707	147428.1	223.6822	46.28796	35.0553	2.377667

Table A2.2 Biodiesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Biodiesel

Test condition : Full load at 10 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	228.535	77778.25	672.552	112935.6	50.03191	48.78554	29.03576	2.33197
1200	250.3201	83229.66	814.9501	105842.8	48.12956	47.82584	27.31669	2.193717
1400	303.1914	90543.33	855.1221	96201.29	53.47663	48.33394	25.15202	2.020003
1600	300.4671	93200.65	799.4844	92261.04	52.40284	48.34729	24.43917	1.963
1800	430.8791	110793.2	866.9036	69111.23	51.5705	47.89608	20.81455	1.671667
2000	1835.86	132748.8	927.7928	39587.47	40.32483	47.66643	17.51176	1.405333
2200	2198.317	136172.1	872.286	37897.03	48.72813	47.66134	17.29934	1.389793
2400	1682.44	133252.1	827.3263	43070.32	64.36641	47.75891	17.76823	1.427333
2600	1552.444	129049.2	774.3172	48200.48	99.23432	47.40251	18.26628	1.467427
2800	1329.289	122966.6	721.7456	56223.08	157.5974	47.08212	19.08893	1.534333
3000	289.2247	60664.87	411.56	136225.3	168.312	48.07413	36.75803	2.951667

Table A2.3 Diesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel

Test condition : Full load at 11 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	326.0896	77574.26	674.0596	103433	125.0741	52.25752	27.75215	1.929667
1200	302.7622	85876.11	963.7589	90564.67	98.40904	51.8083	25.00267	1.720667
1400	332.1419	91339.74	963.227	83572.37	100.1582	51.88952	23.61456	1.625
1600	359.1693	95754.44	900.8815	76805	97.78689	52.20378	22.49274	1.543333
1800	1000.899	113677.8	931.8885	52859.44	82.24648	51.47422	19.08744	1.307667
2000	4655.548	133005.2	931.4041	22573.56	36.93996	51.22419	15.97481	1.089
2200	6213.267	135006.7	870.8537	18881.26	57.86607	51.56	15.6057	1.071667
2400	5053.385	132617.8	843.3819	24165.59	80.09259	50.75515	16.06659	1.102333
2600	4644.252	128015.2	835.3207	31101.96	160.2863	50.80307	16.65467	1.136667
2800	3845.367	122933.7	827.2685	40457.37	165.9315	51.19711	17.52641	1.19
3000	358.1193	68158.78	610.6037	117584.1	277.6189	51.67641	31.53659	2.202

Table A2.4 Biodiesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Biodiesel

Test condition : Full load at 11 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	223.2719	77756.07	824.2437	110374.1	55.52074	52.30311	28.69404	2.304333
1200	253.3956	85362.52	1057.552	99929.52	53.52719	51.72978	26.23204	2.106667
1400	281.1856	88581.37	992.0226	95015.33	60.15133	51.79456	25.25937	2.028333
1600	294.9915	92124.3	941.4067	89905.3	58.48019	51.93415	24.30219	1.951667
1800	416.0093	109549.3	1036.122	66833.48	53.93048	51.52589	20.68496	1.662333
2000	1973.859	131088.5	1055.156	39199.7	41.46007	50.72274	17.51822	1.405
2200	2555.011	135429.6	1012.854	33326.63	42.5993	50.89774	16.9673	1.364
2400	2025.148	133848.9	953.3641	36406.11	50.78722	51.00956	17.239	1.385
2600	1851.167	129320.4	919.6215	43378.96	93.45159	51.30722	17.86537	1.435667
2800	1478.644	122603.7	872.3337	52077.26	158.513	51.57152	18.75033	1.506333
3000	287.9741	61342.19	502.6993	132716.7	189.7163	51.92985	35.97119	2.89

Table A2.5 Diesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel

Test condition : Full load at 12 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	282.2929	118287	630.8496	126049.3	91.24092	57.83779	25.12663	1.732333
1200	286.0287	136168.9	909.3337	110948.9	78.40024	57.45778	22.64244	1.560667
1400	315.7448	145051.1	895.6207	103671.5	81.08032	57.22554	21.646	1.491667
1600	344.0169	155131.9	846.3041	95313.3	69.77281	57.36587	20.64667	1.423
1800	776.1762	192237.8	913.0893	64457.44	64.86733	57.31767	17.85904	1.229333
2000	4328.51	241168.5	905.4685	26453.3	29.49585	57.00168	15.51985	1.066333
2200	5954.194	246183	840.4781	21769.7	36.10547	57.39967	15.25948	1.051667
2400	4527.853	240519.6	803.3011	27304.96	49.88547	56.8715	15.541	1.071333
2600	3977.748	230705.9	786.4237	36647.48	75.65058	56.7938	15.9973	1.102333
2800	3619.099	220530	778.6385	45526.52	141.4121	56.65627	16.47863	1.136
3000	3002.074	101158.7	556.7126	142517.8	272.3944	56.92156	28.5787	1.969333

Table A2.6 Biodiesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Biodiesel

Test condition : Full load at 12 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	215.6752	121167.4	680.8315	129725.2	54.2	55.46381	25.26152	2.028333
1200	237.9685	137608.1	902.63	116688.9	51.57948	55.41985	23.05907	1.853
1400	266.8052	143829.6	852.6241	111419.3	58.02389	55.26211	22.33211	1.795
1600	262.1393	149820	799.7641	106759.3	53.38333	55.20919	21.71756	1.743333
1800	387.7874	188195.9	884.4148	76364.81	51.32422	55.03367	18.67993	1.501
2000	1931.715	237425.6	929.6378	41925.67	32.17715	55.12774	16.36415	1.313667
2200	2661.093	249524.8	876.76	34975.96	36.75815	54.60093	15.98763	1.284
2400	1791.252	241986.3	817.1041	40940.26	46.4637	54.68922	16.29711	1.31
2600	1597.589	230810	773.09	49314.85	83.69411	54.72919	16.73626	1.343333
2800	1241.311	216907	734.7522	58792.37	137.4496	54.92074	17.30581	1.390333
3000	283.4296	91538.22	419.5	155521.1	206.6763	55.41852	31.44237	2.524333

Table A2.7 Diesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel

Test condition : Full load at 13 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	258.4052	79944.78	891.3507	104234.8	111.997	51.733	27.45033	1.929
1200	296.7552	89557.85	1285.711	90496.85	90.20374	51.52474	24.563	1.714667
1400	313.8667	94786.74	1310.037	83079	91.10804	51.24019	23.241	1.614
1600	365.2015	99555.96	1215.781	76669.96	87.43207	51.19507	22.18722	1.534333
1800	1106.736	117749.6	1233.504	52042.96	76.41189	50.98333	18.86881	1.299
2000	5192.133	138534.8	1191.219	21298.44	37.40222	51.05122	15.81178	1.085
2200	6715.007	140478.1	1139.237	17306.33	53.03089	51.29833	15.44996	1.063333
2400	5988.015	137701.5	1101.559	25040.07	101.6944	51.8473	16.02693	1.105
2600	4877.711	133407	1105.23	28140.26	138.3968	51.07815	16.37281	1.114333
2800	4844.17	129612.2	1076.959	34400	185.5815	51.88159	16.89833	1.169
3000	300.3396	65641.81	743.1756	123604.8	203.4537	52.03715	33.28733	2.337333

Table A2.8 Biodiesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Biodiesel

Test condition : Full load at 13 degree BTDC

Enging speed	CO	CO2	NO/NOx	O2	THC	ECO2	AFR	Lambda
(rpm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)	(ppm)		
1000	187.8204	81315.56	989.9689	109991.1	51.27804	50.60107	28.09252	2.246667
1200	271.3607	89880.96	1288.481	98747.33	54.16115	50.46989	25.52952	2.050667
1400	305.3122	94120.48	1261.637	92802.78	55.26215	50.34493	24.41115	1.965667
1600	294.237	97089.41	1192.6	88644.59	50.24459	50.25652	23.698	1.907667
1800	519.6815	114656.3	1242.804	66443.7	53.869	50.17663	20.3873	1.625667
2000	2142.87	136610.7	1261.563	37364.74	44.42533	49.87293	17.26796	1.371
2200	2623.144	139909.6	1183.181	34715.74	51.03041	49.91111	16.98493	1.354333
2400	2092.144	136764.1	1152.563	39347.52	62.82433	49.65956	17.39793	1.386
2600	1748.83	131370.4	1099.852	46146	102.6199	50.25867	18.031	1.424667
2800	1349.07	124936.7	1029.17	54994.33	145.7296	49.99852	18.92367	1.499
3000	258.5919	62371.67	600.973	135504.1	155.5856	50.29489	36.0987	2.904333

Table A2.9 Diesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Diesel — Test condition : Full load at 14 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	246.1948	78056.59	1075.141	110470.7	120.3737	51.76978	28.57293	1.954896
1200	291.2785	87628.04	1497.263	95789.89	110.9363	52.40459	25.377	1.748426
1400	320.507	91876.07	1495.089	88865.78	103.8961	51.90544	24.1273	1.660399
1600	384.467	96535.07	1392.981	82379.48	98.96059	52.24793	22.99319	1.580693
1800	1423.337	114809.3	1383.541	55122.41	81.12174	51.94533	19.19911	1.297612
2000	6678.163	134258.1	1257.359	20989.67	49.50744	51.52759	15.739	1.082668
2200	10678.11	134942.2	1166.126	20319.52	124.9304	51.212	15.4753	1.071978
2400	8237.022	132320	1209.119	25581.26	165.6889	51.472	15.98356	1.10037
2600	7806.793	128816.3	1197.37	31208.63	346.6441	51.61285	16.43511	1.132326
2800	5716.537	124234.8	1221.796	40981.78	342.8756	51.37396	17.38133	1.199576
3000	238.4819	64365.04	869.9126	130302.2	232.7252	51.48407	34.63348	2.384213

Table A2.10 Biodiesel results under full load (exhaust gas emission, AFR and lambda)

Fuel type : Biodiesel　　Test condition : Full load at 14 degree BTDC

Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)	ECO2 (ppm)	AFR	Lambda
1000	152.0322	75346.59	1184.648	111972.6	56.1243	54.28456	29.35	2.355
1200	224.3996	82620.89	1490.019	101060.3	60.91956	54.24426	26.7433	2.149333
1400	260.2826	86277.96	1474.789	96070.44	60.9423	54.86393	25.6523	2.063333
1600	246.7056	88716.96	1388.944	92683.41	52.42878	54.62259	24.98896	2.007333
1800	521.8281	106607.8	1433.485	66848.37	52.44341	54.38896	20.82863	1.67
2000	2659.637	125925.2	1404.952	33088.78	44.18111	53.35385	17.09422	1.39
2200	3449.481	129257	1319.944	33327.81	46.58037	53.81237	17.00207	1.364
2400	2890.774	127532.2	1288.615	38287.74	62.89952	54.18874	17.44237	1.402333
2600	2873.319	124283.7	1240.207	43497.52	112.2832	54.461	17.91659	1.439333
2800	1893.433	116923.3	1173.085	55870.59	210.1619	54.42133	19.21126	1.543667
3000	221.4604	57933.04	690.6822	140971.5	154.8593	55.11274	38.59893	3.1

APPENDIX B

Tested Data under Part Load

B-1: BSFC and Temperature Data

Table B1.1 Diesel results under part load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Part load at 10 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50	1000	319.49	5.24	64.36	90.32
50	1500	330.97	7.85	65.82	103.26
50	2000	344.54	10.47	67.53	115.62
50	2500	367.11	13.09	70.08	135.38
50	3000	398.89	15.71	74.27	159.54
100	1000	244.78	10.47	76.46	196.83
100	1500	249.76	15.71	72.84	167.22
100	2000	259.29	20.94	73.68	176.92
100	2500	267.65	26.18	76.12	198.29
100	3000	285.88	31.42	79.23	220.33
150	1500	232.01	23.56	77.18	217.28
150	2000	236.26	31.42	77.32	226.51
150	2500	243.55	39.27	79.60	250.91
150	3000	255.52	47.12	81.81	274.09

Table B1.2 Biodiesel results under part load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Part load at 10 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50.00	1000	363.93	5.24	66.34	94.93
50.00	1500	358.46	7.85	67.49	105.98
50.00	2000	383.23	10.47	69.39	119.36
50.00	2500	420.13	13.09	71.51	138.39
50.00	3000	451.45	15.71	76.12	161.46
100.00	1000	287.81	10.47	75.22	163.53
100.00	1500	278.69	15.71	74.96	168.79
100.00	2000	295.16	20.94	75.36	176.26
100.00	2500	308.42	26.18	77.04	194.84
100.00	3000	324.24	31.42	80.66	218.67
150.00	1500	261.43	23.56	79.52	222.39
150.00	2000	267.56	31.42	79.52	230.24
150.00	2500	277.38	39.27	80.99	251.36
150.00	3000	292.00	47.12	83.77	276.38

Table B1.3 Diesel results under part load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Part load at 11 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50	1000	330.88	5.24	66.18	87.94
50	1500	323.42	7.85	67.24	102.29
50	2000	345.35	10.47	69.59	119.67
50	2500	360.32	13.09	72.29	139.52
50	3000	391.62	15.71	76.41	161.84
100	1000	260.61	10.47	73.69	165.71
100	1500	247.97	15.71	73.56	170.43
100	2000	252.44	20.94	74.52	179.63
100	2500	267.72	26.18	77.70	201.66
100	3000	283.48	31.42	82.33	230.64
150	1500	232.36	23.56	80.36	235.32
150	2000	233.77	31.42	80.26	240.83
150	2500	242.49	39.27	82.32	260.31
150	3000	256.27	47.12	84.36	282.91

Table B1.4 Biodiesel results under part load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Part load at 11 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50.00	1000	375.88	5.24	65.06	86.54
50.00	1500	377.33	7.85	67.28	106.17
50.00	2000	389.69	10.47	69.29	119.62
50.00	2500	412.62	13.09	72.79	142.98
50.00	3000	454.35	15.71	76.39	161.89
100.00	1000	293.76	10.47	75.39	166.49
100.00	1500	284.43	15.71	74.92	170.56
100.00	2000	286.48	20.94	75.82	180.98
100.00	2500	304.55	26.18	77.61	195.58
100.00	3000	322.14	31.42	80.94	217.52
150.00	1500	261.53	23.56	80.20	227.52
150.00	2000	266.64	31.42	80.06	234.24
150.00	2500	276.59	39.27	81.80	251.20
150.00	3000	291.43	47.12	84.97	281.39

Table B1.5 Diesel results under part load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Part load at 12 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50	1000	336.75	5.24	67.47	94.43
50	1500	321.27	7.85	68.03	103.83
50	2000	339.49	10.47	69.67	116.33
50	2500	364.80	13.09	72.43	136.27
50	3000	397.90	15.71	75.87	154.70
100	1000	253.30	10.47	76.03	169.87
100	1500	246.36	15.71	75.87	174.93
100	2000	256.19	20.94	76.43	182.93
100	2500	271.43	26.18	78.33	196.00
100	3000	286.26	31.42	81.10	215.97
150	1500	233.81	23.56	81.17	235.53
150	2000	236.19	31.42	81.30	244.17
150	2500	244.65	39.27	83.63	264.73
150	3000	260.64	47.12	85.43	283.33

Table B1.6 Biodiesel results under part load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Part load at 12 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50.00	1000	381.64	5.24	66.61	94.49
50.00	1500	375.64	7.85	67.30	106.62
50.00	2000	390.15	10.47	70.10	126.03
50.00	2500	414.38	13.09	73.46	148.99
50.00	3000	457.44	15.71	77.73	170.77
100.00	1000	285.28	10.47	76.81	171.61
100.00	1500	283.09	15.71	76.12	175.58
100.00	2000	292.47	20.94	76.69	185.97
100.00	2500	310.79	26.18	78.94	205.97
100.00	3000	324.11	31.42	81.93	227.41
150.00	1500	263.52	23.56	79.97	236.97
150.00	2000	265.04	31.42	80.13	244.28
150.00	2500	280.46	39.27	81.96	264.66
150.00	3000	296.27	47.12	84.86	292.52

Table B1.7 Diesel results under part load (performance, BSFC and temperature)

Fuel type : Diesel

Test condition : Part load at 13 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50	1000	330.12	5.24	64.82	85.93
50	1500	328.28	7.85	65.68	98.61
50	2000	339.01	10.47	67.76	113.19
50	2500	353.78	13.09	71.08	135.58
50	3000	389.46	15.71	75.28	154.88
100	1000	263.37	10.47	74.19	159.20
100	1500	241.59	15.71	73.68	162.73
100	2000	252.24	20.94	74.26	170.66
100	2500	264.51	26.18	76.07	187.03
100	3000	280.70	31.42	80.47	213.87
150	1500	225.20	23.56	79.31	221.82
150	2000	231.41	31.42	78.91	227.63
150	2500	240.92	39.27	80.40	246.58
150	3000	250.10	47.12	83.19	268.50

Table B1.8 Biodiesel results under part load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Part load at 13 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50.00	1000	370.30	5.24	66.68	85.26
50.00	1500	370.86	7.85	67.50	101.78
50.00	2000	397.57	10.47	69.33	115.52
50.00	2500	412.83	13.09	72.08	136.14
50.00	3000	449.83	15.71	76.79	161.37
100.00	1000	276.49	10.47	76.50	171.86
100.00	1500	286.39	15.71	76.26	176.92
100.00	2000	282.28	20.94	76.71	185.56
100.00	2500	300.07	26.18	78.74	201.37
100.00	3000	319.96	31.42	81.84	221.89
150.00	1500	260.67	23.56	82.03	236.03
150.00	2000	264.07	31.42	81.92	246.48
150.00	2500	272.66	39.27	83.33	259.90
150.00	3000	285.13	47.12	85.96	283.14

Table B1.9 Diesel results under part load (performance, BSFC and temperature)

Fuel type : Diesel Test condition : Part load at 14 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50	1000	345.07	5.24	66.93	92.09
50	1500	325.04	7.85	67.37	101.08
50	2000	345.27	10.47	68.68	111.96
50	2500	361.88	13.09	71.14	131.31
50	3000	387.85	15.71	74.79	150.73
100	1000	256.06	10.47	74.27	155.46
100	1500	246.91	15.71	73.81	159.88
100	2000	254.23	20.94	74.33	168.41
100	2500	264.10	26.18	76.00	185.60
100	3000	280.37	31.42	79.12	204.98
150	1500	227.22	23.56	78.42	215.79
150	2000	226.86	31.42	78.33	223.26
150	2500	238.06	39.27	79.43	239.22
150	3000	249.76	47.12	82.09	259.93

Table B1.10 Biodiesel results under part load (performance, BSFC and temperature)

Fuel type : Biodiesel Test condition : Part load at 14 degree BTDC

Torque (N·m)	Engine speed (rpm)	BSFC (g/kW-hr)	Power (kW)	Lubricant temperature (°C)	Exhaust gas temperature (°C)
50.00	1000	371.03	5.24	66.28	89.88
50.00	1500	375.17	7.85	66.88	97.86
50.00	2000	396.23	10.47	68.50	109.98
50.00	2500	405.99	13.09	70.74	127.40
50.00	3000	452.80	15.71	74.74	150.04
100.00	1000	283.05	10.47	74.76	155.07
100.00	1500	280.10	15.71	74.22	159.02
100.00	2000	287.40	20.94	74.58	166.18
100.00	2500	303.91	26.18	75.89	179.23
100.00	3000	319.92	31.42	78.62	197.81
150.00	1500	260.36	23.56	78.77	210.30
150.00	2000	261.87	31.42	78.68	218.72
150.00	2500	271.40	39.27	80.06	238.72
150.00	3000	285.32	47.12	82.34	256.14

B-2: Emission, Air/Fuel Ratio and Lambda Data

Table B2.1 Diesel results under part load (exhaust gas emission)

Fuel type : Diesel

Test condition : Part load at 10 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	198.5656	33448.7	404.0738	173694.7	171.0247
50	1500	239.3905	33560.88	282.0518	173630.4	149.1181
50	2000	296.2251	35808.93	278.9815	170561.9	161.334
50	2500	349.0665	40190.33	281.5305	164649.7	186.4617
50	3000	392.7373	45293.53	342.2564	157640.9	244.9863
100	1000	232.5062	53984.1	509.2531	145893.5	151.2191
100	1500	263.0459	52031.31	433.5587	148578.3	166.4913
100	2000	276.2737	54806.18	449.6861	144809.9	178.4556
100	2500	281.1929	59817.39	462.694	137911.5	183.6289
100	3000	362.5707	65877.19	540.9907	129427.7	212.3552
150	1500	293.2526	72794.17	615.7302	119765.6	176.784
150	2000	259.8524	76272.17	664.1321	114704.9	166.1197
150	2500	250.0975	82804.65	642.4286	105493.1	133.7126
150	3000	383.0437	89444.07	702.7887	95797.37	143.3508

Table B2.2 Biodiesel results under part load (exhaust gas emission)

Fuel type : Biodiesel

Test condition : Part load at 10 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	187.967	34511	355.9583	168439	71.2164
50	1500	225.3197	34630.73	246.5807	168281.7	72.03867
50	2000	223.8703	36915.07	246.515	165324	77.27107
50	2500	238.269	41133.17	242.402	159912.3	90.2786
50	3000	267.121	46461.83	301.337	152925.7	131.88
100	1000	194.2107	54913.17	500.1327	141952.3	68.67527
100	1500	241.1487	54052.37	380.1313	143036	80.68673
100	2000	245.1677	56420.3	400.8123	139929.3	93.33857
100	2500	233.064	61120.03	405.481	133764.7	92.81937
100	3000	265.0723	67300.3	463.095	125519	126.3637
150	1500	261.2267	75039.5	621.3163	114991.7	81.2235
150	2000	221.377	77390	619.3453	111907	84.68077
150	2500	212.5543	83668.47	574.8887	103538.3	81.94527
150	3000	260.237	90345.03	615.4017	94163.07	100.0362

Table B2.3 Diesel results under part load (exhaust gas emission)

Fuel type : Diesel Test condition : Part load at 11 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	185.0724	34442.84	406.784	172106.4	143.7912
50	1500	215.0028	34416.16	303.0728	172064.4	117.6356
50	2000	251.3752	36762.12	297.6996	169024.8	130.0592
50	2500	284.4024	41266.6	300.7772	163190.4	158.1568
50	3000	330.7108	46619.92	367.8404	156196.4	221.7896
100	1000	213.7032	55659.08	545.1464	144517.6	136.8312
100	1500	233.7208	53133.04	457.2016	147800.4	140.7332
100	2000	242.1428	56313.6	460.9368	143656.8	150.3324
100	2500	244.9152	61730.2	484.6976	136589.6	168.7404
100	3000	330.7508	67750.36	572.9848	128609.6	205.1716
150	1500	260.1912	74139.96	660.15	120271.6	157.5724
150	2000	232.1396	78075.56	728.9692	115090.8	165.784
150	2500	224.3268	85335.12	685.2052	105351.6	130.6568
150	3000	338.9716	92012.76	739.7236	96237.84	137.4192

Table B2.4 Biodiesel results under part load (exhaust gas emission)

Fuel type : Biodiesel Test condition : Part load at 11 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	194.134	35286.33	396.3507	172501.3	70.9154
50	1500	231.1093	35464.47	286.3073	172242	75.567
50	2000	232.828	38080.87	299.536	169004	85.89727
50	2500	237.0827	42155.6	279.1087	163929.3	104.1413
50	3000	260.796	47761.2	351.846	156846.7	165.5133
100	1000	180.0287	56157.2	559.408	146206	75.3806
100	1500	226.1787	54601.67	455.4067	148136	89.4952
100	2000	245.7867	57523.87	457.3713	144368.7	122.296
100	2500	220.438	63170.47	466.926	137204.7	107.9193
100	3000	246.708	68899.53	539.284	129790	153.0113
150	1500	231.5573	74693.33	706.7333	122256	89.6764
150	2000	209.8773	79258.2	738.4773	116489.3	109.56
150	2500	190.9633	86495	673.6233	107134.7	92.54927
150	3000	247.7187	92784.07	722.4253	98839.33	112.0667

Table B2.5 Diesel results under part load (exhaust gas emission)

Fuel type : Diesel Test condition : Part load at 12 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	135.8935	32637.05	468.637	167827.5	151.321
50	1500	174.6755	32421.8	341.63	168173	143.9815
50	2000	227.28	35010.1	354.842	164709.5	150.503
50	2500	263.7225	38528.05	342.2055	160018	171.386
50	3000	299.8165	43900.5	423.66	152732	218.818
100	1000	151.927	51770	625.126	141998.5	144.672
100	1500	170.9335	49918.65	527.722	144577	141.6885
100	2000	184.1315	52808.4	542.0015	140700.5	155.942
100	2500	187.763	57875.75	561.327	133789.5	164.811
100	3000	246.7135	63533.05	658.595	125938	193.1195
150	1500	190.269	69307.55	740.205	117858	168.133
150	2000	187.836	72843.95	820.014	112814	178.346
150	2500	162.0115	79064.7	779.178	104069.5	126.518
150	3000	285.438	85670.45	859.0325	94235.45	150.829

Table B2.6 Biodiesel results under part load (exhaust gas emission)

Fuel type : Biodiesel Test condition : Part load at 12 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	129.7736	32781.12	433.3996	168022.8	78.2928
50	1500	165.8556	32745.28	306.514	168085.2	83.43996
50	2000	166.3964	35039.28	317.5028	165170	92.57032
50	2500	172.3664	39106.88	313.5184	159939.6	106.9188
50	3000	194.2304	44220.56	393.2852	153176	145.3736
100	1000	116.5412	52042.8	647.5084	142750	79.19164
100	1500	157.0152	50249.36	496.2816	145120.8	89.98288
100	2000	172.6276	53377.84	500.5772	140942.4	105.162
100	2500	147.2504	58613.88	518.166	133895.2	96.62988
100	3000	171.8044	63720.4	597.3504	126888.4	130.41
150	1500	172.8116	69769.16	781.6388	118605.6	88.93908
150	2000	150.72	73448	815.96	113960	106.4
150	2500	135.2904	79195.48	736.6368	105686.4	90.038
150	3000	199.092	85890.96	797.6204	96265.68	110.6884

Table B2.7 Diesel results under part load (exhaust gas emission)

Fuel type : Diesel Test condition : Part load at 13 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	184.185	37332.53	518.0063	182140	144.5237
50	1500	202.748	37123.4	379.0593	182266.7	121.9563
50	2000	234.6577	39664.27	386.8213	179005.3	137.3297
50	2500	272.41	44273.1	381.4205	173256.5	168.5725
50	3000	316.8037	50133.07	460.4726	165967.4	235.0893
100	1000	189.9083	60196.83	750.4403	152298.3	145.3557
100	1500	213.589	57713.77	590.8507	155877.3	142.3703
100	2000	221.86	60973.77	612.994	152135.7	155.269
100	2500	201.7063	67167.03	624.159	144723.3	135.5317
100	3000	281.395	73320.97	729.126	137075.7	188.723
150	1500	232.8217	81012.27	848.791	127653	154.9437
150	2000	222.5713	85272.97	935.124	122385.7	163.1247
150	2500	212.4833	92553.3	880.7053	113396.7	131.5913
150	3000	298.3987	101362.3	950.444	103796.7	136.7977

Table B2.8 Biodiesel results under part load (exhaust gas emission)

Fuel type : Biodiesel Test condition : Part load at 13 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	190.332	38438.32	508.4932	180507.6	79.6382
50	1500	224.46	38301.84	353.6008	180597.2	82.93496
50	2000	231.2644	41226.08	379.6212	177082.8	95.09092
50	2500	228.44	45619.12	366.3788	171778.8	106.5456
50	3000	253.8748	51348.2	453.7548	164774.4	168.4988
100	1000	165.19	61193.16	696.3548	153007.2	81.4508
100	1500	208.28	59326.28	580.696	155174.8	91.99508
100	2000	216.6872	62467.84	591.1936	151410	107.0372
100	2500	194.8336	68307.44	605.248	144481.2	101.7702
100	3000	229.0296	74790.8	701.5688	136678.8	144.2932
150	1500	237.3252	81757.76	918.5912	128322.4	97.29944
150	2000	190.7524	86832.72	952.1864	122295.2	108.6768
150	2500	182.26	94511.28	868.5952	113112.8	95.87924
150	3000	234.8868	102721.6	928.376	104714	115.7124

Table B2.9 Diesel results under part load (exhaust gas emission)

Fuel type : Diesel Test condition : Part load at 14 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	199.1235	37945.15	600.03	180067.5	170.494
50	1500	223.22	37645.55	442.532	180376	149.3145
50	2000	257.2645	40536.3	458.2345	176789.5	157.1605
50	2500	272.1295	44752.95	456.2835	171589.5	173.468
50	3000	291.218	50600.05	556.077	164341	221.441
100	1000	196.3485	60961.9	883.704	150707	161.7625
100	1500	213.139	58784.65	704.6545	153687	155.3765
100	2000	220.352	61630	743.2045	150414	178.1565
100	2500	201.814	67653.3	757.713	143244.5	166.535
100	3000	278.6505	74086.65	881.8125	135359	212.8155
150	1500	239.0845	80817.8	1003.825	126934	167.331
150	2000	226.975	85993.2	1119.65	120897	180.851
150	2500	207.1275	93463.5	1068.275	111721	139.655
150	3000	300.71	101930	1151.585	102688	154.045

Table B2.10 Biodiesel results under part load (exhaust gas emission)

Fuel type : Biodiesel Test condition : Part load at 14 degree BTDC

Torque (N·m)	Enging speed (rpm)	CO (ppm)	CO2 (ppm)	NO/NOx (ppm)	O2 (ppm)	THC (ppm)
50	1000	170.778	34949.1	604.055	173538	80.7986
50	1500	190.296	34176.9	434.766	174444	85.9116
50	2000	198.467	36213.9	444.434	171673	85.4866
50	2500	233.319	40393.8	241.187	158149	83.3681
50	3000	221.078	45035.6	523.559	159548	125.047
100	1000	128.344	54629.8	903.892	145929	71.073
100	1500	173.315	53056.8	680.247	148107	84.7768
100	2000	174.209	55178.8	693.596	145120	88.3328
100	2500	161.629	59385.2	694.123	139224	89.1428
100	3000	183.237	65081.1	794.984	131037	111.284
150	1500	174.365	73404	1096.47	118834	83.7887
150	2000	165.929	75414.2	1068.85	115983	96.4807
150	2500	148.948	80938.9	979.281	108165	82.8688
150	3000	211.031	88073.1	1062.75	98331.8	92.8624

APPENDIX C

Diesel Standard of Department of Energy Business

Table C1 Characteristic and quality of Diesel fuel (Department of Energy Business, 1997)

			Diesel		
Item	Description	Rates (low-high)	High Speed		Low speed
			Normal	B5	
1	Specific Gravity at 15.6 °C	Not lower than	0.81	0.81	-
		And not higher than	0.87	0.87	0.92
2	Cetane Number				
	or Calculated Cetane Index				
	Before January 1, 2012	Not lower than	47	47	45
	Form January 1, 2012	Not lower than	50	50	45
3	Viscosity, cSt				
	3.1 at 40 °C or	Not lower than	1.8	1.8	-
		And not higher than	4.1	4.1	8
	3.2 at 50 °C	Not higher than	-	-	6
4	Pour Point, °C	Not higher than	10	10	16
5	Sulphur, %wt.				
	Before January 1, 2012	Not higher than	0.035	0.035	1.5
	Form January 1, 2012	Not higher than	0.005	0.005	1.5
6	Copper Strip Corrosion	Not higher than	N. 1	N. 1	-
7	Oxidation Stability, g/m^3	Not higher than	-	25	-
8	Carbon Residue, %wt	Not higher than	0.05	0.05	-
9	Water and Sediment, %vol	Not higher than	0.05	0.05	0.3
10	Ash, %wt	Not higher than	0.01	0.01	0.02
11	Flash Point, °C	Not higher than	52	52	52
12	Distillation (90% recovered), °C	Not higher than	357	357	-
13	Polycyclic Aromatic Hydrocarbon, % wt				
	Before January 1, 2012	-	-	-	-
	Form January 1, 2012	Not higher than	11	11	-
14	Colour				
	14.1 Hue		-	Blue	-
	14.2 Dye , mg/L	Not lower than	-	7.0	-
	14.3 Intensity	Not lower than	-	-	4.5
		And not higher than	4.0	-	7.5
15	Methyl Ester of Fatty Acid, %vol	Not lower than	1.5	4	-
		And not higher than	2	5	-
16	Lubricity, µm	Not higher than	460	460	-
17	Additive	According to the regulation of Department of Energy Business			

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Publications:

1. M. Kananont, N. Chollacoop, S. Topaiboul, C. Charoenphonphanich and T. Kamimoto, "Investigations of Engine Performance, Combustion Characteristics and Emissions of a Direct-Injection Engine Using Neat Biodiesel," 2nd Thammasart University International Conference on Chemical, Environmental and Energy Engineering (TU-ChEEE 2009), March 3-4, 2009, Bangkok, Thailand.