Study on Performance and Emission Characteristics of Diesel Engines Using Ethanol-Blended Diesel Fuel

by

Muhammad Bin Ismail

Dissertation submitted in partial fulfilment of
the requirements for the
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CERIFICATION OF APPROVAL

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Approved by,

(Ir. Dr. Chalilullah Rangkuti)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
June 2004

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own concept as specified in the references and acknowledgements, and that the original work contained herein have not been under taken or done by unspecified sources or persons.

MUHAMMAD BIN ISMAIL

ABSTRACT

The objective of this project is to study the reliability of Ethanol-Diesel Blend Fuel, or 'E-diesel', as an alternative fuel source for diesel engines. The recommended E-diesel blend should be based on the study of performance and emission characteristics.

This study focused on two characteristics: *performance* and *emission.* In performance, BHP, torque, BMEP and BSFC via the combustion of ethanol-diesel blends in diesel engine are studied. As for emission, the amount of the combustion by-products, namely particulates matters (PM), carbon monoxide (CO) and nitrogen oxide (NOx) are studied.

In order to achieve the objectives, project planning using Gant chart has been developed. It started with Literature Study mainly on the underlying theories of E-diesel and diesel engine principles. Series of experiment has been performed to test various E-diesel blends (ranging between 5% v- to 25% v-ethanol) using Diesel Engine Test Bed, Particulate Matter Sampler and Exhaust Gas Analyzer. Then, analysis on the collected data has been conducted to come up with the best E-diesel blends.

Form the results obtained, E-diesel has proven its reliability as the alternative fuel source for diesel engines since it successfully reduced the emission by-product. But the engine performance seemed to increase slightly compared to diesel fuel. Furthermore, 15%-Ethanol blend has been recommended as the best blend in this project since it met almost all the criteria set for the evaluation purposes.

ACKNOWLEDGMENT

In the name of ALLAH, the Most Graceful and Most Merciful,

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Since Diesel Engine Emission Regulations seems to be more stringent each year, the permits level of engine emission became very crucial in the Automotive Industry. Global Environmental Bodies seems to go from Ultra-Low Emission Vehicles (ULEV) to Super Ultra-Low Emission Vehicles (SULEV), which permits only about 0.64 g/mile of carbon monoxide (CO), 0.56 g/mile of hydrocarbon (HC) + nitrogen oxides (NOx) and 0.05 g/mile of particulate matter (PM) emissions [1].

Therefore, there is a need for continuous improvement of new engine design to maximize fuel efficiency and reduce emissions, primarily PM and NOx. The emissions profiles of new and older engine can be improved through the use of a newly developed exhaust aftertreatment products, including catalytic converters. Moreover, the fuel itself can be oxygenated to increase combustion efficiency and thus reduce emissions. This is where alternative fuels such as Ethanol-Diesel, Biodiesel, CNG (compressed natural gas) and water-based blends are taken into considerations.

This study focused on the Ethanol-Diesel Blend Fuel, or so-called 'E-diesel', as the alternative fuel source for diesel engine. There are a lot of researches have been done worldwide in order to find the suitable blend for the diesel engines. But what makes this study different from the rest is that the mixture of the E-diesel will be purely ethanol and diesel fuel, no additives will be added. Furthermore, performance is also taken into consideration in determining the best blend instead of only reduction of exhaust emissions.

Upon completion of the study, the outcome will be what is the most suitable ratio of ethanol and diesel in E-diesel in terms of performance characteristic and emissions profiles. The recommended blend should also comply with current emission regulation with reduction of tailpipe exhaust emissions.

1.2 Problem Statement

E-diesel has been identified as a possible alternative source of fuel for diesel engines. Deep understanding of E-diesel itself and diesel engines principles are vital in order to determine how reliable this new fuel in diesel engines. The blend of ethanol in diesel fuels is the main study in this project whereby the best E-diesel blend should be the integration of performance and the emissions profiles. In addition, it also has to comply with the stringent Emission Standard Level practiced.

Series of laboratory experiments are expected to be done to test various blends of ethanol in diesel using the new Diesel Engine Test Bed in order to study the performance and Exhaust Gas Analyzer for the emission characteristics. This requires knowledge on how to operate the equipment, how to conduct the experiments, how to handle the blends and others.

The basic knowledge of underlying theories, including combustion reactions, combustions by-products and emission curves or profiles are important for the analysis of the experimental data collected.

1.3 Objectives of Study

The objectives of this study are: -

1. To study on the reliability of E-diesel as an alternative fuels source for diesel engines.
2. To perform a laboratory experiment for various ethanol-diesels blends using Diesel Engine Test Bed, Particulate Matter Sampler and Exhaust Gas Analyzer to study the performance and emissions characteristic.

3. To conduct analysis to recommend the best blend of ethanol and diesel in E-diesel with regards to the engine power output and reduction of tailpipe exhaust emissions.

1.4 Scope of Study

There are two directions from which this study is focused on; *performance* and *emission* characteristic. In performance characteristic, the trending of brake horsepower (BHP), torque, brake mean effective pressure (BMEP) and brake specific fuel consumption (BSFC) for various ethanol-diesel blends will be studied. And the emission characteristic will be concerning on the amount of combustion by-product, namely particulate matter (PM), carbon monoxide (CO), and nitrogen oxides (NOx) for various blends.

Literature study via books, journals, Internet, etc are conducted to gather information on the theories and to enhance understanding of the study. Laboratory experiments are performed to study the combustion and emission characteristic for various blends using Diesel Engine Test Bed, Exhaust Gas Analyzer and Particulate Mater Sampler. Collected data are analyzed theoretically and graphically using Microsoft Excel software. The integration of the outcome of the combustion and emission characteristic are used as the based to choose the best blend.

CHAPTER 2

LITERATURE REVIEW / THEORY

2.1 Why Ethanol?

One of the methods that can be used to reduce engine emission is to oxygenate the fuel or in other words to introduce oxygen molecule in the fuel [2]. There are many sources of chemicals that has oxygen molecule bounded in its chemical chain, i.e. pure oxygen gas O_2, alcohol, and others. In this project, alcohol is chosen as the sub-mixture to the diesel fuel because not only it has the oxygen molecule but the simplicity of both ethanol and diesel fuel to be blended or mixed. This is simply because both are in the hydrocarbon family. Furthermore, ethanol itself has the energy content that can contribute to the combustion process.

Since there are many types of alcohol, one specific type has to be selected for the study. The idea of the selection is to choose the less carbon-content alcohol in order to minimize the carbon-base combustion by-product. Comparing the first- and the second-class of ethanol family, methanol and ethanol, ethanol seems to have several advantages over methanol. It is far less corrosive and much safer fuel to handle, since it is the same chemical used in beverages. Ethanol also content 33% more energy than methanol, which is more economical in terms of the mileage effect over the blending cost. And in overseas, ethanol has been identified as a renewable fuel and is currently commercial produced for fuel blending purposes.

2.2 'E-Diesel'

Ethanol-Diesel, or so-called 'E-diesel', is an alternative fuel source for diesel engines. E-diesel is a blend of standard diesel fuel and ethanol combined with a propriety additive package. The additive allows diesel fuel and ethanol to mix stably and to maintain certain fuel properties, such as cetane number and lubricity. E-diesel is made by splash blending of diesel, ethanol and additives. No special mixing protocol or temperature control is required.

Compared to other alternative fuels such as Biodiesel, CNG (compressed natural gas) and water-based blends, E-diesel is believe to be the most practical solution to the immediate challenge of providing a reliable, easily implemented, cost-effective method of reducing tailpipe emission for today's Automotive Industry.

It has been proven through serial testing by several US-based Engine Manufacturer that E-diesel is capable to control pollution by significantly reducing tailpipe exhaust emissions, namely PM (particulate matter), CO (carbon monoxide) and NOx (nitrogen oxide). It also helps to extend petroleum feedstock supplies and promote sustainable development by using ethanol, a renewable resource. The use of ethanol reduces crude oil imports and result in lower contribution to greenhouse gasses.

A lot of researches have been done in order to find the suitable blend of E-diesel. Based on the research, the suitable blend is ranging between 10% to 15% of ethanol in diesel fuel depending on the additives added. Each company that produce E-diesel will have its own additives, which will varies the amount of ethanol to suit their specifications.

2.3 Performance Characteristics

The engine performance characteristics that are studied in this project are the brake horsepower (BHP), torque, brake mean effective pressure (BMEP) and brake specific fuel consumption (BSFC). All equation governed in this project are taken from Heywood John B. [3].

2.3.1 Brake Power and Torque

Engine torque is normally measured with dynamometer. The engine is clamped on a test bed and the shaft is connected to the dynamometer rotor. **Figure 2.1** illustrates operating principle of a dynamometer. The rotor is coupled electromagnetically, hydraulically, or by mechanical friction to a stator, which is supported in low friction bearings. The stator is balanced with the rotor stationary. The torque exerted on the stator with the rotor turning is measured by balancing the stator with weights, springs, or pneumatic means.

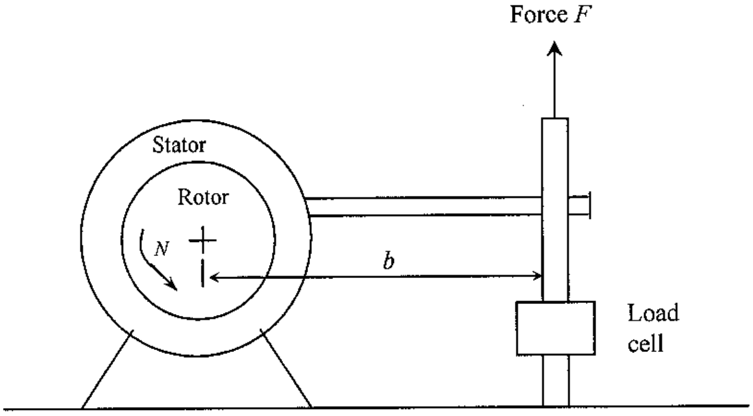

Figure 2.1: Schematic of principle of operation of dynamometer [3]

Using notation in **Figure 2.1**, if the torque exerted by the engine is T:

$$T = Fb \qquad [2.1]$$

The power P delivered by the engine and absorbed by the dynamometer is the product of torque and angular speed:

$$P = 2\pi NT \qquad [2.2]$$

Where N is the crankshaft rotational speed. In SI units:

$$P(kW) = 2\pi N({}^{rev}\!/_{s})T(N.m)\times 10^{-3} \qquad [2.3]$$

or in U.S. units: $$P(hp) = \frac{N(rev/\min)T(lbf.ft)}{5252} \qquad [2.4]$$

Note that torque is a measure of an engine's ability to do work; power is the rate at which work is done.

The value of engine power measured as described above is called *brake power* P_b. This power is the usable power delivered by the engine to the load-in this case, a "brake".

The typical *brake power* P_b versus engine speed (rpm) curve for diesel engine is shown in **APPENDIX 2-1**.

2.3.1.1 Brake Horse Power Correction Factor

The pressure, humidity and temperature of the ambient air induced into an engine, at a given sped, affect the air mass flow rate and the power output. Correction factors are used to adjust measured wide0open-throttle power output values to standard atmospheric conditions to provide more accurate basis for comparisons between engines.

The *Corrected Brake Horse Power* is given by,

$$P_{b,c} = C_F\, P_{b,m} \qquad [2.5]$$

where $P_{b,m}$ is the measured brake horse power and C_F is the Correction Factor, which can be determined by using this formula,

$$C_F = \frac{P_{s,d}}{P_m - P_v}\left(\frac{T_m}{T_s}\right)^{1/2} \qquad [2.6]$$

where $P_{s,d}$ is standard dry absolute pressure (= 736.6 mmHg), P_m is measured barometric pressure, P_v is measured ambient-water vapor pressure, T_m is measured ambient temperature and T_s is standard ambient temperature (= 29.4°C).

Measured ambient-water vapor pressure, P_v, can be calculated using this formula,

$$P_v = P_{v,sat} - \phi \qquad [2.7]$$

where ϕ is relative humidity and $P_{v,sat}$ is the saturation water vapor pressure, which can be determine from this equation,

$$\log_{10} P_{v,sat} = 8.10765 - \frac{1750.286}{T_m + 235.15} \qquad [2.8]$$

where T_m is measured ambient temperature.

2.3.2 Brake Mean Effective Pressure

While torque is a valuable measure of a particular engine's ability to do work, it depends on engine on engine size. A more useful relative engine performance measure is obtained by dividing the work per cycle by the cylinder volume displaced per cycle. The parameter so obtained has units of force per unit area and is called the *Brake Mean Effective Pressure* (BMEP).

$$Work/cycle = \frac{Pn_R}{V_d N} \qquad [2.9]$$

where n_g is the number of crank revolutions for each power stroke per cylinder (two for four-stroke cycles; one for two-stroke cycles), then

$$BMEP(kPa) = \frac{P(kW) n_R \times 10^{-3}}{V_d(dm^3) N(rev/s)} \qquad [2.10]$$

$$BMEP(lb/in^2) = \frac{P(hp) n_R \times 396{,}000}{V_d(in^3) N(rev/\min)} \qquad [2.11]$$

Brake mean effective pressure can also be expressed in terms of torque:

$$BMEP(kpa) = \frac{6.28 n_R T(N.m)}{V_d(dm^3)} \qquad [2.12]$$

$$BMEP(lb/in^2) = \frac{75.4 n_R T(lbf.ft)}{V_d(in^3)} \qquad [2.13]$$

The maximum *brake mean effective pressure* of good engine designs is well established, and is essentially constant over a wide range of engine sizes. Thus, the actual *BMEP* that a particular engine develops can be compared with this norm, and the effectiveness with which the engine designer has used the engine's placement required to provide a given torque or power, at specified speed, can be estimated by assuming appropriate values for *BMEP* for that particular application.

The typical *BMEP* versus engine speed (rpm) curve for diesel engine is shown in **APPENDIX 2-1.**

2.3.3 Brake Specific Fuel Consumption

In engine tests, the fuel consumption is measured as a flow rate – mass flow per unit time, $\dot{m}_f$. A more useful parameter that is used is the *Brake Specific Fuel Consumption* (BSFC) – the fuel flow rate per unit power output. It measures how efficiently an engine is using the fuel supplied to produce work: -

$$BSFC = \frac{\dot{m}_f}{P} \qquad [2.14]$$

and the unit in SI is $BSFC(mg/J) = \frac{\dot{m}_f(g/s)}{P(kW)}$ [2.15]

where $\dot{m}_f$ is the fuel mass flow per unit time and P is the power produced for the combustion of the fuel. In engine testing, the lowest values of *BSFC* are obviously desirable.

The typical best values of *BSFC* for gasoline engine and diesel engine are different. The best values of *BSFC* for diesel engine are lower than the gasoline engine and is about 55 µg/J = 200 g/kWh [3].

The measurement of the engine's efficiency is actually the ratio of the work produced per cycle to the amount of the fuel energy supplied per cycle that can be released in the combustion process. The fuel energy supplied, which can be released by combustion, is given by the mass of fuel supplied to the engine per cycle times the heating value of the fuel: -

$$\text{Fuel energy supplied} = m_f Q_{HV} \qquad [2.16]$$

The heating value of fuel, Q_{HV}, defines its energy content. Typical heating values for the commercial hydrocarbons fuels used in engine are in the range of 42 to 44 MJ/kg (1,000 to 19,000 Btu/lbm) [3].

The measurement of an engine's 'efficiency', which will be called the *Fuel Conversion Efficiency*, η_f, is given by: -

$$\eta_f = \frac{W_c}{m_f Q_{HV}} = \frac{P}{\dot{m}_f Q_{HV}} = \frac{1}{bsfc Q_{HV}} \qquad [2.17]$$

where m_f is the mass of fuel inducted per cycle.

Thus, it can be seen that brake specific fuel consumption is inversely proportional to fuel conversion efficiency for normal hydrocarbon fuels.

The typical *BSFC* versus engine speed (rpm) curve is shown in **APPENDIX 2-1.** At a certain rpm, the fuel consumption is at the minimum where the amount of fuel that is consumed during the combustion process produced the maximum power output. The curve's characteristic can varies depends on various engine's parameters, such as type of fuel injection used, injection timing, valve timing, number of valves, etc.

2.4 Emission Chracteristics

The combustion processes that occur in each type of engines are very different. As for compression ignition engine or 'diesel engines', it has a separate fuel and air streams that combust as they are mixed together. The chemical reaction, which produces a diffusion flame, takes place at the interface between the fuel and the air. The heat release begins at a relatively high value and then decreases as the available oxygen is depleted.

The main combustion products from internal combustion engine emissions are namely nitrogen oxide (NOx), carbon monoxide (CO), hydrocarbons (HC) and particulates (PM). These products are a significant source of air pollution. Internal combustion engines are the source of roughly half of the NOx, CO and HC pollutants in our air. For example, NOx reacts with water vapor to form nitric acid, and reacts with solar radiation to form ground level ozone, both of which cause respiratory system problems. And hydrocarbons can cause cellular mutations and also contribute to the formation of ground level ozone too.

2.4.1 Nitrogen Oxides

Nitrogen oxides (NOx) are formed throughout the combustion chamber during the combustion process due to the reaction of atomic oxygen and nitrogen. The reactions forming NOx are very dependent on temperature, so the NOx emissions from the engine scale proportionally to the engine load and NOx emissions are relatively low during engine start and warm-up.

The reaction mechanism the produced NO is called "Zeldovich mechanism'[3], in which NO is formed in the high temperature burned gases left behind by the flame front. The prompt mechanism occurs within the flame front, and is relatively small if the volume of the high temperature burned gases is much grater the instantaneous volume of the flame front, as is usually the case in internal combustion engines.

The chemical reactions [3] are:-

$O + N_2 ==== NO + N$, a nitrogen dissociation reaction triggered by an oxygen atom. This reaction is endothermic.

$N + O_2 ==== NO + O$, a nitrogen atom reacts exothermically with an oxygen molecule to form nitric oxide and an oxygen atom.

$N + OH ==== NO + H$, an exothermic reaction between a nitrogen atom and a hydroxide radical which forms nitric oxide and a hydrogen atom.

2.4.2 Carbon Monoxide

Carbon monoxide appears in the exhaust of rich-running engines since there is insufficient oxygen to convert all the carbon in the fuel to carbon monoxide. The most important engine parameter influencing carbon monoxide emissions is the fuel-air equivalence ratio.

The chemical reaction for combustion when air is insufficient,

$$C_nH_n + O_2 \longrightarrow CO_2 + H_2O + CO$$

Form the reaction, it can be clearly seen that carbon monoxide will be produced when insufficient air or 'oxygen' is drawn into the combustion chamber. Lacks of oxygen will only permits the carbon atoms to combine with only one oxygen atom to produce CO instead of two which sill produce CO_2.

For fuel-rich mixture, CO concentrations in the exhaust increase steadily with increasing of fuel-to-air ratio since the amount of excess fuel increases. And for fuel-lean mixture, CO concentrations in the exhaust vary little with the fuel-to-air ratio. Since diesel engines run lean overall, their emissions of carbon monoxide are low and generally not considered a problem. It does appear the direct-injection diesel engines emit relatively more CO than indirect-injection diesel engines.

2.4.3 Particulate Matter

Diesel particulates consist principally of combustion generated carbonaceous material (soot), on which some organic compounds have become absorbed. Most particulate material results from incomplete combustion of fuel hydrocarbons.

The composition of the particulate material depends on the condition in the engine exhaust and particulate collection system. At temperatures above 500°C, the individual particles are principally clusters of many small spheres of carbon. As temperature decreases, the particles become coated with absorbed and condensed high molecular weight organic compounds which include: unburned hydrocarbons, oxygenated hydrocarbons and polynuclear aromatic hydrocarbons. Smoke also forms in diesel engines because diesel engines combustion is heterogeneous.

The rate amount of particulate matter produced can be determined by,

$$PM\ (g / bhp - hr) = \frac{m_{d,PM}}{P_{bhp} t_s} \qquad [2.18]$$

where $m_{d,PM}$ is dry mass of particulate matter, P_{bhp} is brake horse power and t_s is sampling time.

2.5 Expected E-Diesel Results

The results of engine performance obtained by using 100% diesel fuel will be the benchmarking for the E-diesel fuel. Based on the findings, there would be a slight difference in the trending of the performances curve or the E-diesel fuel as compared with the 100% diesel fuel may be due to the existing of ethanol in the diesel fuel.

For the torque developed and the brake horse power, the expected curve trending would be same but the values would be a slight lesser than the result obtained using 100% fuel. This is due to the lower energy content of the E-diesel fuel since ethanol has less energy content than diesel. This expected trending would be also expected for the brake mean effective pressure curve since brake horse power has a direct proportional relationship with the brake mean effective pressure.

As for the brake specific fuel consumption, the curve trending that is expected will be the same but the values will be slightly higher compared to the 100% diesel. This is also due to the lower energy content of the E-diesel fuel since ethanol has less energy content than diesel. In order to coup up or maintain the power output, more E-diesel fuel has to be burn so that the energy produced via the combustion process is also maintained. It is expected the brake specific fuel consumption will be increased about 3% to 5%.

In this study, various blends of E-diesel fuels will be tested with the similar procedure. For each blend, it is expected that the more ethanol percentage exist in the diesel fuel, the values of torque developed, brake horse power and brake mean effective pressure will decrease accordingly. Whereas the brake specific fuel consumption trending will increase accordingly.

As for emission profiles, it is expected that the amount of exhaust gases, namely CO and NOx will decrease with additional of ethanol in diesel fuel. This is because more oxygen molecules are added into the fuel mixture which could increase the efficiency of combustion towards complete combustion. Since NOx formation is much likely influence by the combustion temperature, with reduction in energy content due to the introduction of ethanol in diesel fuel, the heat release by the combustion process will also likely to be decrease, which may result in reducing of engine temperature. This will surely reduce the NOX production.

Another exhaust by-product that is considered in this project is Particulate Matter (PM). Mixing diesel fuel with ethanol will much likely oxygenate the fuel and more oxygen molecule is present. Thus, more complete combustion can take part and instead of carbon particles are produced, it will react with oxygen to form CO_2. This will results in less PM produced as well as soot or smoke.

2.6 Summary

From this Chapter, why ethanol is chosen as the mixture for diesel fuel in this project has been explained. The best of E-diesel blend that would be achieved in this project is expected to be in range of 5% to 25% of ethanol since no additive is considered in this project. Thus various blends within this range of ethanol will be tested in order to study the performance and emission characteristics.

The performance characteristics that are focused on this study is *brake horsepower (BHP)*, *torque*, *brake mean effective pressure (BMEP)* and *brake specific fuel consumption (BSFC)*. The emission characteristics are focused on the main hazardous engine tailpipe gaseous: *nitrogen oxides (NOx)*, *carbon monoxides (CO)* and *particulate matter (PM)*.

CHAPTER 3

METHODOLOGY / PROJECT WORK

3.1 Procedure Identification

Step-by-step procedures have been done as to meet the objectives of this project such as literature study, laboratory experiments, analysis of experimental data and project work timeline or Gantt chart.

3.1.1 Literature Study

Literature study has been done on the underlying theory of internal combustion, performance and emission profiles, diesel engine principles, E-diesel Blends, etc. (sources: books, journals, articles, web pages and laboratory procedure).

3.1.2 Laboratory Experiments

Series of laboratory experiments have been conducted in order to test various blends of ethanol and diesel (ranging between 5% to 25% of ethanol in diesel) using Diesel Engine Test Bed and Exhaust Gas Analyzer. The interests of these experiments are the performance characteristic, combustion by-products and emission profiles. The detailed laboratory procedures are explained in **Section 3.3.**

3.1.3 Analysis of Experimental Data

Analyses of the experimental data are performed in order to come out with the best E-diesel blends with regards to the engine performance and reduction of tailpipe exhaust emissions. Some graphical analysis using Microsoft Excel has been plotted to exhibit the findings and comparisons of the various blends.

3.1.4 Gantt Chart

Gantt chart is used for project monitoring purposed to ensure the smoothness of the study. The project is divided into two semesters and there are several milestones to be completed.

3.2 Material Required

Some materials are used to perform laboratory experiment on various blends of E-diesel in order to study the performance and emissions characteristics. Analyses of these characteristics are based on the data collected throughout the laboratory experiments.

3.2.1 Experiment Equipment

Several testing equipment are used to conduct the laboratory experiments – Diesel Engine Test Bed, Exhaust Gas Analyzer and Particulate Matter Sampler.

3.2.1.1 Diesel Engine Test Bed

Diesel Engine Test Bed (refer **Figure 3.1**) is used to study on the performance characteristics. The specifications of this equipment are shown in **Table 3.1**.

Table 3.1 - Diesel Engine Test Bed specifications [4]

Manufacturer	Ford Motor Company Ltd.
Model	XLD 418
Engine Type	Diesel, 4 cylinder, in-line OHC, indirect injection
Compression Ratio	21.5:1
Cubic Capacity	1753 cc

Source: *XLD 418 Engine – P8621 Diesel Engine: Instruction Manual*

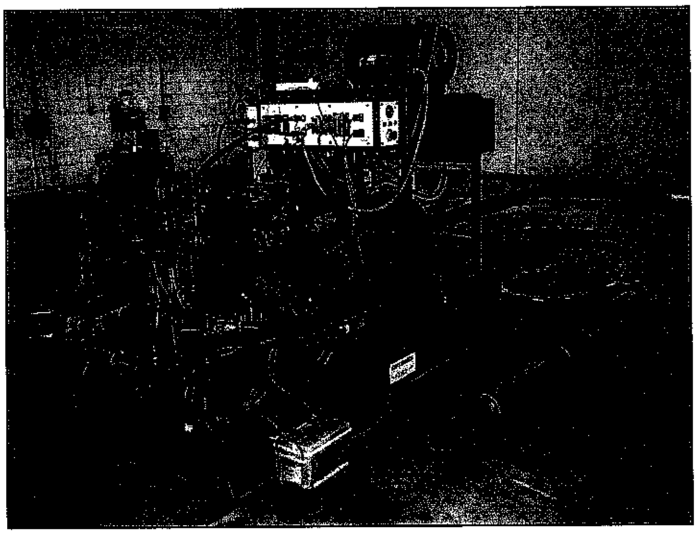

Figure 3.1 – Diesel Engine Test Bed

3.2.1.2 Exhaust Gas Analyzer

Exhaust Gas Analyzer (refer **Figure 3.2**) is used to study the emission characteristic. It detects the type and amount of emission gaseous from the Diesel Engine Test Bed exhaust. The specifications of this equipment are shown in **Table 3.2**.

Table 3.2 - Exhaust Gas Analyzer specifications [5]

Manufacturer	TELEGAN GAS MONITORING LIMITED
Model	TEMPEST 100
Ambient Operating Temperature	0° to 40°C
Detectable Gas	Oxygen (O_2) Carbon Monoxide (CO) Carbon Dioxide (CO_2) Nitrogen Oxide (NOx) Sulfur Dioxide (SO_2) – require upgrade Hydrogen Sulfide (H_2S) – require upgrade

Source: Tempest 100 – Exhaust Gas Analyzer Manual

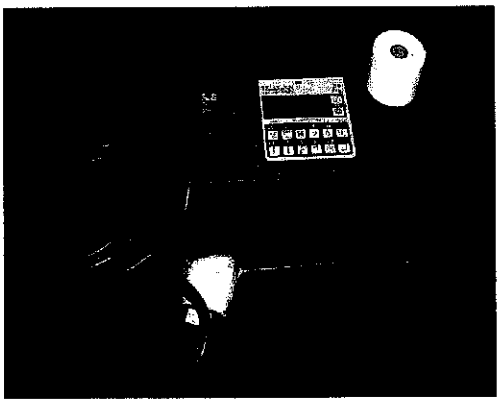

Figure 3.2 – Exhaust Gas Analyzer

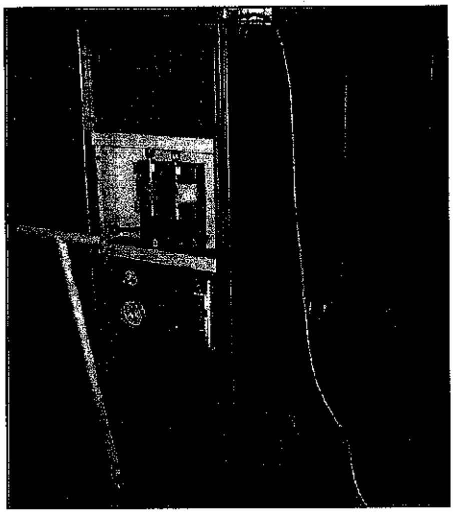

Figure 3.3 – Particulate Matter Sampler

3.2.1.3 Particulate Matter Sampler

Particulate Matter Sampler (refer **Figure 3.3**) is used to collect the amount of particulate matter produced form Diesel Engine Test Bed exhaust. The specifications of this equipment are shown in **Table 3.3**.

Table 3.3 - Particulate Matter Sampler specifications [6]

Manufacturer	Oliver IGD Limited
Model	P 1810 – Particulate Sampler
System Controller	PLC (Programmable Logic Control)
Exhaust Gas Temperature	< 52°C

Source: P 1810 – Particulate Sampler Manual

3.2.2 Supplies

Supplies that are used in this study are Diesel Fuel and Ethanol. Ethanol is mixed with diesel fuel in specified percentage of volume to form E-diesel. Diesel fuel used in this study is a standard No. 2 diesel fuel purchased from PETRONAS petrol stations. Ethanol specifications are shown in **Table 3.4**.

Table 3.4 - Ethanol specifications

Manufacturer	HmbG Chemicals
Chemical	Ethanol absolute (C_2H_6O)
Purity	99.8 vol%

3.2.3 Computer Software

Computer software used in this project is Microsoft Excel. It is used to tabulate the experimental data collected and generate graphs. AutoTest4 Software is also used to log the data from the Diesel Engine Test Bed. This software is dedicated for the equipment.

3.3 Experimental Methodology

The procedures for conducting the experiments are listed below. It is important to follows the step carefully in order to archive an accurate data and also for safety reasons.

3.3.1 Ethanol-diesel Blending

Based on the research done, there is no specific method or protocol required to blend the ethanol and diesel fuel. These two materials can be simply mixed together in a container.

Ethanol and diesel are mixed in volumetric-base. For example, 5% ethanol means that for 10L of ethanol-diesel mixture, 0.5L is ethanol whereas the rest is diesel fuel.

In this project, the mixture that will be tested is only 5%- up to 25%- ethanol with incremental of 5%. This range of ethanol in E-diesel fuel is chosen because from the preliminary research, the optimum or the best blend of E-diesel is about 10%- to 20%- ethanol.

3.3.2 Laboratory Experiment Procedures

In this project, testing equipments listed previously are used to study the performance and emission characteristics. Several step-by-step procedures are practiced in order to obtain an accurate result. Experimental procedures for each equipment are listed as follows:-

3.3.2.1 Diesel Engine Test Bed

The desired data from this experiment is the performance characteristics: *BHP*, *Torque*, *BSFC* and *BMEP*.

Procedures: -

(1) Fill fuel tank with ethanol-diesel blend fuel (100% diesel fuel).
(2) Run AutoTest 4 Software on the computer provided.
(3) Perform pre-start check on the engine is to ensure all the items are within appropriate level to prevent any damage to the engine.
    - Lube oil pressure and temperature
    - Water pressure and temperature
    - Coolant and fuel level
(4) In the software, select *Part_Load_Test*.
(5) Start the engine and let it warm up for 5 minute for better and more accurate readings.
(6) Select *Manual_Interuption*.
(7) In the *Manual_Interuption* task bar, set engine speed to 1000 rpm.
(8) Let the engine run for about 5 minutes. Record required parameters from the software interface provided (refer **Figure 3.4**).
(9) Then, increase the engine speed by 500 rpm.
(10) Repeat step (8) and (9) until engine speed reaches 5000 rpm.
(11) Slowly ramp down engine to 1000 rpm.
(12) Stop engine and let it cool down.
(13) Analyze and discuss on the collected data.
(14) Repeat this experiment for 5%, 10%, 15%, 20% and 25% E-diesel blends.

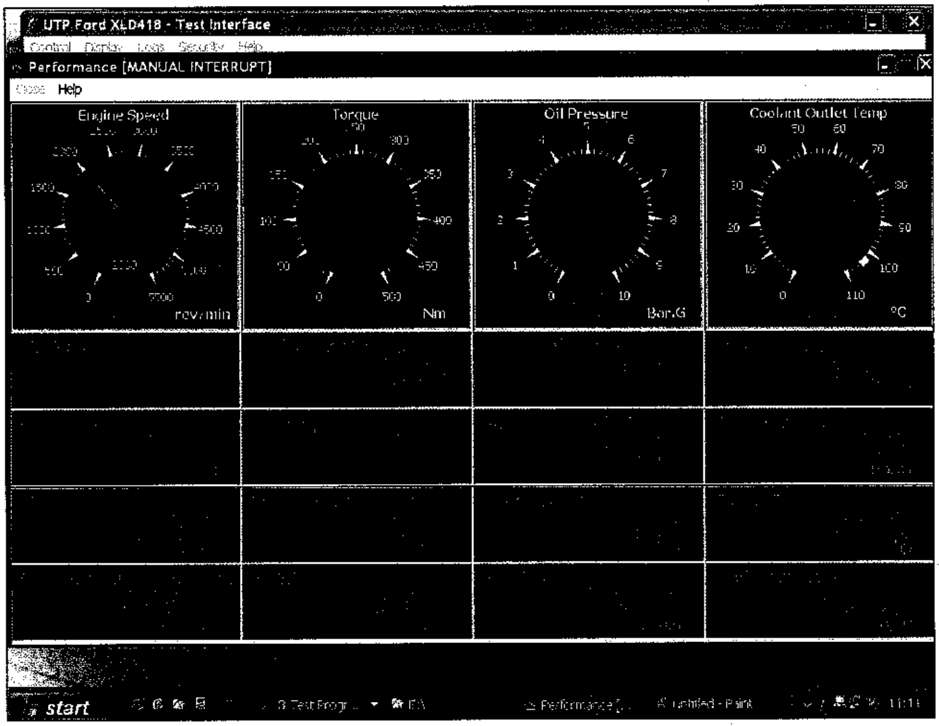

Figure 3.4 – Example of AutoTest 4 Software interface

3.3.2.2 Exhaust Gas Analyzer

The desired data from this experiment are the emission profiles of NOx and CO gas for various blends of E-diesel from Diesel Engine Test Bed exhaust pipe.

<u>Procedures:-</u>

(1) The content supply must be checked in a good condition. The analyzer parts should be assembled properly.

(2) Switch on the analyzer.

(3) The analyzer will display a 30 seconds stabilizing sequence. Let the sequence completed.

(4) The pump should be ensured running.

(5) The battery level should be checked. It is advisable to be above 40% or else it should be charged.

(6) The probe then must be paced at the end tip of the engine exhaust pipe.

(7) Set the engine speed to 1000 rpm. Let it stable.

(8) Press the data button to capture the emission data. The analyzer would give out the emission concentration level.

(9) Wait until the reading becomes stable (about 10 minutes). Record desired data.

(10) Increase engine speed to 2000 rpm. Repeat step (7) to (9) until engine speed reaches 5000 rpm.

(11) Tabulate all readings obtained and analyze the result.

3.3.2.3 Particulate Matter Sampler

The desired data from this experiment is the amount of particulate matter mass produce from the exhaust gas.

Procedures: -

(1) Check all host is tightly connected.

(2) Switch on the air compressor and the equipment main switch.

(3) Press leak test button to check for leakage.

(4) Insert filter paper into the filter slot and lock the filter slot.

(5) Press the filter sampling button and wait for 15 minutes. Let the machine collect the sample.

(6) Then press standby button to stop sampling process.

(7) Open the filter slot and take out the filter sample.

(8) Weight the filter sample using Micro-Weight Measuring Machine (refer **Figure 3.5**) and calculate the mass of particulate matter.

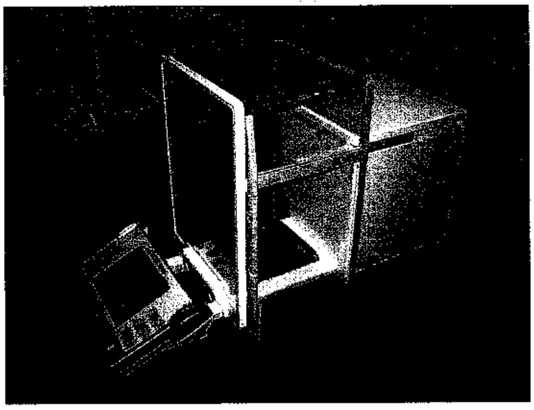

Figure 3.5 – Micro-Weight Measuring Machine

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Diesel Engine Test Bed Reliability

Before proceeding to the laboratory experiment, it is important to justify whether the testing equipment – Diesel Engine Test Bed is reliable enough in terms of obtaining the accurate data for performance characteristic. Therefore, a pre-experiment has been done to determine the reliability of this equipment.

4.1.1 Pre-Experiment

Pre-experiment has been performed on Diesel Engine Test Bed using 100% diesel fuel. Step-by-step procedures (as explained in **Section 3.3.2**) have been conducted and the raw data obtained from this experiment are recorded and tabulated in **APPENDIX III.**

4.1.1.1 Results

Based on the experimental data obtained in **APPENDIX 4-1**, performance characteristics curves – *Brake Horse Power (BHP)*, *Brake Mean Effective Pressure (BMEP)* and *Brake Specific Fuel Consumption (BSFC)* – are plotted, as shown in **Figure 4.1**. The curves obtained are compared with the theoretical curves taken from Heywood John B., *Internal Combustion Engine Fundamentals* [3] as shown in **Figure 4.2**.

4.1.1.2 Conclusion

From the results, it shows that the performance curves that are obtained are quite similar to the theoretical curves. Thus it can be said that the Diesel Engine Test Bed is reliable and can be used for further experiments practice in this project.

4.2 Performance Characteristics

Various blends of E-diesel, ranging between 5% v- to 25% v- ethanol, have been successfully tested for the performance characteristics – BHP, torque, BMEP and BSFC – using Diesel Engine Test Bed. The raw data captured from AutoTest 4 Software for all blends – 5% v-, 10% v-, 15% v-, 20% v- and 25% v- are tabulated in **APPENDIX 4-2** until **4-6** respectively. Comparisons between E-diesel blends for each of the parameters are as follows:-

4.2.1 Brake Horse Power (BHP)

The raw data captured by AutoTest 4 Software are uncorrected BHP. In order to achieve a more accurate data for better comparison, the obtained values are corrected using **Equation 2.5** until **2.8** as listed in **Section 2.3.1**. The sample calculations are attached in **APPENDIX 4-7**.

Corrected BHP values for each blend are tabulated in **Table 4.1** below:-

Table 4.1 – Corrected BHP values for various E-diesel blends

Engine Speed (rpm)	**Corrected BHP (hp)**					
	100% Diesel	**% Ethanol in Diesel Fuel**				
		5%	**10%**	**15%**	**20%**	**25%**
1000	10.04	9.35	8.90	8.54	8.39	7.89
1500	17.24	15.53	15.34	14.68	14.17	13.48
2000	25.74	23.16	22.95	21.97	21.24	20.08
2500	34.95	31.48	31.20	29.78	27.92	27.38
3000	39.59	35.59	35.41	33.73	32.02	30.89
3500	45.30	40.92	40.59	38.51	36.83	35.31
4000	48.48	43.77	43.62	41.26	39.42	37.79
4500	52.47	47.23	47.22	44.70	42.14	40.89
5000	52.06	46.93	46.90	44.27	42.48	40.68

Based on the data shown in **Table 4.1**, Corrected BHP (hp) against engine speed (rpm) curves are plotted for each E-diesel blends, as shown in **Figure 4.3**.

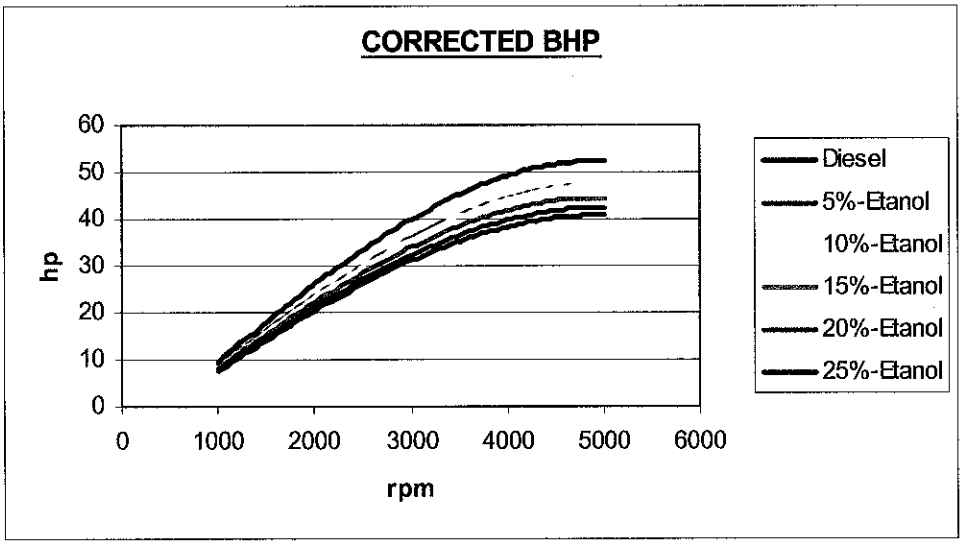

Figure 4.3 – Corrected BHP vs. engine speed for various E-diesel blends

From **Figure 4.3**, it can be seen that the power output from the diesel engine combustion process increased with increase in engine speed. Basically, more complete cycles have been done by the engine within a specific period of time. This surely increased the power cycles performed by the engine, thus more power output are developed.

Although the brake horse power increased with engine speed, it also can be seen that the degree of increment declined gradually and towards the engine maximum rpm, the power output seems to maintain with increase in engine speed. This might be related to the power output formula where power output is a function of torque developed, Nm and the engine speed, rpm. Based on **Figure 4.4**, initially torque increased with engine speed until it reaches a maximum value at about 2500 rpm and then it will drop. This is why power output increased quite rapidly at the first 2500 rpm. After that, although the engine sped increased, the torque started to decrease, thus the slope of power output declined gradually with engine speed. But the power outputs still remain increased as the increase in engine speed is relatively higher than the decrease in torque developed.

BHP curve for 100 % Diesel fuel are plotted for the basis of comparison between various blends of E-diesel. As shown in **Figure 4.3**, the BHP curves for all blends exhibit a similar trending as the 100% Diesel fuel although the power output decreased with increase in volume of ethanol in diesel fuel, from 5% v- to 25% v-.

The percentage of reduction in power output for the E-diesel compared to the 100% Diesel fuel is shown in **Table 4.2**.

Table 4.2 - Percentage reduction of BHP for various E-diesel blends

Engine Speed (rpm)	**% Reduction of BHP (hp)**				
	% Ethanol in Diesel Fuel				
	5%	**10%**	**15%**	**20%**	**25%**
1000	6.89	11.36	14.95	16.44	21.40
1500	9.90	11.01	14.84	17.79	21.83
2000	10.04	10.86	14.66	17.49	22.00
2500	9.93	10.73	14.79	20.12	21.65
3000	10.12	10.56	14.81	19.13	21.97
3500	9.68	10.39	14.99	18.70	22.06
4000	9.73	10.03	14.90	18.69	22.06
4500	9.99	10.00	14.82	19.69	22.07
5000	9.85	9.91	14.97	18.40	21.86
Avg %	**9.57**	**10.54**	**14.86**	**18.49**	**21.88**

Based on **Table 4.2**, the average percentage reduction of BHP increased as more ethanol volume is added into diesel fuel, from 10% for 5% v- to 22% for 25% v-. This is mainly because of the energy content of ethanol which is much less than diesel fuel. As more ethanol volume present in diesel fuel, the total energy content of the mixture will decrease. Thus, the energy released through the combustion process, which is converted into the power output, will be decreased.

4.2.2 Torque

The values for torque developed for each blend are tabulated in **Table 4.3**. Based on the values obtained, Torque (Nm) against engine speed (rpm) curves are plotted for each E-diesel blends, as shown in **Figure 4.4**.

Table 4.3 – Torque values for various E-diesel blends

Engine Speed (rpm)	Torque (Nm)					
	100% Diesel	% Ethanol in Diesel Fuel				
		5%	10%	15%	20%	25%
1000	71	67	64	61	58	56
1500	81	78	74	69	66	63
2000	90	85	82	78	74	71
2500	91	88	84	81	78	74
3000	90	86	82	80	77	74
3500	88	85	81	77	75	72
4000	84	82	78	75	71	67
4500	81	77	74	69	66	63
5000	72	70	68	65	62	59

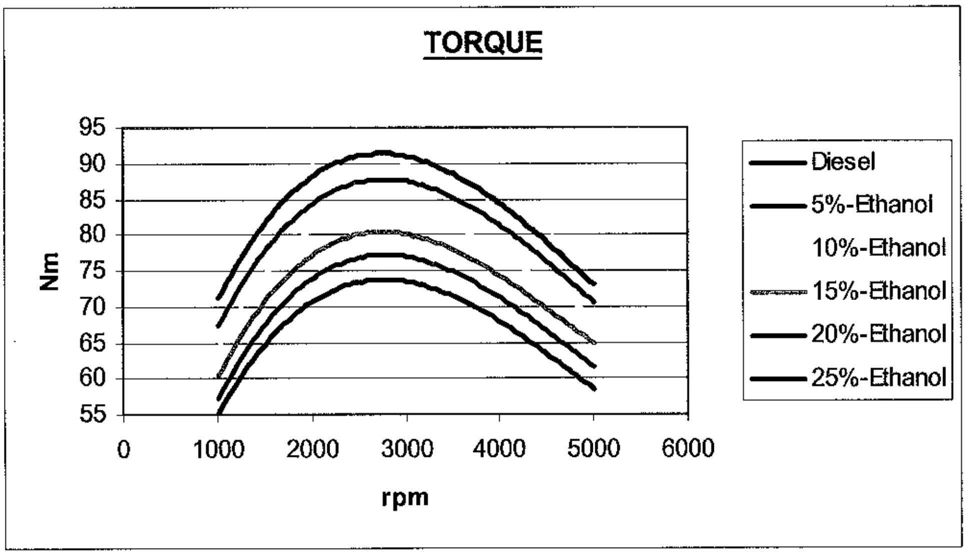

Figure 4.4 – Torque vs. engine speed for various E-diesel blends

Based on **Figure 4.4**, initially torque developed increased with increase in engine speed until it reaches a maximum value, which is about 2500 rpm. And after that, the torque started to decrease gradually with increased in engine speed. This is due to aerodynamic friction (air flow inlet and outlet of cylinder) and mechanical friction (between piston and cylinder wall). At low speed, the pressure developed on the piston head due to combustion process can easily overcome both frictions to produce torque. Although torque increased with engine speed, the degree of increment is decreasing since the frictions increase with engine speed. At high speed, the frictions are greater compared to the pressure developed. Aerodynamic friction cause less air to enter the combustion chamber thus less complete combustion occurred. As a result, torque seems to decrease gradually with engine sped.

Also exhibited in **Figure 4.4** are the comparisons of torque curves developed by using 100% Diesel fuel until 25% v- E-diesel blend. Although the trending of the curves obtained are similar to each other, there are a slight decreased in torque developed when more volume of ethanol is added into diesel fuel. The percentage reduction of torque developed for various blends of E-diesel are depicted in **Table 4.4** below.

Table 4.4 - Percentage reduction of torque for various E-diesel blends

Engine Speed (rpm)	**% Reduction of Torque (Nm)**				
	% Ethanol in Diesel Fuel				
	5%	**10%**	**15%**	**20%**	**25%**
1000	5.63	9.86	14.08	18.31	21.13
1500	3.70	8.64	14.81	18.52	22.22
2000	5.56	8.89	13.33	17.78	21.11
2500	3.30	7.69	10.99	14.29	18.68
3000	4.44	8.89	11.11	14.44	17.78
3500	3.41	7.95	12.50	14.77	18.18
4000	2.38	7.14	10.71	15.48	20.24
4500	4.94	8.64	14.81	18.52	22.22
5000	2.78	5.56	9.72	13.89	18.06
Avg %	**4.02**	**8.14**	**12.45**	**16.22**	**19.96**

Based on **Table 4.4**, the average percentage reduction of torque developed increased as more ethanol volume is added into diesel fuel, from 4% for 5% v- to 20% for 25% v-. Similar to BHP, this is caused by the lower energy content of ethanol compared to diesel fuel. As more ethanol volume present in diesel fuel, the total energy content of the mixture will decrease. Thus, the energy released through the combustion process, which is also converted into the torque, will be decreased.

4.2.3 Brake Mean Effective Pressure (BMEP)

Another parameters that is taken into consideration in evaluating the performance characteristics is the brake mean effective pressure.

The values for BMEP captured by AutoTest 4 Software are tabulated for each blend of E-diesel (refer **Table 4.5**).

Table 4.5 – BMEP values for various E-diesel blends

Engine Speed (rpm)	BMEP (kPa)					
	100% Diesel	% Ethanol in Diesel Fuel				
		5%	10%	15%	20%	25%
1000	507	482	467	448	425	407
1500	581	552	523	494	476	453
2000	640	608	579	544	517	497
2500	648	616	586	558	531	506
3000	646	614	581	550	530	503
3500	642	610	579	543	526	497
4000	602	572	548	520	498	476
4500	578	548	520	491	474	451
5000	518	494	473	453	425	404

Based on the BMEP values shown in **Table 4.5**, BMEP (kPa) against engine speed (rpm) curves are plotted for each E-diesel blends, as shown in **Figure 4.5**.

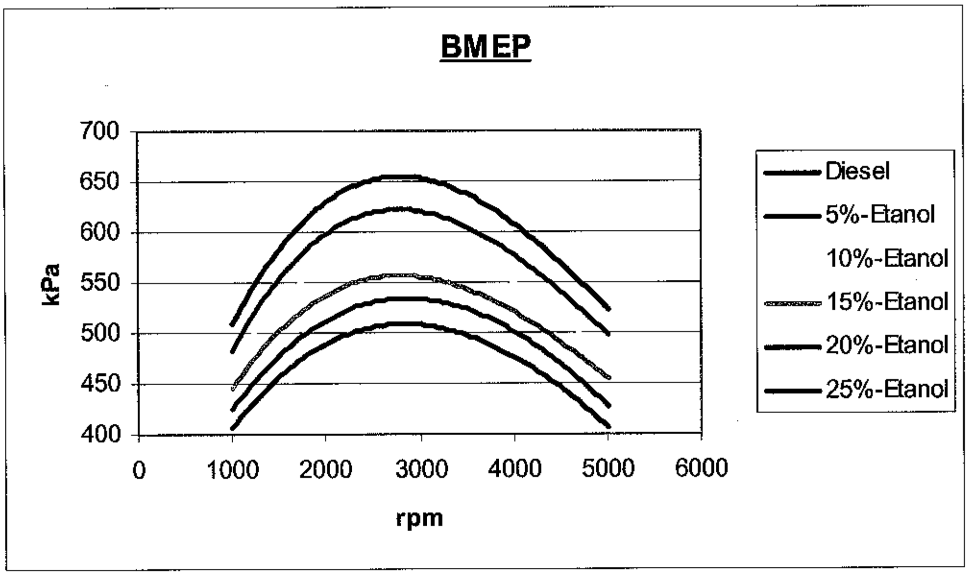

Figure 4.5 – BMEP vs. engine speed for various E-diesel blends

Based on **Figure 4.5**, initially BMEP increased with increase in engine speed until it reaches a maximum value, which in this experiment it occurs at about 2500 rpm. And after that, the BMEP values started to decrease gradually with increased in engine speed.

The trending of BMEP curves obtained is quite similar to the torque curves. This is because BMEP has a direct proportional relationship with torque developed as shown in **Equation 2.12** (see **Section 2.3.2**).

Figure 4.5 also shows the BMEP curves obtained for various E-diesel blends. The trending of the curves obtained are quite similar to each other although there are a slight decreased in BMEP as more percent of ethanol volume is added into the blends.

The percentage of reduction in BMEP for the E-diesel compared to the 100% Diesel fuel is shown in **Table 4.6**.

Table 4.6 - Percentage reduction of BMEP for various E-diesel blends

Engine Speed (rpm)	**% Reduction of BMEP (kPa)**				
	% Ethanol in Diesel Fuel				
	5%	**10%**	**15%**	**20%**	**25%**
1000	4.93	7.89	11.64	16.17	19.72
1500	4.99	9.98	14.97	18.07	22.03
2000	5.00	9.53	15.00	19.22	22.34
2500	4.94	9.57	13.89	18.06	21.91
3000	4.95	10.06	14.86	17.96	22.14
3500	4.98	9.81	15.42	18.07	22.59
4000	4.98	8.97	13.62	17.28	20.93
4500	5.19	10.03	15.05	17.99	21.97
5000	4.63	8.69	12.55	17.95	22.01
Avg %	**4.96**	**9.39**	**14.11**	**17.86**	**21.74**

Based on **Table 4.6**, the average percentage reduction of BMEP increased as more ethanol volume is added into diesel fuel, from 5% for 5% v- to 22% for 25% v-. The results obtained are much likely influenced by the torque curves achieved due to the relationship discussed earlier.

4.2.4 Brake Specific Fuel Consumption (BSFC)

Table 4.7 summarized the values of BSFC obtained from the experiments for each blends of E-diesel fuel.

Table 4.7 – BSFC values for various E-diesel blends

Engine Speed (rpm)	BSFC (g/kW-hr)					
	100% Diesel	% Ethanol in Diesel Fuel				
		5%	10%	15%	20%	25%
1000	292	297.8	303.4	309.5	315.4	320.2
1500	283.8	289.5	295.2	300.8	306	311.4
2000	276.2	281.6	287.2	293	298.3	303.8
2500	273	278.5	283.9	289.4	294.8	300.3
3000	278.6	284.2	289.7	295.3	301	306.5
3500	286.3	292	297.8	303.5	309.2	314.9
4000	298	303.9	309.5	315.9	321.6	327.8
4500	309.7	315.8	322	328.3	334.2	341.3
5000	338.4	345.2	351.7	358.7	365.8	372.3

Like other parameters, the BSFC values depicted in **Table 4.7** are used to plot the BSFC (g/kW-hr) against engine speed (rpm) curves for each E-diesel blends, as shown in **Figure 4.6**.

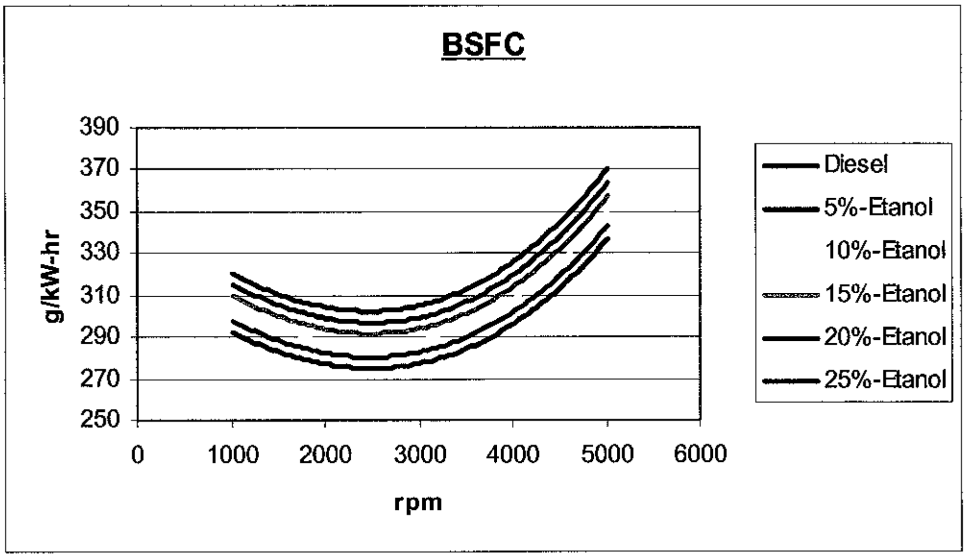

Figure 4.6 – BSFC vs. engine speed for various E-diesel blends

Based on **Figure 4.6**, BSFC curves obtained has a mirror-effect with torque and BMEP curves achieved. Initially, BSFC decreased with increase in engine speed until it reaches minimum value, which in this experiment it occurred at about 2500 rpm. After that, as the engine speed increased, BSFC also increased because when the engine is running at a high speed, more fuel is consumed to produce power and torque.

The minimum point of BSFC obtained shows that at a specific engine speed, which is 2500 rpm, the amount of fuel that is consumed during the combustion process are fully utilized to produce the maximum power output.

Also shown in **Figure 4.6** are the BSFC curves obtained for various blends of E-diesel compared to the 100% Diesel fuel. The curves trending are similar to each other although there are slight increase in BSFC values obtained as more ethanol volume is added into the diesel fuel.

The percentage of increase in BSFC for various blends of E-diesel compared to the 100% Diesel fuel are shown in **Table 4.8**.

Table 4.8 - Percentage increment of BSFC for various E-diesel blends

Engine Speed (rpm)	**% Increment of BSFC (g/kW-hr)**				
	% Ethanol in Diesel Fuel				
	5%	**10%**	**15%**	**20%**	**25%**
1000	1.95	3.76	5.65	7.42	8.81
1500	1.97	3.86	5.65	7.25	8.86
2000	1.92	3.83	5.73	7.41	9.08
2500	1.97	3.84	5.67	7.39	9.09
3000	1.97	3.83	5.66	7.44	9.10
3500	1.95	3.86	5.67	7.41	9.08
4000	1.94	3.72	5.67	7.34	9.09
4500	1.93	3.82	5.67	7.33	9.26
5000	1.97	3.78	5.66	7.49	9.11
Avg %	**1.95**	**3.81**	**5.67**	**7.39**	**9.05**

Based on **Table 4.8**, the average percentage increment of BSFC increased as more ethanol volume is added into diesel fuel, from 2% for 5% v- to 9% for 25% v-.. This is due to the lower energy content of the E-diesel blends since ethanol has less energy content compared to diesel fuel. In order to coup up or maintain the power output, more E-diesel fuel has to be burn so that the energy produced via the combustion process is also maintained.

4.3 Emission Characteristics

Various blends of E-diesel, ranging between 5% v- to 25% v- ethanol, have been successfully tested for the emission characteristics. The amounts of three main elements of combustion by-product – Particulate matter, Nitrogen oxide and Carbon monoxide – are determined by using Particulate Matter Sampler and Exhaust gas Analyzer.

4.3.1 Particulate Matter (PM)

In order to take the sample for particulate matter, Diesel Engine Test Bed must be set to run at a constant speed. In this experiment, the engine speed is maintained at 2500 rpm for sampling purposes. The sampling time is also set to be 15 minutes per sample.

The amount of dry particulate matter collected and BHP value at 2500 rpm for various E-diesel blends are tabulated in **Table 4.9**. From the collected data, the rate amount of PM produced is calculated by using **Equation 2.18** (see **Section 2.4.3**) and tabulated in **Table 4.9**.

Table 4.9 – Rate of PM produced for various E-diesel blends

Type of Fuel	Dry mass of PM Collected (g)	BHP @ 2500 rpm (bhp)	Rate of PM Produced (g/bhp-hr)
100% Diesel	0.2971	34.95	0.0340
5%-Ethanol	0.1125	31.48	0.0143
10%-Ethanol	0.1076	31.20	0.0138
15%-Ethanol	0.0946	29.78	0.0127
20%-Ethanol	0.0789	27.92	0.0113
25%-Ethanol	0.0726	27.38	0.0106

Based on **Table 4.9**, rate of PM produced (g/kW-hr) for each blends are shown graphically in **Figure 4.7**.

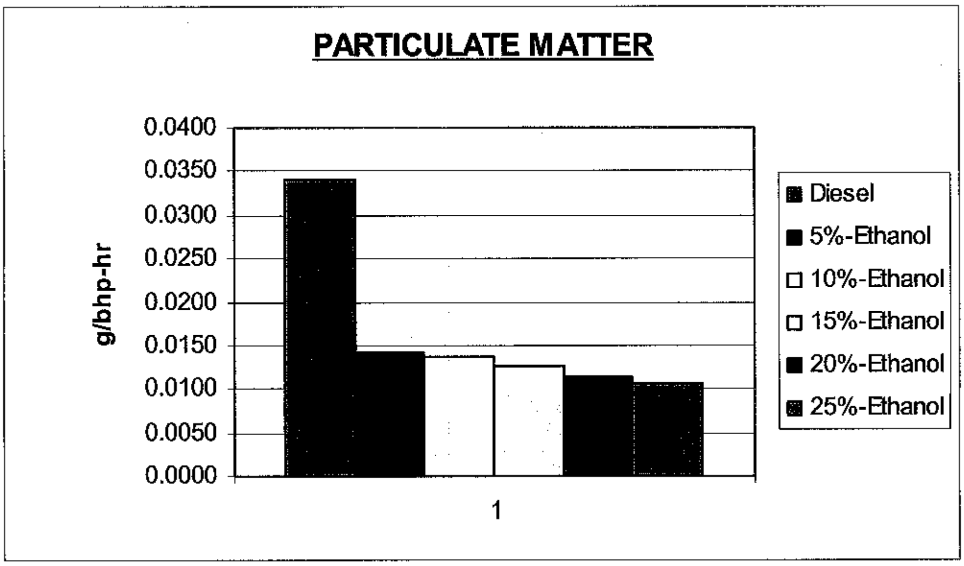

Figure 4.7 – PM produced of various E-diesel blends

From **Figure 4.7**, there is a significant drop in PM produced when ethanol is added into diesel fuel. As more volume of ethanol is added, PM produced is also reduced respectively. The percentage reductions of PM produced compared to 100% Diesel fuel are shown in **Table 4.10**.

Table 4.10 - Percentage reduction of PM produced for various E-diesel blends

Type of Fuel	PM (g/bhp-hr)	Reduction (%)
100% Diesel	0.0340	0.00
5%-Ethanol	0.0143	57.94
10%-Ethanol	0.0138	59.41
15%-Ethanol	0.0127	62.65
20%-Ethanol	0.0113	66.76
25%-Ethanol	0.0106	68.82

Form **Table 4.10**, the amount of PM produced reduced by 58% when 5% v- ethanol is added into diesel fuel. The percentage reduction of PM produced increase as more ethanol is added. Basically, this is due to the present of oxygen molecule from the ethanol in the blends.

Mixing diesel fuel with ethanol will much likely oxygenate the fuel and more oxygen molecule is present in the blend. Thus, more complete combustion can take place with these additional oxygen molecules. Instead of carbon particles that are produced, which is the major compound in PM, it will react with oxygen to form CO_2. This will results in less PM produced as well as soot or smoke.

The engine speed is specified at 2500 rpm for PM sampling because from the performance characteristic results, it shows that the minimum fuel consumption for the engine is at 2500 rpm. This is to minimize the usage of ethanol in this project due to the limitation of ethanol resource.

4.3.2 Nitrogen Oxide (NOx)

The amounts of NOx produced from various E-diesel blends are measured using Exhaust Gas Analyzer. The data obtained from the experiments conducted are tabulated in **Table 4.11**.

Table 4.11 – Amount of NOx produced for various E-diesel blends

Engine Speed (rpm)	**NOx (ppm)**					
	100% Diesel	**% Ethanol in Diesel Fuel**				
		5%	**10%**	**15%**	**20%**	**25%**
1000	143	122	117	112	108	105
2000	150	128	123	117	114	110
3000	220	187	181	172	167	163
4000	405	344	332	316	308	299
5000	753	640	617	587	572	557

Based on **Table 4.11**, NOx produced (ppm) against engine speed (rpm) curves are plotted as shown in **Figure 4.8**.

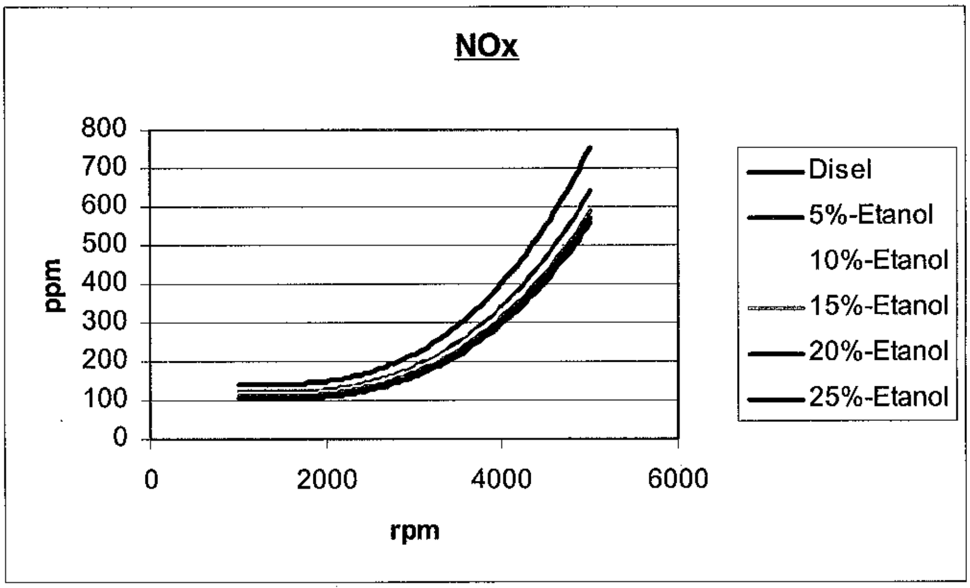

Figure 4.8 – NOx produced vs. engine speed for various E-diesel blends

Based on **Figure 4.8**, the amount of NOx produced increased with increase in engine speed. The production started slow initially and after engine speed reached about 3000 rpm, the amount of NOx produced increased rapidly. This is because NOx production is very much depending on the engine temperature. Higher engine temperature will results in higher NOx production. The underlying theory is sufficient amount of energy (heat) is required for nitrogen molecules to react with oxygen molecules to form NOx. Therefore, increasing engine speed will increase the combustion process which more energy (heat) is being released. Thus, greater energy in form of heat is released; the greater amount of NOx is produce from the combustion process. Furthermore, at high speed, less time for heat to dissipate thus more heat is trapped in the combustion chamber which also contributes to the formation of NOx.

Also depicted in **Figure 4.8** are the NOx produced curves for various blends of E-diesel ranging from 5% v- to 25% v-. From the graph plotted, it can be seen that the amount of NOx produced decreased with increase in ethanol volume in diesel fuel. The percentage reduction of NOx produced for the blends are shown in **Table 4.12**.

Table 4.12 - Percentage reduction of NOx produced for various E-diesel blends

Engine Speed (rpm)	**% Reduction of NOx (ppm)**				
	% Ethanol in Diesel Fuel				
	5%	**10%**	**15%**	**20%**	**25%**
1000	14.69	18.18	21.68	24.48	26.57
2000	14.67	18.00	22.00	24.00	26.67
3000	15.00	17.73	21.82	24.09	25.91
4000	15.06	18.02	21.98	23.95	26.17
5000	15.01	18.06	22.05	24.04	26.03
Avg %	**14.88**	**18.00**	**21.90**	**24.11**	**26.27**

Referring **Table 4.12**, the production of NOx reduced by 15% when 5% v- ethanol is added into diesel fuel. From the trending, the amount of NOx produced reduced by 3% for every 5% v- ethanol added. This phenomenon occurred because of the engine power output is reduced by the addition of ethanol (refer **Section 4.2.1**). The reduction in power output indicates that less energy (heat) is produced during the combustion process, thus it can be said that the engine temperature also decreased. Therefore less NOx is produced.

4.3.3 Carbon Monoxide (CO)

Carbon monoxide produced from the engine exhaust is also measured by using Exhaust Gas Analyzer. The amount of CO produced for various E-diesel blends are tabulated in **Table4.13**.

Table 4.13 – Amount of CO produced for various E-diesel blends

Engine Speed (rpm)	**CO (ppm)**					
	100% Diesel	**% Ethanol in Diesel Fuel**				
		5%	**10%**	**15%**	**20%**	**25%**
1000	1107	941	908	863	841	819
2000	1123	955	921	876	853	833
3000	1410	1199	1156	1099	1072	1043
4000	1762	1498	1445	1374	1339	1304
5000	2203	1873	1807	1718	1674	1631

Similarly, CO produced (ppm) against engine speed (rpm) curves, as shown in **Figure 4.9**, are plotted based on the values obtained.

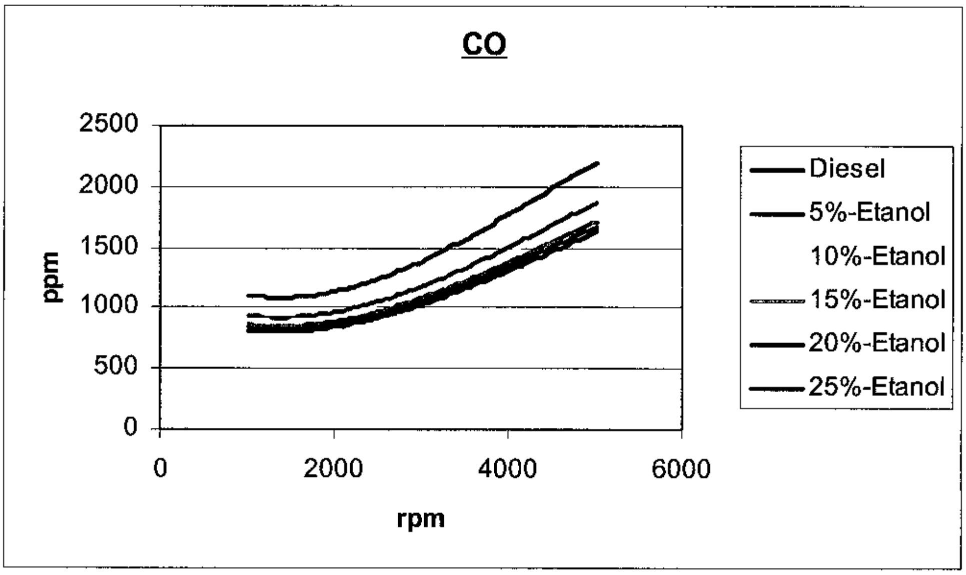

Figure 4.9 – CO produced vs. engine speed for various E-diesel blends

Based on **Figure 4.9**, the amount of CO produced started to increase gradually when the engine speed reached 2000 rpm. When engine speed increased, more fuel are injected into the combustion chamber, thus more chances of incomplete combustion to occur which results in higher production of CO.

Figure 4.9 also shows the results of CO produced when various E-diesel blends are run in the diesel engine. It can be seen that the additional of ethanol in diesel fuel results in reduction of CO produced. The percentage reduction of CO produced for various E-diesel blends compared to 1005 Diesel fuel are shown in **Table 4.14**.

Table 4.14 - Percentage reduction of CO produced for various E-diesel blends

Engine Speed (rpm)	**% Reduction of CO (ppm)**				
	% Ethanol in Diesel Fuel				
	5%	**10%**	**15%**	**20%**	**25%**
1000	15.00	17.98	22.04	24.03	26.02
2000	14.96	17.99	21.99	24.04	25.82
3000	14.96	18.01	22.06	23.97	26.03
4000	14.98	17.99	22.02	24.01	25.99
5000	14.98	17.98	22.02	24.01	25.96
Avg %	**14.98**	**17.99**	**22.03**	**24.01**	**25.97**

As shown in **Table 4.14**, the production of CO reduced by 15% when 5% v- of ethanol is added into diesel fuel. Greater amount of ethanol added into the diesel fuel resulted in higher CO reduction. The results obtained are due to the additional oxygen molecules provided by ethanol in the E-diesel blends. With the present of more oxygen molecules, higher chances of complete combustion to occur in the combustion chamber, thus carbon molecule has sufficient oxygen molecules to react with to form CO_2 instead of CO.

4.4 Selection of Best E-Diesel Blend

Based on the results obtained in **Section 4.3**, one of the objectives of this project is completed. It is proven that E-diesel is reliable to be an alternative fuel source for diesel engines.

Another objective of this project is to recommend the best E-diesel blend with regard to performance and emission characteristics. In order to achieve this, certain criteria has been set as the baseline for evaluation of each of the blends. For each characteristics studied in this project, a maximum percentage of reduction or increment is set. The criteria set for each characteristics are shown in **Table4.15**. These criterions are set based on the findings during Literature Review.

Table 4.15 – Criteria set for each characteristic

Criteria	Max % of Reduction (Increment)
BHP	15%
Torque	15%
BMEP	15%
BSFC	(5%)
PM	60%
NOx	20%
CO	20%

Table 4.16 – Summary of various E-diesel blends evaluations'

Criteria	[<15%]	[<15%]	[<15%]	[>60%]	[>20%]	[>20%]	[<5%]
Type of Fuel	% of Reduction (Increment)						
	BHP	Torque	BMEP	PM	NOx	CO	BSFC
5%-Ethanol	9.57	4.02	4.96	57.94	14.88	14.98	(1.95)
10%-Ethanol	10.54	8.14	9.39	59.41	18.00	17.99	(3.81)
15%-Ethanol	14.86	12.45	14.11	62.65	21.90	22.03	(5.67)
20%-Ethanol	18.49	16.22	17.86	66.76	24.11	24.01	(7.39)
25%-Ethanol	21.88	19.96	21.74	68.82	26.27	25.97	(9.05)

Basically, the concept of evaluation is the selected blend that is to be recommended must comply with all the criteria set. From **Table 4.16**, it is clearly shown that 15%-Ethanol blend has met almost all the criteria set except for BSFC, which only exceed about 0.67% from the margin.

Therefore, based on the results, the recommended E-diesel blend for this project is 15%-Ethanol blend. This recommendation is based on the specified procedures practiced in this project and also based on the equipment – Diesel Engine Test Bed, Exhaust Gas Analyzer and Particulate Matter Sampler – provided and used in this project. Comparison with other experiment results cannot be considered except if only the same procedure and equipment is practiced.

The idea of this selection or recommendation is actually instead of only gaining the benefits in reducing the emission, the reduction of performance parameters should also be taken into consideration. Therefore, a certain percentage of reductions on performance parameters are set to convey with the desired amount of emission to be reduced. Thus, the selected E-diesel blend should portray the minimum reduction of engine performance while reducing the exhaust emission products to the desired amount or level.

4.5 Summary

From this Chapter, based on the Pre-experiment results, it can be concluded that the Diesel Engine Test bed is reliable to be used to conduct further experiments in this project.

The values of 100% Diesel fuel are used as the baseline for further analysis of performance and emission characteristics for other various E-diesel blends.

From the results obtained, it shows that the additional of ethanol in diesel fuel reduced the performance characteristic. BHP, torque developed and BMEP experienced a drop in performance up to 22% from normal performance using 100% Diesel fuel. Whereas, BSFC experienced an increment up to 10% from its normal value. As for emission characteristics, improvement on the engine emission can be seen. PM production has been successfully cut down by at least 58%, while NOx and CO produced has also been reduced by at least 26% for normal diesel fuel.

Therefore, it is concluded that the additional ethanol in diesel fuel has been successfully reduced the exhaust emission by-product. But this achievement is only possible at the expenses of reduction of performance characteristics.

5%-Ethanol blend has been recommended as the best blend of E-diesel in this project. This selection is based on the results of performance and emission characteristics obtained and also the evaluation of each characteristic with the criteria set for this project.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This project is being conducted with the goal of studying the performance and emission characteristics of diesel engine using ethanol-blend diesel fuels. The outcome of the project would be the best blend of ethanol-diesel fuel with regards to both characteristics mentioned.

From the Pre-experiment, the reliability of Diesel Engine Test Bed to conduct any study on performance characteristics has been proven. This shown by the performance characteristics curves obtained which has a similar trending with the theoretical or typical curves.

Based on the results obtained from laboratory experiments, it shows that the additional of ethanol in diesel fuel reduced the performance characteristic. BHP, torque developed and BMEP experienced a drop in performance up to 22% from normal performance using 100% Diesel fuel. Whereas, BSFC experienced an increment up to 10% from its normal value.

The reason behind the reduction of these performance parameters when using E-diesel is probably because of the energy content of ethanol which is much less than diesel fuel. As more ethanol volume present in diesel fuel, the total energy content of the mixture is decreased. Thus, the energy released through the combustion process, which is converted into the power output and torque, is also decreased. Furthermore, this also increased the fuel consumption as more fuel has to be burned in order to coup up or maintain the power output.

As for emission characteristics, improvement on the engine emission can be seen when E-diesel blend is tested. PM production has been successfully cut down by at least 58%, while NOx and CO produced has also been reduced by at least 15% for normal diesel fuel.

PM and CO production is reduced by using E-diesel probably because mixing diesel fuel with ethanol will much likely oxygenate the fuel and more oxygen molecule is present in the blend. Thus, more complete combustion can take place with these additional oxygen molecules. Instead of carbon particles and CO that are produced, they will react with oxygen molecules to form CO_2. The reduction of NOx probably related to the reduced of power output. It indicates that less energy (heat) is produced during the combustion process, thus less energy is available for nitrogen and oxygen molecules to react with each other to form NOx. Therefore less NOx is produced.

Therefore, it is concluded that E-diesel has been proven to be reliable as an alternative fuel source for diesel engine since it has been successfully reduced the exhaust emission by-product. But these achievements are only possible at the expenses of reduction of performance characteristics.

The idea of recommending the best E-diesel blend is besides only gaining the benefits of reducing the exhaust by-product to the desired level, the reduction of engine performance parameters should also be minimized. From the results obtained, 15%-Etahnol blend is recommended as the best blend since it complies with almost of the criteria set for selection. It reduced the emission product to desired level while minimized the reduction in performance parameters.

5.2 Suggested Future Work for Expansion and Continuation

It has to be stress here that the results obtained and the conclusions made are based on the equipment and procedures used in this project. For further work expansion and continuation of this project, it is recommended that the E-diesel blends also should be tested in other or different diesel engines, light- to heavy-duty engines. By doing this, the results obtained can be compared with each other and a more accurate conclusion can be made in selecting the best blend. This initiative should be considered if the E-diesel is to be commercialized in the market so that the recommended blend can be used for a wide range of diesel engines, light- to heavy-duty engines.

Also for the continuation of this project, it is recommended that a more narrow range of E-diesel blends is studied. This project is actually the initial steps to identify the best range of ethanol volume in diesel fuel. For future work, the study can concentrate on 10% v- to 20% v- ethanol in diesel engines with maybe 1% v-difference. This can be done if the amount of ethanol supplied is sufficient to perform all the laboratory experiments. By this recommendation, a more accurate of E-diesel blend can be recommended for commercialization.

Another recommendation for further research or continuation on this project is that additives should be taken into consideration when preparing the E-diesel. The additive allows diesel fuel and ethanol to mix stably and to maintain certain fuel properties, such as cetane number and lubricity. It has been proven from other research that mixing E-diesel with additive can give a better result both in performance and emission characteristics. Greater emission by-product can be reduced and the engine performance can be maintained or even improved by the introduction of additives. This is very much essential when E-diesel is set to be commercialized in the automotive industry.

For further improvement of the project, it is also suggested that more exhaust gas can be studied such as Sulfur dioxide (SO_2). SO_2 is also classified as one of the hazardous exhaust by-product. With this additional gas taken into focus, perhaps it can be determine whether E-diesel fuel can also reduce the amount of SO_2 which can really give an extra benefit to the environment.

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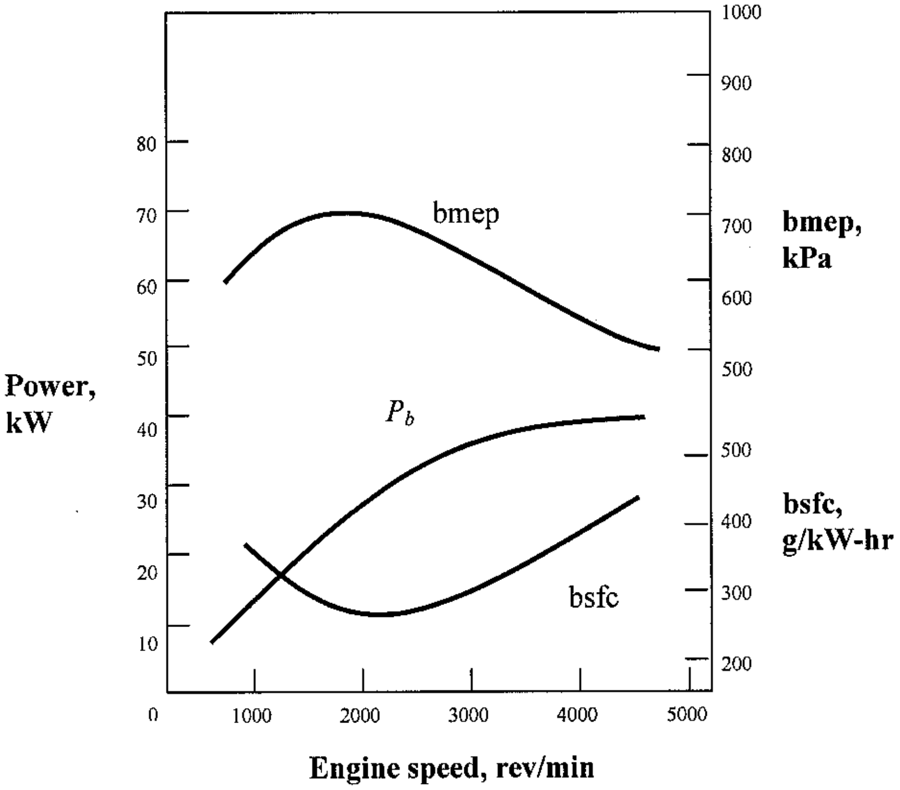
APPENDICES

APPENDIX 2-1

Gross indicated and brake power (P_b), brake mean effective pressure (bmep) for 1.8-dm^3 four cylinder naturally aspirated indirect-injection swirl-chamber diesel engine : bore = 84 mm, stroke = 82 mm, r_c = 22.



Source: John B. Heywood, 1988, Internal Combustion Engine Fundamentals, USA, McGraw Hill Book Company

APPENDIX 4-1

Performance Data for 100% Diesel Fuel

Performance Characteristic - 100% Diesel fuel

			calc.	calc.	calc.			calc.	calc.				
Engine Speed rev/min	Air Temp °C	Barometric Pressure kPa	log10(water vapor pressure)	Water Vapor Pressure kPa	Power Correction Factor	Uncorrected Brake Power kW	Uncorrected Brake Power BHP hp	Corrected Brake Power kW	Corrected Brake Power BHP hp	BMEP Bar	BMEP kPa	Specific Fuel Consumption g/kWhr	Torque Nm
1000	35.9	102	1.6466	3.8439	1.0119	7.4	9.9	7.49	10.04	5.07	507	292	71
1500	36.1	102	1.6514	3.8863	1.0127	12.7	17.0	12.86	17.24	5.81	581	283.8	81
2000	37	102	1.6728	4.0822	1.0162	18.9	25.3	19.21	25.74	6.4	640	276.2	90
2500	37.6	102	1.6869	4.2175	1.0186	25.6	34.3	26.08	34.95	6.48	648	273	91
3000	38.2	101.9	1.7010	4.3567	1.0220	28.9	38.8	29.54	39.59	6.46	646	278.6	90
3500	38.7	101.9	1.7127	4.4757	1.0241	33	44.3	33.80	45.30	6.42	642	286.3	88
4000	39.5	101.9	1.7314	4.6720	1.0275	35.2	47.2	36.17	48.48	6.02	602	298	84
4500	40.1	101.9	1.7453	4.8240	1.0301	38	51.0	39.14	52.47	5.78	578	309.7	81
5000	39.5	101.9	1.7314	4.6720	1.0275	37.8	50.7	38.84	52.06	5.18	518	338.4	72

APPENDIX 4-2

Performance Data for 5% E-Diesel Fuel

Performance Characteristic - 5% E-Diesel fuel

			calc.	calc.	calc.			calc.	calc.		calc.		
Engine Speed rev/min	Air Temp °C	Barometric Pressure kPa	log10(water vapor pressure)	Water Vapor Pressure kPa	Power Correction Factor	Uncorrected Brake Power kW	Uncorrected Brake Power BHP hp	Corrected Brake Power kW	Corrected Brake Power BHP hp	BMEP Bar	BMEP kPa	Specific Fuel Consumption g/kWhr	Torque Nm
1000	37.2	101.2	1.6775	4.1269	1.0253	6.8	9.1	6.97	9.35	4.82	482	297.8	67
1500	37.5	101.3	1.6846	4.1947	1.0255	11.3	15.2	11.59	15.53	5.52	552	289.5	78
2000	38.2	101.3	1.7010	4.3567	1.0284	16.8	22.5	17.28	23.16	6.08	608	281.6	85
2500	38.6	101.3	1.7104	4.4517	1.0300	22.8	30.6	23.48	31.48	6.16	616	278.5	88
3000	39.3	101.3	1.7267	4.6222	1.0330	25.7	34.5	26.55	35.59	6.14	614	284.2	86
3500	39.7	101.3	1.7360	4.7222	1.0347	29.5	39.6	30.52	40.92	6.1	610	292	85
4000	40.1	101.3	1.7453	4.8240	1.0365	31.5	42.2	32.65	43.77	5.72	572	303.9	82
4500	40.3	101.4	1.7499	4.8756	1.0363	34	45.6	35.23	47.23	5.48	548	315.8	77
5000	40.2	101.4	1.7476	4.8498	1.0359	33.8	45.3	35.01	46.93	4.94	494	345.2	70

APPENDIX 4-3

Performance Data for 10% E-Diesel Fuel

Performance Characteristic - 10% E-Diesel fuel

			calc.	calc.	calc.			calc.	calc.		calc.		
Engine Speed rev/min	Air Temp °C	Barometric Pressure kPa	log10(water vapor pressure)	Water Vapor Pressure kPa	Power Correction Factor	Uncorrected Brake Power kW	Uncorrected Brake Power BHP hp	Corrected Brake Power kW	Corrected Brake Power BHP hp	BMEP Bar	BMEP kPa	Specific Fuel Consumption g/kWhr	Torque Nm
1000	36.4	101.3	1.6585	3.9507	1.0211	6.5	8.7	6.64	8.90	4.67	467	303.4	64
1500	36.6	101.3	1.6633	3.9941	1.0219	11.2	15.0	11.45	15.34	5.23	523	295.2	74
2000	37.4	101.3	1.6822	4.1720	1.0251	16.7	22.4	17.12	22.95	5.79	579	287.2	82
2500	38	101.5	1.6963	4.3099	1.0254	22.7	30.4	23.28	31.20	5.86	586	283.9	84
3000	38.6	101.5	1.7104	4.4517	1.0279	25.7	34.5	26.42	35.41	5.81	581	289.7	82
3500	39.1	101.5	1.7221	4.5730	1.0300	29.4	39.4	30.28	40.59	5.79	579	297.8	81
4000	39.8	101.5	1.7383	4.7475	1.0330	31.5	42.2	32.54	43.62	5.48	548	309.5	78
4500	40.5	101.5	1.7545	4.9277	1.0361	34	45.6	35.23	47.22	5.2	520	322	74
5000	39.8	101.3	1.7383	4.7475	1.0352	33.8	45.3	34.99	46.90	4.73	473	351.7	68

APPENDIX 4-4

Performance Data for 15% E-Diesel Fuel

Performance Characteristic - 15% E-Diesel fuel

			calc.	calc.	calc.			calc.	calc.		calc.		
Engine Speed rev/min	Air Temp °C	Barometric Pressure kPa	log10(water vapor pressure)	Water Vapor Pressure kPa	Power Correction Factor	Uncorrected Brake Power kW	Uncorrected Brake Power BHP hp	Corrected Brake Power kW	Corrected Brake Power BHP hp	BMEP Bar	BMEP kPa	Specific Fuel Consumption g/kWhr	Torque Nm
1000	35.8	101.9	1.6443	3.8228	1.0126	6.29	8.4	6.37	8.54	4.48	448	309.5	61
1500	36.2	101.9	1.6538	3.9076	1.0141	10.8	14.5	10.95	14.68	4.94	494	300.8	69
2000	37.2	101.9	1.6775	4.1269	1.0180	16.1	21.6	16.39	21.97	5.44	544	293	78
2500	37.5	101.9	1.6846	4.1947	1.0192	21.8	29.2	22.22	29.78	5.58	558	289.4	81
3000	38.4	101.9	1.7057	4.4040	1.0229	24.6	33.0	25.16	33.73	5.5	550	295.3	80
3500	38.9	101.8	1.7174	4.5241	1.0260	28	37.5	28.73	38.51	5.43	543	303.5	77
4000	39.7	101.8	1.7360	4.7222	1.0294	29.9	40.1	30.78	41.26	5.2	520	315.9	75
4500	40.6	101.9	1.7568	4.9539	1.0323	32.3	43.3	33.34	44.70	4.91	491	328.3	69
5000	39.8	101.9	1.7383	4.7475	1.0288	32.1	43.0	33.02	44.27	4.53	453	358.7	65

APPENDIX 4-5

Performance Data for 20% E-Diesel Fuel

Performance Characteristic - 20% E-Diesel fuel

			calc.	calc.	calc.			calc.	calc.		calc.		
Engine Speed rev/min	Air Temp °C	Barometric Pressure kPa	log10(water vapor pressure)	Water Vapor Pressure kPa	Power Correction Factor	Uncorrected Brake Power kW	Uncorrected Brake Power BHP hp	Corrected Brake Power kW	Corrected Brake Power BHP hp	BMEP Bar	BMEP kPa	Specific Fuel Consumption g/kWhr	Torque Nm
1000	37.3	101.2	1.6799	4.1494	1.0257	6.1	8.2	6.26	8.39	4.25	425	315.4	58
1500	37.5	101.2	1.6846	4.1947	1.0266	10.3	13.8	10.57	14.17	4.76	476	306	66
2000	38.1	101.2	1.6987	4.3333	1.0290	15.4	20.7	15.85	21.24	5.17	517	298.3	74
2500	38.6	101.2	1.7104	4.4517	1.0311	20.2	27.1	20.83	27.92	5.31	531	294.8	78
3000	39.3	101.2	1.7267	4.6222	1.0341	23.1	31.0	23.89	32.02	5.3	530	301	77
3500	39.7	101.1	1.7360	4.7222	1.0369	26.5	35.5	27.48	36.83	5.26	526	309.2	75
4000	40.2	101.1	1.7476	4.8498	1.0391	28.3	38.0	29.41	39.42	4.98	498	321.6	71
4500	40.6	101.1	1.7568	4.9539	1.0409	30.2	40.5	31.43	42.14	4.74	474	334.2	66
5000	40.2	101.1	1.7476	4.8498	1.0391	30.5	40.9	31.69	42.48	4.25	425	365.8	62

APPENDIX 4-6

Performance Data for 25% E-Diesel Fuel

Performance Characteristic - 25% E-Diesel fuel

			calc.	calc.	calc.			calc.	calc.		calc.		
Engine Speed rev/min	Air Temp °C	Barometric Pressure kPa	log10(water vapor pressure)	Water Vapor Pressure kPa	Power Correction Factor	Uncorrected Brake Power kW	Uncorrected Brake Power BHP hp	Corrected Brake Power kW	Corrected Brake Power BHP hp	BMEP Bar	BMEP kPa	Specific Fuel Consumption g/kWhr	Torque Nm
1000	36.1	101.8	1.6514	3.8863	1.0147	5.8	7.8	5.89	7.89	4.07	407	320.2	56
1500	36.3	101.8	1.6562	3.9291	1.0155	9.9	13.3	10.05	13.48	4.53	453	311.4	63
2000	37.2	101.8	1.6775	4.1269	1.0190	14.7	19.7	14.98	20.08	4.97	497	303.8	71
2500	37.8	101.8	1.6916	4.2635	1.0215	20	26.8	20.43	27.38	5.06	506	300.3	74
3000	38.5	101.8	1.7081	4.4278	1.0243	22.5	30.2	23.05	30.89	5.03	503	306.5	74
3500	38.9	101.9	1.7174	4.5241	1.0249	25.7	34.5	26.34	35.31	4.97	497	314.9	72
4000	39.8	101.9	1.7383	4.7475	1.0288	27.4	36.7	28.19	37.79	4.76	476	327.8	67
4500	40.2	101.9	1.7476	4.8498	1.0305	29.6	39.7	30.50	40.89	4.51	451	341.3	63
5000	39.8	101.9	1.7383	4.7475	1.0288	29.5	39.6	30.35	40.68	4.04	404	372.3	59

APPENDIX 4-7

Sample calculation for Corrected BHP (100% Diesel fuel @ 1000 rpm)

- *Corrected Brake Power,* $P_{b,c}$

a) Saturated water vapor pressure $P_{v,sat}$ at ambient temperature T_m of $35.9^\circ C$:

$$\begin{aligned}\log_{10} P_{v,sat} &= 8.10765 - \frac{1750.286}{T_m + 235} \\ &= 8.10765 - \frac{1750.286}{35.9 + 235} \\ &= 1.6466\end{aligned}$$

$$\begin{aligned}P_{v,sat} &= 10^{1.6466} \\ &= 44.32 mmHg \\ &= 5.909 kPa\end{aligned}$$

b) Ambient-water vapor partial pressure, P_v (assuming a relative humidity ϕ = 0.65):

$$\begin{aligned}P_v &= P_{v,sat} \times \phi \\ &= 5.909 \times 0.65 \\ &= 3.8439 kPa\end{aligned}$$

c) Power correction factor, C_F (given $P_{s,d}$= 98.274 kPa and T_s = 29.4 °C)

$$\begin{aligned}C_F &= \frac{P_{s,d}}{P_m - P_v}\left(\frac{T_m}{T_s}\right)^{1/2} \\ &= \frac{98.274}{102 - 3.8439}\left(\frac{271.05}{302.55}\right)^{1/2} \\ &= 1.0119\end{aligned}$$

d) $$\begin{aligned}P_{b,c} &= C_F \times P_{b,m} \\ &= 1.0119 \times 7.4 kW \\ &= 7.49 kW \\ &= \underline{\underline{10.04 hp}}\end{aligned}$$