The Effects of Neutralized Palm Oil Methyl Esters (NPOME) on Performance and Emission of a Direct Injection Diesel Engine

Azhar Abdul Aziz, Mohd Farid Said, Mohamad Afiq Awang, Mazlan Said
Automotive Development Centre (ADC)
Faculty of Mechanical Engineering
Universiti Teknologi Malaysia
Skudai, 81310, Johor, Malaysia
azhar@fkm.utm.my

Abstract: The used of palm oil-based biodiesels have been proposed as an alternative fuel for diesel engines in Malaysia. The purpose of this study is to investigate the performance and exhaust emissions of various blends of neutralized palm oil methyl ester (NPOME) in a small-unmodified direct-injection diesel engine and to compare them with that of a reference diesel fuel (D2). The NPOME has been blended together with D2 in several percentages (10%, 20% and 50%) and known as B10, B20 and B50. The acquisition of operating parameters such as performances, emission concentrations, cylinder pressure and fuel line pressure were performed as a function of engine loads, at the engine speed of 1500 rpm. The effect of engine load and blend percentages on brake specific fuel consumption (BSFC), brake thermal efficiency, heat release, cylinder pressure, ignition delay, carbon monoxide (CO), carbon dioxide (CO_2), unburned hydrocarbon (HC), nitrogen oxide (NOx) and exhaust smoke were carried out in this study. As a whole it was found that the palm oil-based alternatives behaved comparably well to the D2 in terms of performance (fuel consumption and thermal efficiency). Smoke density readings show improvements as compared to that emitted by the diesel fuel in which operating under similar conditions. The emissions of CO, CO_2 and HC were reduced by using biodiesel fuels, while NOx emissions for biodiesels were slightly higher.

Keywords: bio-diesel, performance, emissions, ignition delay.

1. Introduction

Malaysia is fortunate to have plentiful supplies of petroleum and natural gas. These two sources of energy are expected to contribute to the lion's share of the commercial energy requirements of the nation in the future. However, the increase in price of diesel fuels, stringent emission regulations and foreseeable future depletion of petroleum reserves force us to research new technologies to meet human's demands for environment and energy. Malaysia has embarked on an extensive Palm-oil based alternatives fuel program since 1982 [1, 2, and 3]. The program includes the development of production technology to convert palm oil to palm methyl esters (palm diesel), pilot plant study of palm diesel production as well as exhaustive evaluation of palm diesel as diesel substitute in conventional diesel engines (both stationary engines and exhaustive field trials). Therefore, in this study, the bio-diesel fuels supplied by MPOB have been tested on the direct-injection (DI) diesel engine in order to examine the effect of engine performance and exhaust emission and also to know the capability of the fuel on the diesel engine.

2. Previous Research

The positive outcome of bio-diesel utilization in diesel engines is the reduction of emissions. This was proven in a number of research studies. Chang et al. [4] tested a 4-cylinder, direct injection, turbocharged John Deere 4276T diesel engine with methyl, isopropyl and winterized methyl esters of soybean oil. Ester blends with No. 2 diesel fuel (20%, 50%, and 70%, by wt.) showed no change of engine thermal efficiency compared with No. 2 diesel fuel. However, the brake specific fuel consumption was increased due to the lower energy content of the esters (about 12% less than No. 2 diesel fuel). The HC emissions were reduced by 29% by the same fuel blend. The maximum reduction of CO, by 25%, was from the blend of 50% methyl esters of soybean oil. The combustion characteristics of the blends, as indicated by heat release analysis, were similar to No. 2 diesel fuel. Chang et al. [5] also studied the effects of some specially treated bio fuels on diesel engine performance, emissions as well as combustion. An example of this is methyl ester of soybean oil which was derived from a genetically modified strain of soybeans. It is partially transesterified soybean oil and a synthetic fuel that contained 80% methyl palmitate and 20% methyl stearate. The results of the study confirmed that bio-diesel has a higher cetane number than No. 2 diesel fuel. Their research also showed that fuel injection timing was advanced slightly when bio-diesel was used due to its having slightly higher viscosity than No. 2 diesel fuel. All of the bio-diesel fuels that were tested lowered the emissions of CO and HC emissions compared with No. 2 diesel fuel. They all also showed small increases in NOx. The combustion characteristics of bio-diesels were similar to the baseline diesel fuel.

Last et al. [6] tested methyl esters of soybean oil, blended with low sulphur diesel, in a Navistar T444E diesel engine. Their tests with the SAE 13-mode steady state test using bio-diesel blends in diesel fuel between 10% and 100% showed reduction in CO and HC. The emission of CO was reduced by at least 6.9% and HC was reduced by 28%. However, the emission of NOx was increased from 3.5% to 28% as the percentage of bio-diesel in the fuel blends was increased. Alfuso et al. [7] found that, at the same fuel injection timing, methyl esters of rapeseed oil caused a rise in NOx emissions, a decrease in HC and CO emissions and a strong reduction in smoke. Alfuso found that emissions of NOx, HC and CO from bio-diesel may be reduced by the adoption of EGR in the presence of an exhaust oxidation catalyst.

Diesel engine performance and emission tests fuelled with refined, bleached and deodorised palm olein (RBDPO) have been conducted at ADC UTM Skudai Johor [8, 9, and 10]. Diesel engine was fuelled with RBDPO and diesel at various volumetric proportions, B2, B5 and B10. A single cylinder unmodified direct injection Yanmar L70AE engine was used. It was found that the bio-diesel fuels provided similar brake thermal efficiency curves as diesel at low and medium engine loads, while BSFC were slightly higher over the entire engine speed and load. The brake power was generally lower throughout the engine speed range due to the lower calorific values of the blended fuels. Bio-diesel fuels produced less smoke than diesel under similar engine operating conditions. It is also produced slightly more NOx emissions, especially at the higher engine load. The bio-diesel and reference fuels provided similar combustion pressure patterns. The bio-diesel fuels lowered the premixed combustion of heat release because of the lower volatility.

3. The Experimental Setup

The experimental program was carried out using a *YANMAR*-L70AE single cylinder engine. This is a naturally-aspirated, direct injection diesel engine with a bore of 78 mm, stroke 62 mm. Its injection pressure is more or less set to 206 bar and a compression ratio of 19.5. It is an air-cooled, low-speed and the maximum power was 4.9 kW at 3400 rpm. A 19-inch rack exhaust gas analyzer *TOCSIN* IGD 300 systems complete with a 3 meter sampling probe was used for emissions measurements. For smoke density, a dedicated Sampling Pump Type EFAW/65 *BOSCH* smoke meter was used. The darkening of the filter paper from smoke meter is assessed by means of an evaluating unit type EFAW/68. The sampling probes of smoke meter and gas analyzer were mounted centrally at the end of the engine exhaust pipe.

The engine was directly coupled to an eddy-current brake *MAGTROL* dynamometer equipped with a load controller. The engine, dynamometer and other auxiliary items are mounted on a seismic steel bed (2m x 4m) to cushion the excessive engine vibration emitted during the trial. Intake engine airflow was measured by means of a sharp edged orifice mounted in the side of an air box, coupled to the engine inlet to damp out the inevitable pulsations of air flow into the engine. Manometer tube was used to measure the pressure drop across the orifice. The overall experimental set-up was shown in Figure 1. All the equipments were calibrated in accordance to the respective manufacturer specifications, prior conducting the tests.

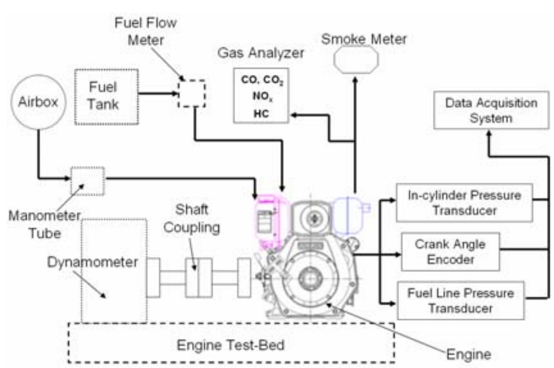

Fig. 1. Schematic engine diagram test set up

A water cooled piezoelectric pressure transducer (*Kistler* 6061B) was flush mounted with cylinder head to measure combustion pressure. The flush mounting was preferred in order to minimize the lag in the pressure signal and avoid pipe connecting passage resonance. Combustion pressure data were average over 120 consecutive engine cycles with a crank angle encoder (*Kistler* 2613B) having resolution of 0.2° crank angle. Heat release rate is computed using formula proposed by Heywood [11]. The XPM6 miniature pressure transducer was used to measure the fuel line pressure and the range of this transducer is from 0 to 500 bars. This transducer was located at high pressure fuel line pipe between the fuel pump and injector. The sensor was installed inside 25.4 x 25.4 x 50.8 mm mild steel block. The mild steel block was drilled to make a hole and thread in order to place the sensor. The brazing process was applied to mild steel block and fuel line pipe in order to attach them. Fuel line pressure data were average over 120 consecutive engine cycles with a crank angle encoder (Kistler 2613B) having resolution of 0.2° crank angle. The large numbers of cycles were collected to cancel out the random noise. These data were intended for use in defining the start of injection.

Data logging capability was required to record the pressure and crank angle signals during the experiment. Data acquisition system was used to convert and process signals from crank angle encoder and pressure transducers before being stored into a data logger. The computer based data acquisition system was used in the testing facilities is *SPECTRUM* (MI.3112CA) card installed on a *DEWE*-5000 portable data acquisition system. This card provides the analogue to digital (AD) interface. Data that acquire during experiment was retrieved using software provided by *Dewetron*. For data based on crank angle, *DEWECa* was used while data which are not dependant on crank angle, *DEWESoft* was used. Data has been exported using *Flexpro* format for further analysis.

In this study, engine was run at 1500 rpm for various engine loads at steady state condition. The reference fuel in this study was No.2 diesel fuel (D2). It was a commercially available diesel fuel in Malaysia. Besides the reference fuels, the bio-diesel fuels actually used in this study were blends of the D2 with the neutralized palm oil methyl ester (NPOME). These fuel blends included 10%, 20% and 50% of NPOME mixed with No.2 diesel fuel, by volume. The specifications of the fuels are shown in Table 1.

Table 1. The Fuels Specifications

Properties	**Diesel**	**B10**	**B20**	**B50**
Heat Value (MJ/kg)	45.28	44.72	44.17	42.39
Cloud Point (^{0}C)	18	17	17	15
Density @ 15^{0}C (kg/m^3)	853.8	855	855.4	876.8
Total Sulphur (wt %)	0.28	0.25	0.21	0.11
Viscosity @ 40^{0}C (cSt)	3.6	4.16	4.524	4.595
Flash Point (^{0}C)	93.0	96	98	110
Pour Point (^{0}C)	12	9.0	6	6
Cetane Number	54.6	54.4	57.8	59
Carbon (wt %)	84.1	82.3	82	78.5
Hydrogen (wt %)	12.8	12.5	12.5	12.2
Oxygen (wt %)	3.9	4.3	5.5	7.7

4. Results and Discussions

4.1 Diesel engine performance

Figure 2 shows the comparative results of the brake specific fuel consumption (BSFC) for diesel and bio-diesels. The figure illustrates that the BSFC for bio-diesels were higher than D2 over entire engine load. This is due to the bio-diesel has lower heat value than D2 as shown in Table 1. The energy per unit mass of B10, B20 and B50 were 44.72, 44.17 and 42.39 MJ/kg, respectively, while for D2 the energy per unit mass was 45.28 MJ/kg. As the amount of NPOME in the blends increases, heat value of the blends decreases. In order to maintain the same BMEP, more fuels are consumed. As a result, BSFC will increase as the blended fuels with high bio-diesel concentration are used. From the graph, it was found that the B50 depicted the highest BSFC increment compared to all tested fuels for entire engine load. B50 has a maximum increase of 7.4% in BSFC compared with D2, while B20 and B10 have about 6.7% and 3.3% increase, respectively.

The brake thermal efficiency characteristic of the engine operating condition using the tested fuels was shown in Figure 3. It is a good measure in assessing the fuels ability to convert the energy they inherit into outputs. As the figure shows, the brake thermal efficiency for all four fuels at higher load engine condition was about 22% to 24%, while at light load engine condition the thermal efficiency for the fuels was about 13% to 14% for engine speed of 1500 rpm. It was found that the percent change for bio-diesel fuels have lower than 5% compared to D2. Therefore, B10, B20 and B50 depict that the bio-diesel and its blends is the same as for diesel fuel. This indicates that the engine convert the inherited chemical energy of the fuel to mechanical energy with almost similar efficiency for all the fuels used in the test.

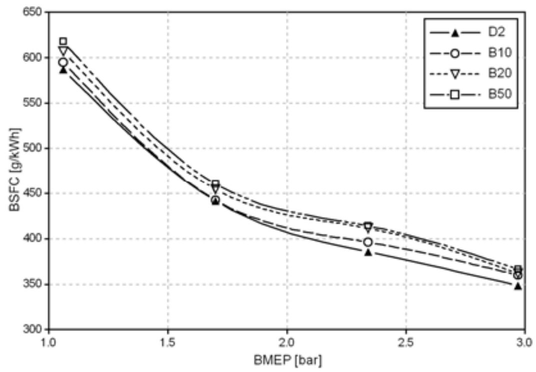

Fig. 2. The comparison of tested fuels on BSFC vs. BMEP.

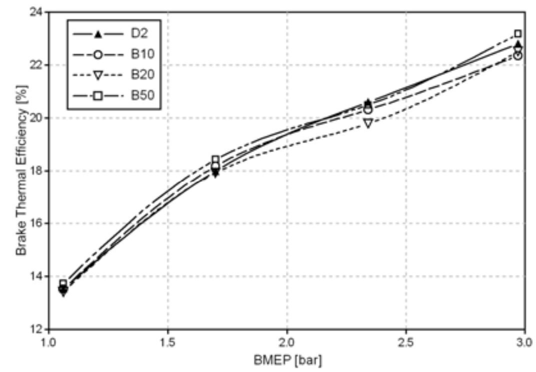

Fig. 3. The comparison of tested fuels on Brake Thermal Efficiency vs. BMEP.

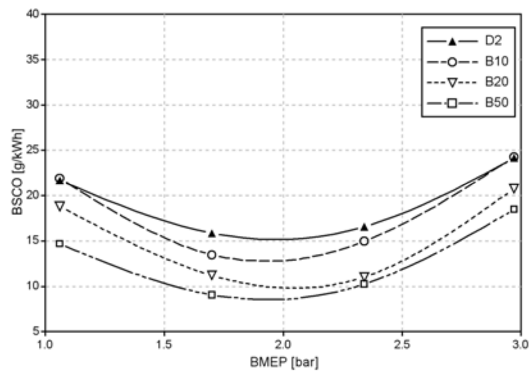

Fig. 4. The comparison of tested fuels on BSCO vs. BMEP.

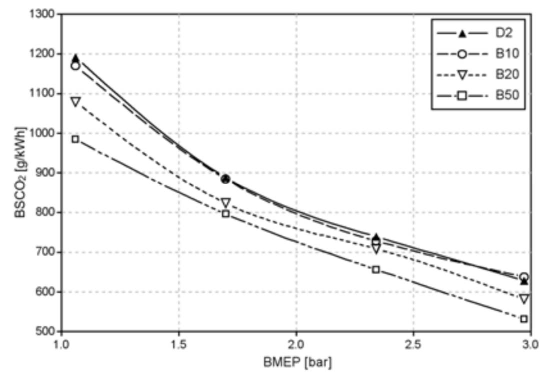

Fig. 5. The comparison of tested fuels on $BSCO_2$ vs. BMEP.

4.2 Diesel engine emissions

The engine exhaust emissions measured were carbon dioxide (CO_2), carbon monoxide (CO), unburned hydrocarbon (HC), nitrogen oxides (NOx) and Bosch smoke number. All emissions were expressed on a brake specific (g/kWh) basis except for the *Bosch* smoke number. All points shown were the average of three data points and the errors between the maximum and the minimum points among the three data points were less than 5%. The brake specific carbon monoxide (BSCO) emissions are shown in Figure 4. At all engine loads, the emissions of BSCO for bio-diesel fuels were less than for the D2. It can be seen that the highest BSCO emission was found at D2 and followed by B10 and B20, while the B50 had the lowest. It is important to note that the B50 had about 23.6% to 42.8% less BSCO emissions than the D2 for entire engine load, while for the B20 and B10 the BSCO emissions were reduced up to 29.3% and 15%, respectively. The brake specific carbon dioxide ($BSCO_2$) emission for diesel and bio-diesel fuels at various engine loads was illustrated in Figure 5. The changes of the BSCO2 emissions for the bio-diesel blends compared to D2 were significant as indicated by the range of values given on the y-axis. The B50 shows the largest reduction in $BSCO_2$ emissions for over entire engine loads and followed by B20 and B10. The reduction of $BSCO_2$ emissions for bio-diesel fuels was logical because of the lower amount of carbon element in the fuel as shown in fuel properties in Table 1. It was found that the B50 has reduced up to 17.35% compared to D2 and followed by B20 and B10 at 9.4% and 1.8%, respectively.

The brake specific hydrocarbon (BSHC) emission for all tested fuels was shown in Figure 6. It was shown that the bio-diesel fuels depicted lower BSHC compared to D2 over the entire loads condition. The reference fuel D2 recorded the highest BSHC followed by B10 and B20, while B50 depicted the lowest. The BSHC emissions were higher at the light load than the high load engine condition. In the same manner as the BSCO, the BSHC of bio-diesels were found to significantly reduce the emissions compared with D2. Relative to the D2, the BSHC for the B50 was reduced in the range of 16.37% to 21.7%, while B20 and B10 were reduced up to 12.06% and 5.93%, respectively. Nitric oxide (NO) and nitrogen dioxide (NO_2) are usually combined together as NOx emissions. The NO is the dominant part of the oxides of nitrogen produced inside the engine cylinder. The oxidation of molecular nitrogen is the principle source of NO emissions. The comparison between diesel and bio-diesel fuels in the brake specific nitrogen oxide (BSNOx) emissions was shown in Figure 7. The BSNOx emissions for bio-diesel fuels were slightly higher than for the reference fuel. The reason is that the bio-diesel fuel contains significant oxygen. The fuel oxygen causes the areas of the cylinder that would ordinarily be rich to be leaner. This fuel oxygen may provide the additional oxygen needed to oxidize the nitrogen. The B50 had about 11% to 21.1% higher BSNOx than the D2, while the B20 and B10 have about 3.54% to 13.93% and 2.4% to 9.15% higher.

The comparisons between diesel and bio-diesel fuels on exhaust smoke were illustrated in Figure 8. The term of Bosch smoke number (BSN) was used to indicate the quality of exhaust smoke. The BSN for all bio-diesel fuels were significantly lower than for the reference fuel D2 for entire engine loads condition. The lowest smoke number was found for the B50 and followed by B20 and B10, while the highest BSN was D2. Compared to the D2, the B10 has 1.9% to 7.12% reduction in BSN. However, the B20 and B50 have even more reduction in BSN and it was found that the both bio-diesels have 9.8% to 16.4% and 19.5% to 28.57% lower smoke number, respectively.

4.3 Diesel engine combustion

The definition of ignition delay is to calculate the heat release rate and use it as the basis of the start of combustion as suggested by Van Gerpen [12]. In this study the start of combustion was defined in terms of the change in slope of the heat release rate which occurs at ignition as shown in Figure 9. The definition of ignition delay used in this study was the time between the injection line pressure had reached 206 bar and when the slope of the heat release rate determined from the cylinder pressure data had started to rise rapidly. The injection fuel line pressure at the BMEP of 1.06 bar for all tested fuels was shown in Figure 10. The start of fuel injection for bio-diesel fuels is slightly advanced compared to D2 and this is maybe due to the higher density and viscosity of bio-diesels. For bio-diesels, the advanced in start of injection was the reason of increase in the NOx emissions. Based on the measured of start of injection and start of combustion, the ignition delay was calculated. It was found in Figure 11 that the ignition delay for bio-diesels were lower compared to D2 fuel. This was due to the higher cetane number of bio-diesel fuels. The cetane number has an effect on the time delay between when the fuel is injected and when it starts to burn. The higher the cetane number, the better the ignition quality of the fuel, and the faster the fuel will start to burn.

5. Conclusions

The NPOME and its blends were successfully tested as fuels in a single cylinder, unmodified diesel engine. The salient points of this investigation are:

1. The formulated fuels provide similar brake thermal efficiency curves as those of the reference fuel over entire engine load.
2. The BSFC for the bio-diesels were slightly higher than reference and is largely attributed to their higher fuel densities.
3. Lower concentration of black smoke were observed than those produced by the reference fuel under similar operating conditions. This is largely due to the inherited oxygen present which will help to oxidize a number of gaseous by-products products.
4. All the bio-diesel blends have the tendency to reduce CO_2 emissions. In this respect B50 reduced CO_2 concentrations more than B20 and B10. The reduction of CO_2 emissions (for bio-diesel blends) was logical because of their oxygenated nature of the oil and the lower amount of carbon element in them.
5. The blends produce lower CO emissions than D2 for all engine load range. B50 produced even more reduction in CO emissions than the B20 and B10. It was recorded that B50 specimen reduced CO emissions in the range of 23.6% to 42.8% compared to the diesel fuel.
6. All blends produce lower emissions of unburned hydrocarbon at all engine loads. The B50 registers the maximum reduction of 21.7%, 21.3% and 18.6%.
7. The use of bio-diesel fuels in diesel engine somehow increase the concentration of NOx emission. The oxygen content in bio-diesel may be the cause of the rise, as more oxygen present during combustion will raise the combustion bulk temperature. The advanced in start of injection also will cause toward higher NOx.
8. Ignition delay is noted to decrease as the palm-oil blends percentage become higher. This in support of the high cetane number as most diesel fuels of high cetane number do depict short ignition delay characteristics

Acknowledgement

The authors would like to thank the Malaysian Palm Oil Board (MPOB) for their cooperation in supplying the fuel specimens and the financial support for this program.

References

[1] Yusof Basiron and Choo, YM, Crude Palm Oil as a Source of Biofuel: Its Impact on Price Stabilization and Environment. 1 1/2 Day Course on Refineries' Crude Palm Oil Purchasing, Hedging, Contractual & its Operational Aspects, Subang Jaya, Selangor, Malaysia. 22 & 23 June 2004.

[2] Choo, Y M, Ma, A. N and Yusof Basiron. Production And Evaluation Of Palm Oil Methyl Esters as Diesel Substitute, Elaeis Special Issue:5-25.

[3] Choo, Y.M., Ma, A. N. and Yusof Basiron. Palm Diesel. Paper presented at 2002 Oils and Fats International Congress (OFIC), 7 – 10 October 2002, Putra World Trade Centre, Kuala Lumpur, Malaysia.

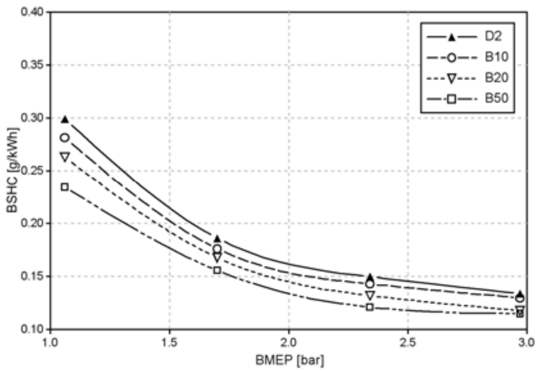

Fig. 6. The comparison of tested fuels on BSHC vs. BMEP.

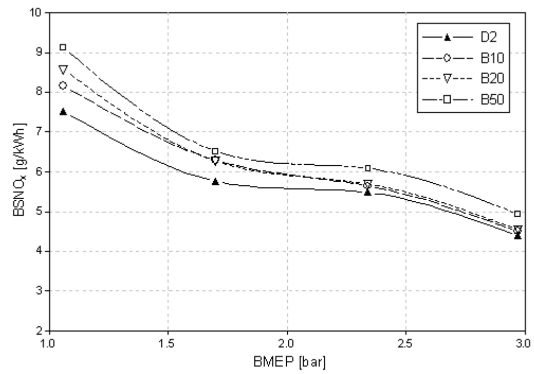

Fig. 7. The comparison of tested fuels on BSNOx vs. BMEP

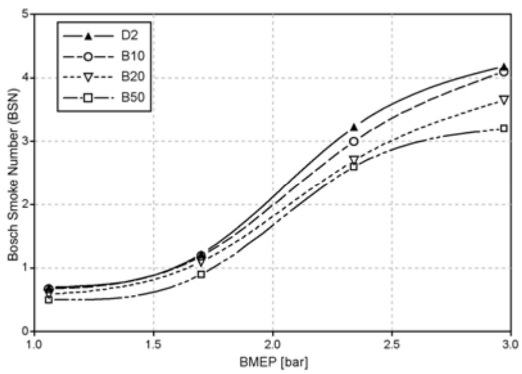

Fig. 8. The comparison of tested fuels on Smoke vs. BMEP.

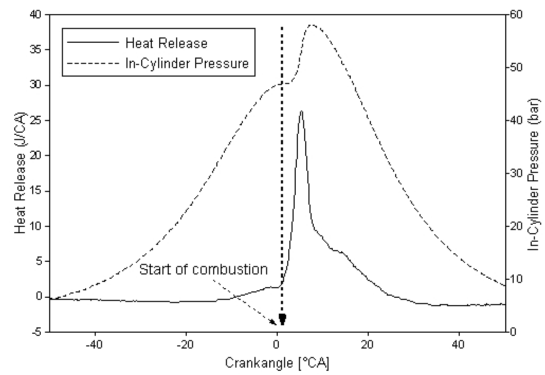

Fig. 9. The method of defining the start of combustion.

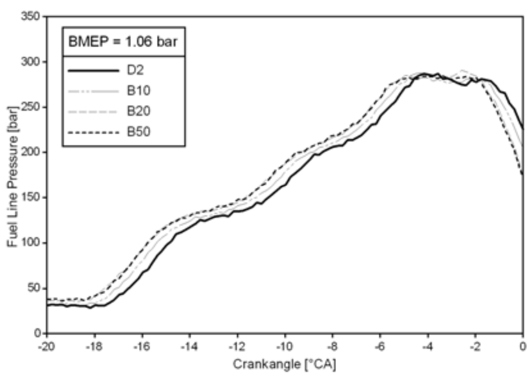

Fig. 10. Fuel line injection pressure profiles of the test fuels.

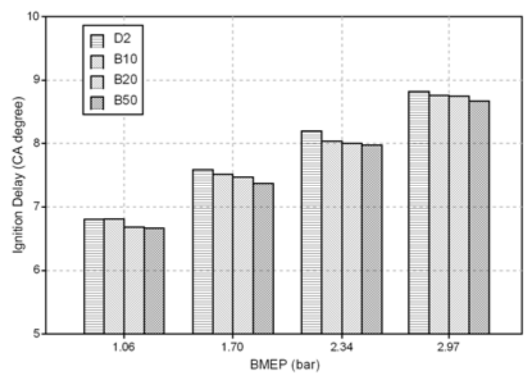

Fig. 11. The comparison of tested fuels on ignition delay.

[4] Chang, D.Y., Van Gerpen, J.H., Lee, I., Johnson, L., Hammond, E.G., and Marley, S. Fuel Properties and Emissions of Esters of Soybean Oil as Diesel Fuel. J. of Amer. Oil Chem. Soc. Vol. 73, No. 11, 1996.
[5] Chang, D.Y. and Van Gerpen, J.H. Fuel Properties and Engine Performance for Biodiesel Prepared from Modified Feedstocks. SAE paper 971684, 1997.
[6] Last, R.J., Kruger, M., and Durnholz, M. Emissions and Performance Characteristics of a 4-Stroke, Direct Injection Diesel Engine Fueled with Blends of Biodiesel and Low Sulfur Diesel Fuel. SAE paper 950054, 1995.
[7] Alfuso, S., Auriemma, M., Police, G., and Prati, M.V. The Effect of Methyl-Ester of Rapeseed Oil on Combustion and Emissions of DI Diesel Engines. SAE paper 932801, 1993.
[8] Azhar Abdul Aziz, Mohd Farid Said and Mohamad Afiq Awang. Laboratory Evaluation of Palm Oil-Based Bio-diesel with Conventional Diesel using Single Cylinder Direct Injection Engine. 2004 MPOB National Seminar on Green and Renewable Biofuel. 6 & 7 December 2004.
[9] Azhar Abdul Aziz, Mohd Farid Said and Mohamad Afiq Awang. Performance of Palm Oil-Based Biodiesel Fuels in a Single Cylinder Direct Injection Engine. Palm Oil Developments, No. 42, June 2005.
[10] Azhar Abdul Aziz, Mohd Farid Said and Mohamad Afiq Awang. Performance and Emission Evaluations of Palm Oil-Based Biodiesels with Conventional Diesel using Single Cylinder Direct Injection Engine. SAE Paper 2005-32-0016, The 11th Small Engine Technology Conference (SETC 2005), Bangkok, Thailand, 12-14 October 2005.
[11] Heywood, J.B. Internal Combustion Engine Fundamentals, International Edition, McGraw-Hill, New York, 1988.
[12] Van Gerpen, J.H. The Effects of Air Swirl and Fuel Injection System Parameters on Diesel Combustion. PhD Thesis, University of Wisconsin, Madison.