International Conference on Mechanical Engineering Research (ICMER2013), 1-3 July 2013
Bukit Gambang Resort City, Kuantan, Pahang, Malaysia
Organized by Faculty of Mechanical Engineering, Universiti Malaysia Pahang
Paper ID: P138

CYCLIC VARIATIONS OF COMBUSTION CHARACTERISTICS IN DIESEL ENGINE OPERATING WITH B20 BLENDS WITH ALCOHOL ADDITIVES

Mohd Hafizil Mat Yasin[1*], Rizalman Mamat[1], Amir Aziz[1]
and Ahmad Fitri Yusop[1]

[1]Faculty of Mechanical Engineering, Universiti Malaysia Pahang 26600 Pekan Pahang, Malaysia
*Email: hafizil@psmza.edu.my

ABSTRACT

Biodiesel is a renewable biological fuel which has higher density and viscosity as compared to mineral diesel. However, the simple approach to reduce the viscosity of biodiesel is to blend the mineral diesel with biodiesel. While the use of alcohol additives (ethanol and methanol) in the biodiesel blends fuel is to make lesser viscosity of the blend fuel. Different fuel properties produce different combustion characteristics of the blend fuels. Combustion studies on mineral diesel, B20 (biodiesel 20% + diesel 80%) and B20 blend fuels with alcohol additives (B20 E5 and B20 M5) were carried out using a Mitsubishi 4D68 multi-cylinder diesel engine. The combustion characteristics of an indirect injection diesel engine were examined by means of cyclic variation of peak cylinder pressure and mean indicated pressure (MIP). In-cylinder pressure was investigated for the various pressure crank angle history in this study. Statistical analysis of combustion characteristics for diesel engine have been carried out on three different engine loads; 20%, 40% and 60% at a constant engine speed of 2500 rpm using a combustion data of 200 cycles. The results show that at lower load, mineral diesel dominated the maximum peak cylinder pressure compared to other test fuels. However at higher load, B20, B20 E5 and B20 have surpassed mineral diesel for the maximum peak cylinder. It also remarked the variations of peak cylinder pressure of the test fuels influence most the mean indicated pressure (MIP) at three different engine loads.

Keywords: Biodiesel blend; alcohol additives; combustion; diesel engine.

INTRODUCTION

For centuries, the unlimited use of fossilized fuel to support the country's economic growth has contributed to the shortage fuel supply and ecological problems. This factor remains as the crucial challenges for the engine manufacturers to produce the diesel engines that can work well with the alternative fuels include biodiesel. Most literature discover that the performance of the engine include brake power and brake specific fuel consumption (bsfc) when running with biodiesel is slightly lower as compared to mineral diesel; this occur when the same amount of air and fuel is injected through the cylinder (Buyukkaya, 2010; McCarthy, Rasul, & Moazzem, 2011; Y. V. Hanumantha Rao, 2009). However, Senatore and Cardone concluded from their studies that there is a similar performance between ULSD and RME when comparison is made upon similar relative equivalence ratio (Senatore A, 2000).

Biodiesel or methyl esters of vegetable oils are characterized by its known properties include density, viscosity, cetane number, low heating value, cloud and pour points, flash point, and characteristics of distillation (Atabani et al., 2012; Demirbas, 2009). However, biodiesel has higher density and viscosity compared to diesel. In general, biodiesel has been diluted with diesel to reduce the density and viscosity at different proportions and been used on diesel engines without any modification (Ceviz, Koncuk, Küçük, Gören, & Yüksel, 2011; Chauhan, Kumar, & Cho, 2012; Y. V. Hanumantha Rao, 2009). Previous study by Liaquat et al. stated that neat jathropa methyl ester (JME) and blends with standard diesel have decreased the calorific value of the fuel, which may lead to engine power reduction and increasing in fuel consumption (Liaquat et al., 2012). Pidol et al. who investigated on ethanol and biodiesel blends found that, even the cetane numbers, blend stability and flash point were improved with the addition of ethanol in the biodiesel-diesel blends (Pidol, Lecointe, Starck, & Jeuland, 2012). This factor may affect the ignition delay and increase the amount of fuel for rapid combustion as well as boost the combustion temperature, hence producing higher formation levels of NOx.

Cycle-to-cycle variations are developed from the combustion process in the compression-ignition and spark-ignition engines when the engine operating conditions achieve the fundamental limits include lean flammability (Heywood, 1988; Pulkrabek, 2004). These parameters could indicate the actual engine behaviors for the output characteristics such as output power and exhaust emissions. There were many studies conducted on the cycle-to-cycle variations of pressure in spark-ignition and diesel engines operating with standard gasoline, standard diesel, biodiesel and biofuel include ethanol and methanol (Özkan, 2007; R. Longwic, 2011; Rakopoulos, Rakopoulos, Giakoumis, & Kyritsis, 2011). Those studies were important to enhance a better understanding on the various parameters that could relate with the combustion process and develop some effective control strategies for the combustion enhancement. Among important factors that could much influence the average in-cylinder pressure level and cycle-to-cycle variations include types of fuel, fuel-air ratio during combustion, amount of recycled gases drawn to the engine cylinder and engine aerodynamic designs (Pulkrabek, 2004).

In this comparative experimental study, biodiesel-diesel blends with 5% volume in ratios of methanol and ethanol; were tested in the same diesel engine under the same operating condition with constant engine speed of 2500 rpm at low, medium and high engine load. The combustion cycles for the test fuels were set at 200 consecutive cycles for the cyclic variations analysis. Those finding results were compared to B20 and mineral diesel as for the baseline. Biodiesel-diesel blends with alcohol additives were prepared with biodiesel (20%)-methanol (5%)-diesel (75%) and biodiesel (20%)-ethanol (5%)-diesel (75%) ratios (B20 M5 and B20 E5). Results focused on the in-cylinder pressure variations along the 200 consecutive cycles include the statistical analysis (median, average, mod) and the study of the cycle-to-cycle variations in mean indicated pressure (MIP) for the test fuels.

EXPERIMENT SETUP

The experimental work was conducted on a four-stroke, four-cylinder Mitsubishi 4D68 diesel engine. The engine was water-cooled, indirect injection (IDI) and equipped with an exhaust gas recirculation (EGR) system. Table 1 described the details of the engine. Figure 1 shows the photograph of the test engine used in this study.

Table 1. Specification of test engine.

Engine Specification	Details
Number of cylinders	4 in-line
Combustion chamber	Swirl chamber
Total displacement cm	1.998 cc (121.925 cu. in)
Cylinder bore mm x Piston stroke mm	82.7 x 93
Bore/stroke ratio	0.89
Compression ratio	22.4:1
Maximum Power	(64.9 kW) @ 4500 rpm Specific output 43.5 bhp/litre 0.71 bhp/cu in
Maximum Torque	177.0 Nm @ 2500 rpm
Fuel system	Mechanically control distributor-type injection

Figure 1. Photograph of test engine.

An eddy-current type water-cooled Dynalec dynamometer model ECB-200F SR 617 with capacity of 150 kW was used to load the engine. A Kistler 6041A water-cooled ThermoComp in-cylinder pressure transducer was attached to the first cylinder of four cylinders by replacing the glow plug using the bolt thread, M8 x 1.25 and wired to a Kistler Model 1929A1 cable to the charge module, DAQP- Charge B to convert the analogue signal into digital signal.

In order to determine the crankshaft position during the combustion process and the continuous movements from top dead centre (TDC) to bottom dead centre (BDC) and so on, with comparable to the differential cylinder pressures, a Kistler CAM crank angle encoder type 2613B1 was mounted in alignment to the pulley of the crank shaft at the side of the engine and connected via 1.5 m long cable to the signal conditioner type 2613B2. Both pressure transducer and crank angle encoder were recorded through a Dewetron data acquisition (DAQ) system with Orion 1624 DAQ card installed in a Windows XP based PC, DEW-5000 combustion analyser. The data was recorded for 200 engine cycles so that the average result could be calculated. 19 K-type thermocouples were used to measure the temperatures of the engine include all the exhaust manifolds. Those temperatures were monitored and recorded by a Dewetron DAQ system installed on a DEWE-800, Windows XP based PC.

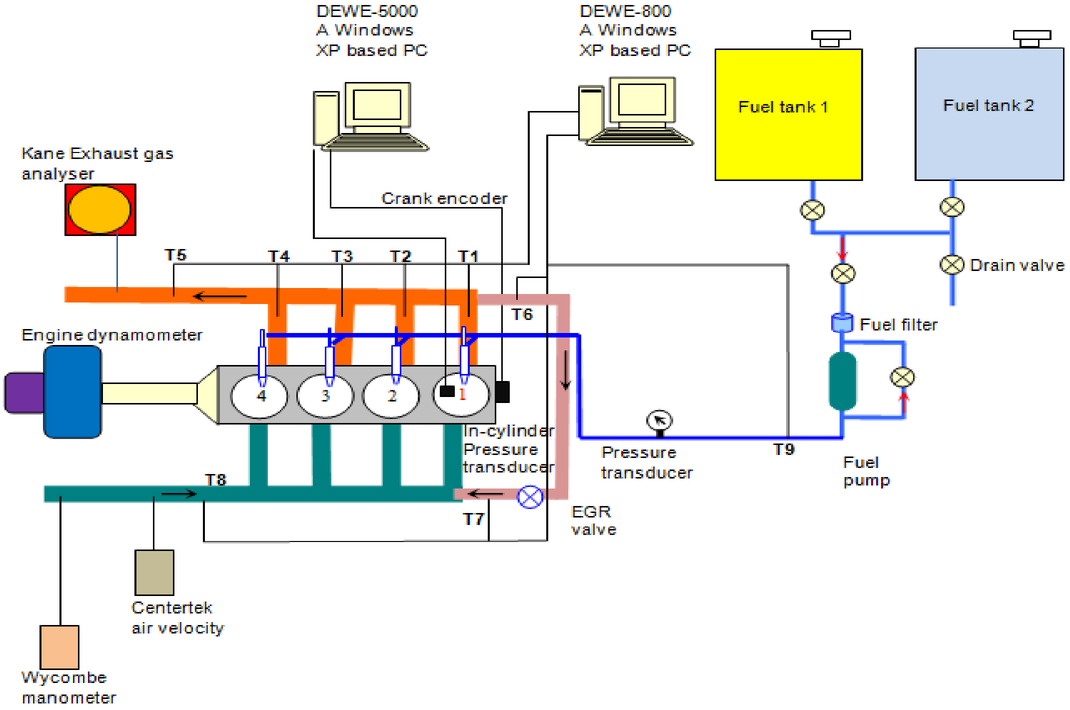


Figure 2. Schematic diagram of a Mitsubishi 4D68 diesel engine system.

Software named DEWECA from Dewetron Inc. provides the off-line steady state analysis based on in-cylinder pressure and crank angle degree and the analysis included the peak pressure, indicated power and indicated mean effective pressure (IMEP). Furthermore, the analysis of mass fraction burn, rate of heat release, brake thermal efficiency and brake specific fuel consumption (bsfc) have been performed to evaluate the overall performance of the combustion. A Kane gas analyzer was used to measure the engine exhaust emission and was recorded in Excel file format. The exhaust gas was sampled at 50 cm downstream of the exhaust extractor. The emission parameters measured include carbon dioxide (CO2), carbon monoxide (CO), nitrogen monoxide (NO) and nitrogen oxides (NOx). In this study, biodiesel blend, B20, biodiesel blend with alcohol additives, B20 M5 (20% biodiesel + 80% mineral diesel +

5% methanol), biodiesel blend with alcohol additives, B20 M5 (20% biodiesel + 80% mineral diesel + 5% ethanol) and mineral diesel as a baseline fuel are used as test fuels. Table 2 summarizes the detail properties of the test fuels.

Table 2. Test fuels properties.

Description	Testing Method (ASTM)	Mineral diesel	B20	B20 E5	B20 M5
Density @ 20 °C g/cm³	D287	0.837	0.845	0.8429	0.8437
Viscosity @40 °C mm²/s	D445	4.237	4.514	3.1354	3.28233
Cetane number	D613	71.6	78.2	76.7	76.4
Flash Point (°C)	D93	70	110	43	45
Acid Number	D3339	0.24	0.02	0.54	0.59
Net heat of combustion (MJ/kg)	D240	49.962	45.714	46.802	43.466
Iodine Number	D1957	N/A	N/A	12.8	10.17
Free fatty acids, %	D664	N/A	N/A	0.270098	0.2953

The engine was controlled by a Dynalec control to increase and decrease the engine speed. It was operated by naturally aspirated and the fuel temperature kept constant at 30°C. Engine test condition for the study is summarized in Table 3.

Table 3. Test condition.

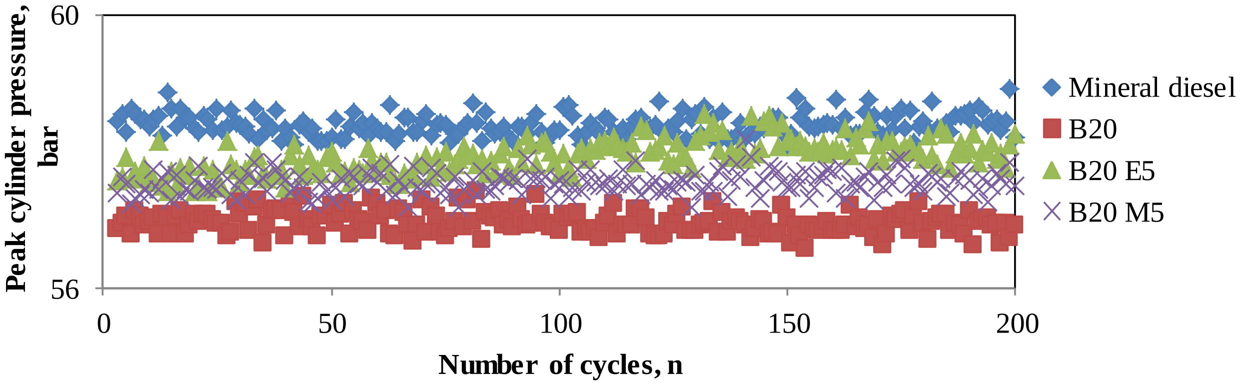
Engine Parameter	Details
Engine speed, n	2500 rpm
Fuel temperature, Tf	30^{o}C
Naturally aspirated air temperature, Tba	35^{o}C
Mode of EGR	OFF

RESULT AND DISCUSSIONS

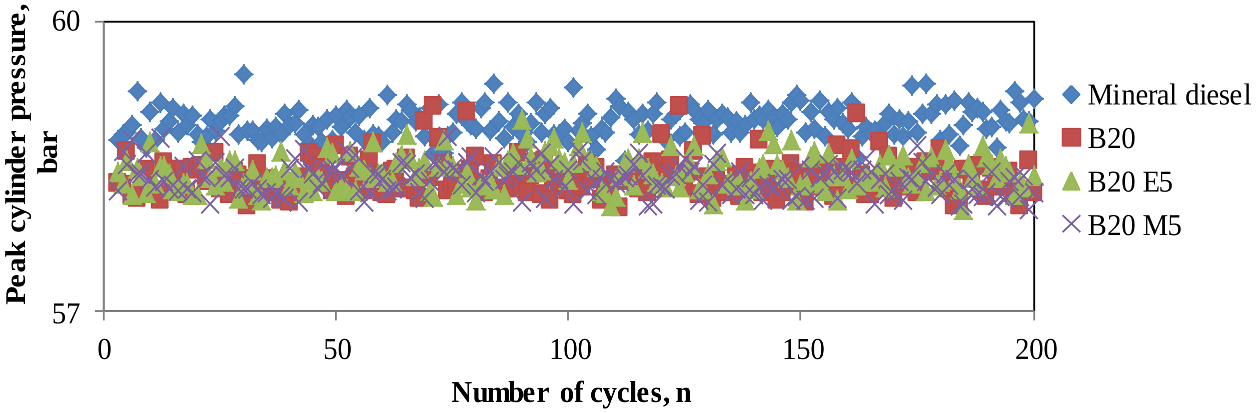
The experimental study has been conducted on a Mitsubishi diesel engine and measured the inner pressure in the cylinder vary with crank angle degree (CAD) over different types of fuel; namely B20, B20 M5, B20 E5 and mineral diesel as a baseline fuel. The series of tests has been performed for the experimental study with the engine working at 2500 rpm in evaluating the cycle-to-cycle variation of different fuel during the combustion in the measured cylinder.

With differences among the oxygen contents and lower heat of combustion for the fuels tested, the comparison can be made with the same condition. The differences in the measured performance of the engine from the baseline operation of the engine when operating with mineral diesel fuel were determined and compared. Mineral diesel as a baseline fuel was carried out first to be tested in order to determine the engine characteristics, followed by B20. The same procedure has been repeated for each test with the same engine operating condition. The test fuel line for each fuel has been cleaned for every fuel change in order to get more accuracy result and the engine was left to operate about 20 minutes to stabilize its condition before starting the new test.

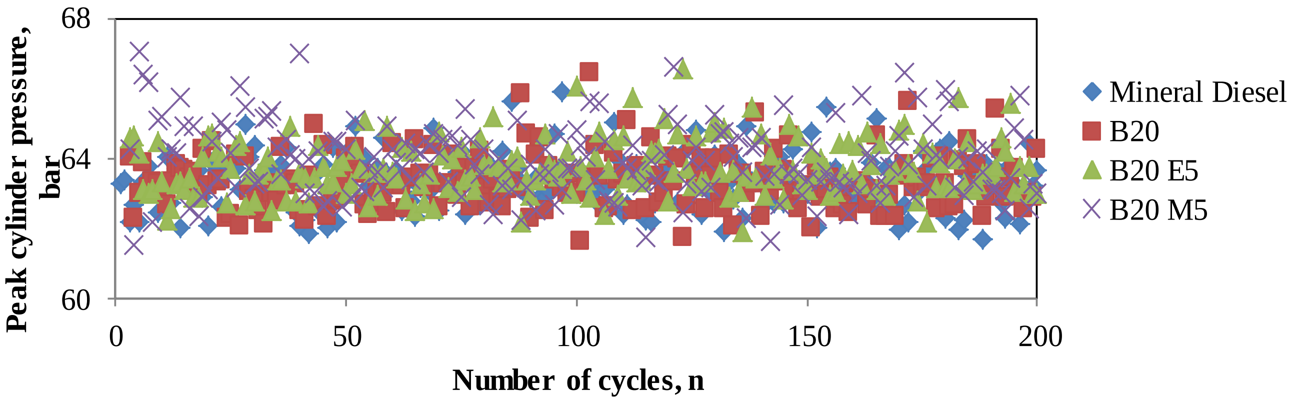
During the test, a recording has been made with the in-cylinder pressure as an indicator for 200 cycles in a combination file, with a sampling rate that correspond to 1^o CA. The indicated cylinder pressure has been corrected by taking the mean value of the pressure during the combustion due to the atmospheric pressure value. The signals from an encoder, which are simultaneously recorded, indicate the position of top dead center (TDC) for each cycle. The position of TDC can be accurately determined in every cycle with referring to those values. The calculation of the accurate engine speed in each cycle with denying friction factor can be done with considering the TDC position of any two following cycles and recognized the sampling rate of the measurements which in this case with the engine speed of 2500 rpm at 1^o CA.



(a)



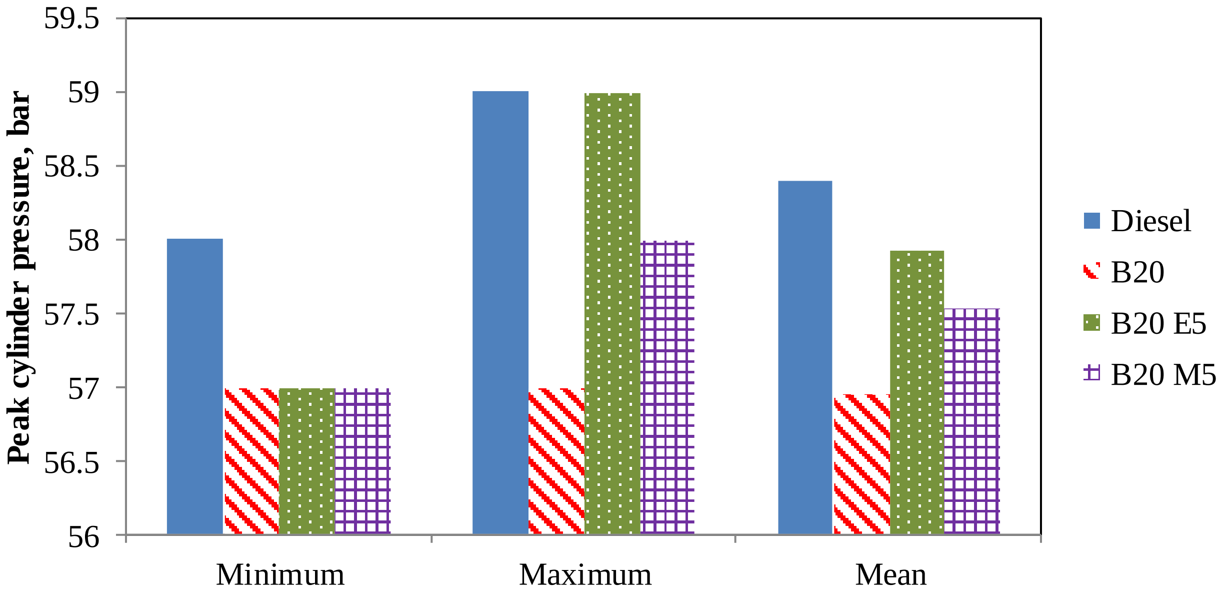
(b)



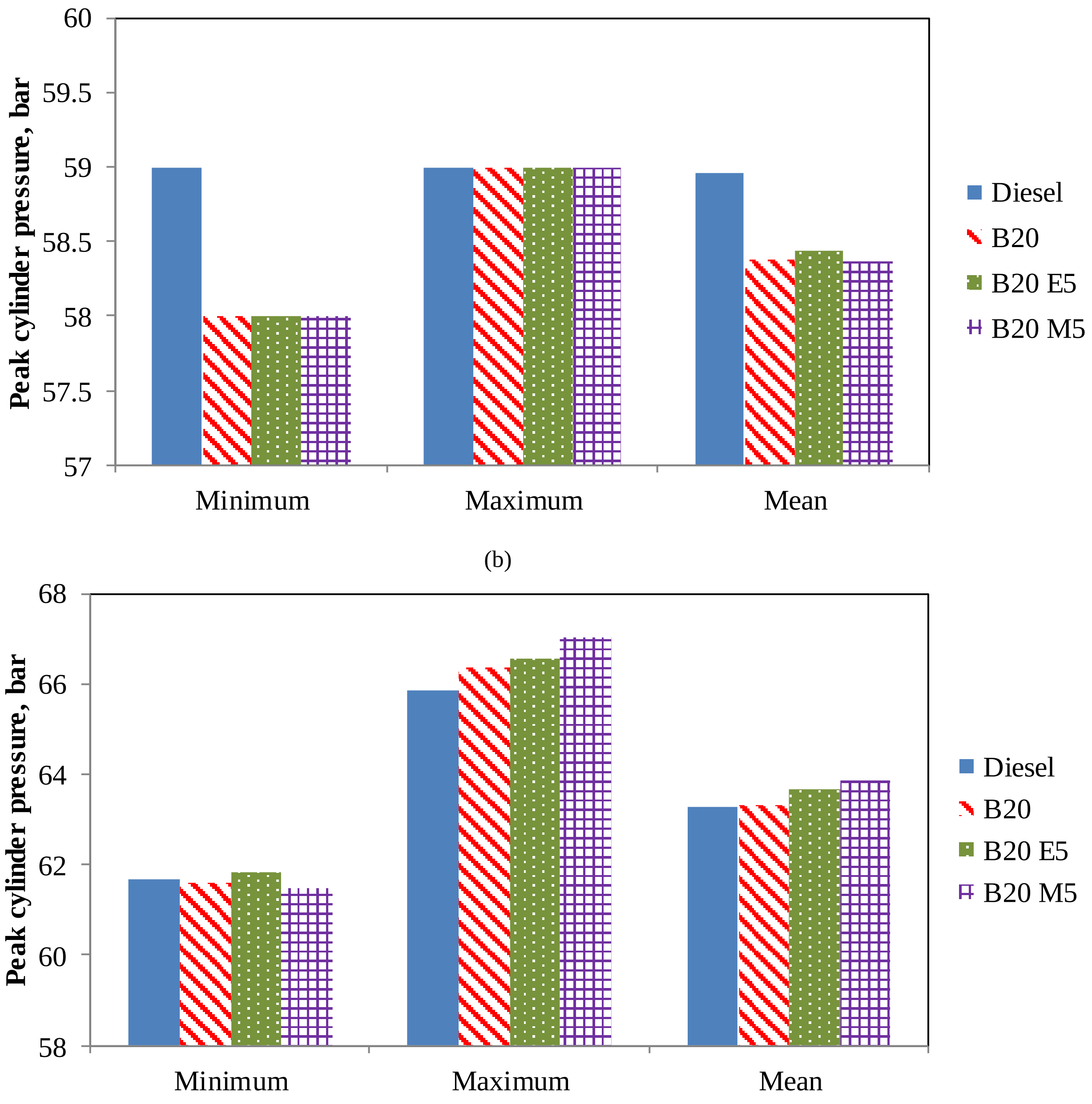
(c)

Figure 3. Variations of peak cylinder pressure for the test fuels within 200 consecutive cycles at constant engine speed, 2500 rpm with engine load (a) 20% (b) 40% (c) 60%.

The variations peak cylinder can be seen in Figure 3 with different fuel; namely mineral diesel, B20, B20 E5 and B20 M5 for 200 consecutive cycles with the constant speed of 2500 rpm and engine loads of 20%, 40% and 60%. It also demonstrated that mineral diesel dominated the overall peak cylinder pressure at low load but at medium and high load, the other test fuels; namely B20, B20 E5 and B20 M5 reached similar level of peak cylinder pressure with mineral diesel. The sudden change of the cylinder pressure during the combustion process affected the heat release rate of the test fuels. All the 200 consecutive pressure cycles are used separately to form the data record values to be statistically computed by defined the involved parameters. The variations of minimum, maximum and mean value for peak cylinder pressures were statistically computed against the number of consecutive cycles.



(a)



(b)

(c)

Figure 4. Statistical analysis (minimum, maximum and mean) of peak cylinder variations for the test fuels within 200 consecutive cycles at constant engine speed, 2500 rpm with engine load (a) 20% (b) 40% (c) 60%.

Figure 4 illustrates the selected minimum, mean and maximum of peak cylinder pressure for the test fuels; mineral diesel, B20, B20 E5 and B20 M5 against the crank angle degree (CAD) at the 200 consecutive cycles with the constant speed of 2500 rpm and engine loads of 20%, 40% and 60%. It is clearly seen from the figure that those single peak cylinder that started from the fuel is injected to the combustion chamber. The air/fuel ratio of the mixture and the types of fuel used in the combustion are the main parameters that influence most of the magnitude of the maximum in-cylinder pressure cyclic variations.

As for the second analysis related to the cyclic combustion with different test fuels, the in-cylinder pressure measurement data were used to compute mean indicated pressure (MIP) which introduced by R Longwic in the previous study (R. Longwic, 2011). The in-cylinder pressure measurements were conducted at the first cylinder of the four cylinder diesel engine with a sampling of 200 consecutive cycles and controlled by the crank angle encoder sensor. Engine loads of 20%, 40% and 60% were given by an eddy-current dynamometer coupled to the engine crankshaft. According to Longwic (R. Longwic, 2011), mean indicated pressure (MIP) is defined as a constant alternative pressure which acting on the engine piston for the period of whole expansion stroke performs the same amount of work regarding to the real variable pressure in the cylinder. Consequently, the mean indicated pressure (MIP) for the test fuels can be computed as:

$$MIP = \frac{L_i}{V_s} \tag{1}$$

Where L_i is the amount of work indicated in the cylinder within the combustion period which was estimated numerically by integrating the measured cylinder pressure. While as for V_s is the engine piston displacement volume of the cylinder at the amount work been executed.

Table 4. Summary of statistical properties of the mean indicated pressure (MIP) at three different engine loads.

Types of fuel	Engine speed, RPM	Engine loads, %	Average MIP [MPa]	MIP Std. dev.	Skewness, skew	Kurtosis, kur
Mineral diesel	2500	20	0.947	0.014	-1.503	4.829
		40	1.292	0.018	-0.219	0.264
		60	1.686	0.018	-0.255	-0.176
B20		20	0.840	0.015	-0.864	0.834
		40	1.219	0.024	-0.431	0.586
		60	1.596	0.018	-0.243	0.043
B20 E5		20	0.909	0.035	-0.270	-0.180
		40	1.181	0.022	-0.502	0.615
		60	1.608	0.017	-0.236	-0.044
B20 M5		20	0.958	0.008	-0.619	2.021
		40	1.364	0.015	-0.107	-0.138
		60	1.739	0.019	-0.263	0.236

The statistical properties for the test fuels are listed in Table 4. Software named IBM SPSS Statistics was used to compute the following MIP data at three different engine loads. The table shows that the averaged indicated pressure level MIP for B20 blends is slightly higher compared to mineral diesel. However, B20 E5 indicates smaller MIP values than mineral diesel at each engine load. While as for B20, the fuel has smaller values of MIP compared to diesel at 60% engine load. In addition for this study, the skewness and kurtosis for the MIP data were computed to validate the actual data condition. Skewness is defined as a measure of symmetry based on the distribution or data set on the certain time series (Groeneveld & Meeden, 1984). While kurtosis can be defined as a measure of how flat the top of a symmetric distribution is when compared to a normal distribution using the same variance (Groeneveld & Meeden, 1984; Pearson, 1905).

The skewness and kurtosis for the MIP data as listed in Table 4 are decreasing with increasing in engine load from 20% to 40% but increase at 60%. Thus, MIP distributions for the mineral diesel change from more concentrated (kur>3) to more flat (kur<3). However, as for B20, B20 E5 and B20 M5, the kurtosis for MIP distributions are more flat (kur<3) at three different engine loads. It also demonstrated that the kurtosis tendencies are not clear for B20 E5 and B20 M5 while in case of B20, there is a faster decrease is observed. It also worth to remark the distribution of MIP for mineral diesel is the closest to Gaussian at all engine loads. By varying the engine loads, it can be observed that the skewness values for B20 show clear flat tendencies which are different for B20 E5 and B20 M5. It also noted that there is a large range of skewness is observed for mineral diesel from low load to high engine load.

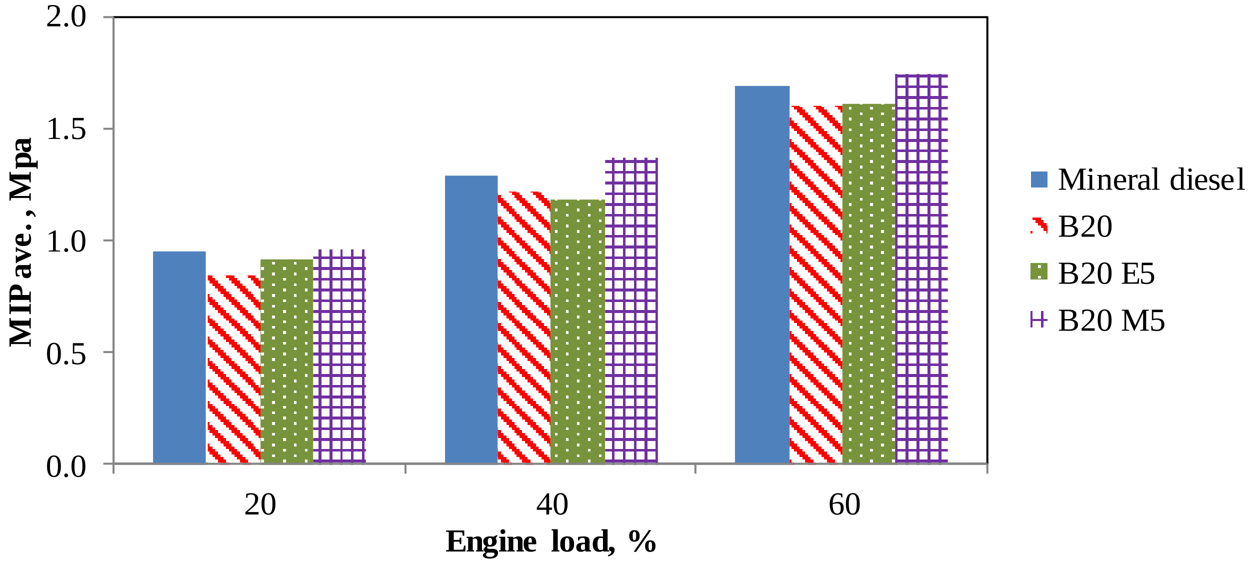


Figure 5. Average mean indicated pressure (MIP) for the test fuels at three engine loads; 20%, 40% and 60%.

Average mean indicated pressure (MIP) for the test fuels at three different engine loads is illustrated in Figure 5. It is clearly seen from the figure that the average MIP for the test fuels are lower at low engine load but slowly increase at the medium and high engine load. This is due to the increasing in-cylinder pressure proportionate to engine load increases with more fuels to be burned and a large amount of work to be executed. It is remarked that B20 M5 has higher average MIP compared to other test fuels and mineral diesel at all engine loads. It is noted that the higher expansion stroke occurs due to the increasing in engine loads and in-cylinder pressure with the assistance from higher oxygenated fuels operated with the diesel engine.

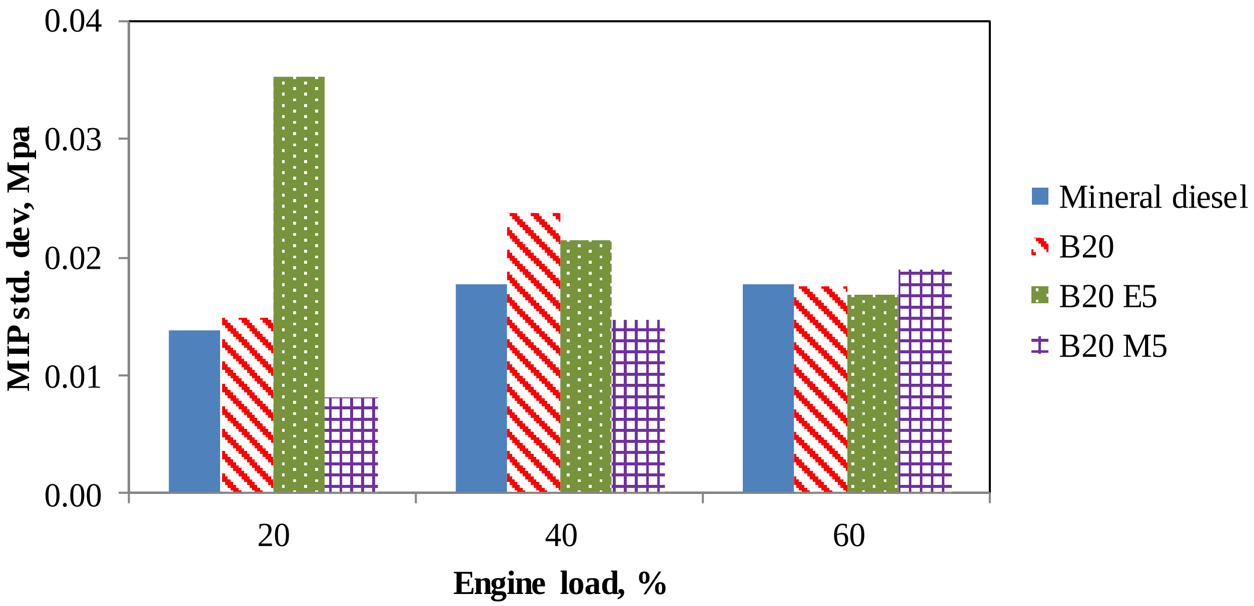


Figure 6. Standard deviation mean indicated pressure (MIP) for the test fuels at three engine loads.

Figure 6 illustrates the standard deviation mean indicated pressure (MIP) for the test fuels at three different engine loads. It is clearly seen from the figure that the standard deviations MIP for B20 E5 is higher at low engine load but slowly decrease at the medium and high engine load. It is observed that MIP values for B20 E5 are not consistently similar to the mean value at low load with a large range of values. While the gap is closer at the medium and high engine loads which demonstrate the MIP values are very close to the mean MIP value. As for B20 M5, the MIP standard deviations are increase proportionate to the increase in engine loads. It is noted that the MIP values distribution for B20 M5 is closer to the mean value at low engine load but advanced at medium and high engine loads. This condition is much relates to the test fuel properties and combustion period from the start of combustion (SOC) to the end of combustion (EOC).

CONCLUSIONS

There are two reasons that motivate the cyclic variation studies on biodiesel blends for diesel engines; (1) to determine and improve the lean combustion efficiency and increase power output, and (2) correlate the diesel engine combustion cycles with the emission produced during start of combustion (SOC) and end of combustion (EOC) operating with different test fuels. This paper focused on the combustion cyclic variations for peak cylinder pressure and different patterns of MIP variations with different test fuels; mineral diesel, B20, B20 E5 and B20 M5 fuels against number of cycle diagrams. Different combustion cyclic variations for diesel and biodiesel blends are observed and mostly due to the differences in psychocemical properties include density, viscosity, Cetane number, etc. Analysis of different in-cylinder pressure patterns is important which could leads to develop advanced control strategies for higher fuel conversion efficiency and lower emission of NOx, CO2, CO and unburned hydrocarbons (UHCs).

ACKNOWLEDGEMENTS

The authors would like to thank the Faculty of Mechanical Engineering in Universiti Malaysia Pahang (UMP) and Universiti Malaysia Pahang for financial support under RDU110332. The first author is grateful to the assistance of Prof Talal Yusaf (University of Southern Queensland).

REFERENCE

Atabani, A. E., Silitonga, A. S., Badruddin, I. A., Mahlia, T. M. I., Masjuki, H. H., & Mekhilef, S. (2012). A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews, 16*(4), 2070-2093.

Buyukkaya, E. (2010). Effects of biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel, 89*(10), 3099-3105.

Ceviz, M. A., Koncuk, F., Küçük, Ö., Gören, A. C., & Yüksel, F. (2011). Analysis of Combustion Stability and Its Relation to Performance Characteristics in a Compression Ignition Engine Fueled with Diesel-biodiesel Blends. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 33*(10), 990-1003.

Chauhan, B. S., Kumar, N., & Cho, H. M. (2012). A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends. *Energy, 37*(1), 616-622.

Demirbas, A. (2009). Characterization of Biodiesel Fuels. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 31*(11), 889-896.

Groeneveld, R. A., & Meeden, G. (1984). Measuring skewness and kurtosis. *The Statistician*, 391-399.

Heywood, J. B. (1988). *Internal combustion engine fundamentals*: McGraw-Hill.

Liaquat, A. M., Masjuki, H. H., Kalam, M. A., Varman, M., Hazrat, M. A., Shahabuddin, M., et al. (2012). Application of blend fuels in a diesel engine. *Energy Procedia, 14*(0), 1124-1133.

McCarthy, P., Rasul, M. G., & Moazzem, S. (2011). Comparison of the performance and emissions of different biodiesel blends against petroleum diesel. *International Journal of Low-Carbon Technologies*.

Özkan, M. (2007). Comparative Study of the Effect of Biodiesel and Diesel Fuel on a Compression Ignition Engine’s Performance, Emissions, and Its Cycle by Cycle Variations. *Energy & Fuels, 21*(6), 3627-3636.

Pearson, K. (1905). " Das Fehlergesetz und Seine Verallgemeinerungen Durch Fechner und Pearson." A Rejoinder. *Biometrika, 4*(1/2), 169-212.

Pidol, L., Lecointe, B., Starck, L., & Jeuland, N. (2012). Ethanol–biodiesel–Diesel fuel blends: Performances and emissions in conventional Diesel and advanced Low Temperature Combustions. *Fuel, 93*(0), 329-338.

Pulkrabek, W. W. (2004). *Engineering fundamentals of the internal combustion engine*: Pearson Prentice Hall.

R. Longwic, A. K. S., K. Górski, W. Lotko, G. Litak*. (2011). Cycle-to-Cycle Variation of the Combustion Process in a Diesel Engine Powered by Different Fuels. [Cycle to Cycle Variation]. *Journal of Vibroengineering, 13*(1), 8.

Rakopoulos, C. D., Rakopoulos, D. C., Giakoumis, E. G., & Kyritsis, D. C. (2011). The combustion of n-butanol/diesel fuel blends and its cyclic variability in a direct injection diesel engine. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 225*(3), 289-308.

Senatore A, C. M., Rocco V, Prati MV. . (2000). A comparative analysis of the combustion process in D.I. Diesel engine fueled with biodiesel and diesel fuel. *SAE Paper 2000-01-0691*.

Y. V. Hanumantha Rao, R. S. V., V. S. Hariharan, A. V. Sitarama Raju, P. Nageswara Redd. (2009). Use of Jatropha Oil Methyl Ester and Its Blends as an Alternative Fuel in Diesel Engine. *J. of the Braz. Soc. of Mech. Sci. & Eng., XXXI*(No. 3), 253-260.