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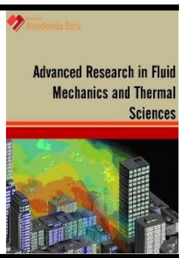

Cyclic Variation Analysis of Palm Biodiesel Fuel in Low Compression Marine Diesel Engine

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ABSTRACT

Environmental pollution due to fossil fuel combustion has made biodiesel a viable option. Biodiesel fuel has been widely used in land-based vehicle engines, but it is limited to marine sectors. This study investigated the cyclic variations effect of palm biodiesel to determine combustion stability in low compression marine diesel engine. The time series of peak pressure and indicated mean effective pressure is examined using statistical and continuous wavelet transformation methods. The results show that the cyclic variations on marine engine operated with palm biodiesel are better than diesel, as indicated by lower COV_{pmax} and COV_{IMEP} values, which are below 1.29% and 2.50% respectively. Increase the percentage of palm biodiesel in blends has gradually reduced the COV_{IMEP} and the B30 palm biodiesel blend produces the minimum cyclic variations of IMEP with 1.91%. This finding was agreed with the wavelet spectrum results which revealed that the B30 palm biodiesel blend has the lowest IMEP frequency oscillation. The B30 palm biodiesel blend has produced the most stable combustion among the tested fuels.

1. Introduction

The environmental awareness issue on greenhouse gas emissions has increased the usage of plant-based biodiesel as alternative fuel [1–3]. It is a viable option and suitable for diesel engines apart from being renewable, non-toxic, environmentally friendly and has similar properties to diesel [4–6]. Biodiesel fuel offers many advantages such as having higher cetane number, is non-aromatics and has 11% of oxygen element [7–9]. Biodiesel can be produced from various sources of feedstocks such as rapeseed, sunflower, palm, soybean, canola, coconuts, peanuts, animal fats and waste oil

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[10,11]. In Europe and the United States, soybean and rapeseed are typically used as the main sources of biodiesel. In tropical countries such as Indonesia, Malaysia, and Thailand, biodiesel is sourced from palm oil. Palm biodiesel, also known as palm fatty acid methyl ester (FAME), is generated through a transesterification process. It has low production cost and is economically suitable for biodiesel production [12–14]. Furthermore, the emissions quality of biodiesel indicates better results compared to fossil fuel diesel [15–22].

Marine engines slightly differ from automotive engines in terms of size and operating parameters. They usually operate at a lower speed of 425–1800 rpm and has a slightly lower compression ratio of between 12:1–18:1 [23]. Low compression engines generate relatively fewer vibrations and thermal pressures to the engine block [24]. Nevertheless, lower compression can cause a detrimental effect to the engine efficiency. Reducing the engine compression ratio from 20.0 to 15.5 has decreased the thermal efficiency and increased the carbon monoxide (CO), carbon dioxide (CO_2) and hydrocarbon (HC) exhaust emissions [25]. In the latest report, the International Maritime Organization stated that CO_2 gas emissions from ships consisted of 2.6% (938 thousand tons) of the total man-made emissions of the same substance. Nitrogen oxide ($NO_{X)}$ and sulphur oxide (SO_X) emissions are 15% and 13% respectively of their global emissions [26]. These figures are projected to grow three folds in 2050 if no follow-up action is taken. Therefore, the use of alternative fuel such as biodiesel appears to be a possible solution in addressing this issue.

Engine cyclic variations refer to the difference of peak cylinder pressure from the cycle-to-cycle combustion process. This process occurs due to several factors including the variation of cylinder mixture motion, variation in the amount of air-fuel injected, fuel properties, combustion temperature and burn angle [23,27–29]. Ultimately, cyclic variation will affect performance and efficiency of engines, which will consequently reduce the output power, increase fuel consumption and exhaust emission, increase noise and decrease engine durability [30–32]. Research related to cyclic variation has produced mixed results. Application of palm biodiesel in automotive diesel engines has increased the peak cylinder pressure variation [33]. Wang *et al.,* stated that the quantity of alternative fuel (dimethyl ether) was directly proportional to the cyclic variation in diesel engines [34]. Ali *et al.,* studied the effects of additive in B30 biodiesel blends. The authors employed wavelet spectrum analysis in assessing engine cyclic variations. The results indicated that the cyclic variations increased as a higher percentage of diethyl ether additive was added to the blends [35]. A study by Chen *et al.,* investigated the influence of fuel injection timing to cyclic variations in dual-fuel engines. The study reported that the reduction in cyclic variations occurred when delayed the injection time [36]. The application of wavelet tool in engine cyclic variation analysis has been widely used in recent studies [37–41].

Apart from the above literature, there is a lack of biodiesel studies that have been reported on marine diesel engine applications. Therefore, this study aims to investigate the combustion cyclic variations of different percentage of palm biodiesel blends in a low compression marine diesel engine. The study evaluates the stability of palm biodiesel combustion in-cylinder pressure and related parameters including the peak pressure, indicated mean effective pressure, rate of pressure rise, coefficient of variation and time-frequency wavelet spectrum analysis.

2. Methodology

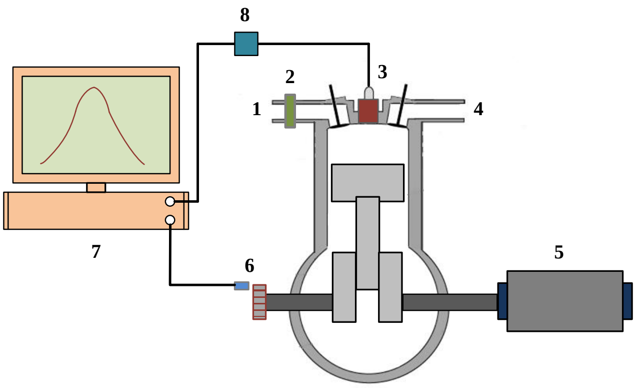
2.1 Test Engine Setup

Laboratory engine testing was performed on a four-stroke, direct injection marine diesel engine. The engine was equipped with in-line six cylinders and had 14 litres displacement volume. The combustion chamber was designed with a low compression ratio of 14.5:1. Such engine is commonly used as a prime mover on medium-sized ships or as an electric power generator engine. The engine was completely instrumented and connected to the data acquisition system. The specifications of the test engine are presented in Table 1.

Table 1
Specifications of marine diesel engine

Engine Model	Cummins NT-855M
Type	Four strokes, direct injection
Number of cylinders	In-line six cylinders
Bore x stroke	139 mm x 152 mm
Compression ratio	14.5:1
Displacement	14 liters
Torque	1068 Nm
Rated power	201 kW
Cooling medium	Water-cooled

The engine was installed with a dynamometer to give a certain braking load. The in-cylinder combustion pressure data was recorded using Optrand fibre-optic pressure transducer and TFX Engineering data acquisition system. The transducer was installed on the top of engine block as illustrated in Figure 1. The Optrand fibre-optic pressure sensor operated using the principle of light, reflection from a flexible metal diaphragm which was exposed to combustion pressure in the engine cylinder. The specifications of the pressure transducer intended for this study are listed in Table 2. A magnetic pickup crank sensor was attached to provide the angular position of the crankshaft. The signal from the pressure transducer and crankshaft encoder was transmitted to the amplifier before being sent to the data acquisition system.



1: Intake air, 2: Air flow meter, 3: Pressure transducer, 4: Exhaust, 5: Dynamometer, 6: Crank angle encoder, 7: Data acquisition system, 8: Charge amplifier

Fig. 1. Experiment schematic diagram

Table 2
Specifications of pressure transducer

Description	Specifications
Brand	Optrand
Model	H 322G1-Q
Range	0 to 200 bar
Frequency response	0.1 Hz to 30 kHz
Temperature range	-40 to 350 °C
Sensor output	0.5 to 5.0 V

2.2 Fuel Preparation and Property Test

The test fuels were prepared by mixing 10%, 20% and 30% of palm biodiesel with Euro 2 diesel fuel as listed in Table 3. The Euro 2 diesel fuel was identified as B0, while the palm biodiesel blends was identified as B10, B20 and B30. The amount of fuel used in the blending process was determined based on volumetric basis. The fuel samples have been blended using an electrical stirrer before subjected to testing. The mixture was stirred continuously for 1 hour and left for another 30 minutes to reach equilibrium at room temperature as recommended [38].

Table 3
Mixing percentage of the test samples

Blend sample	Palm biodiesel (Volume %)	Diesel (Volume %)
B0	0	100
B10	10	90
B20	20	80
B30	30	70

The fuel property test was carried out on the palm biodiesel blended fuel and the results were summarised in Table 4. The findings show that the density and viscosity of the samples are directly proportional to the ratio of palm biodiesel in the blends. Increasing the palm biodiesel percentage in the blends had increased the density and viscosity values. Comparatively, the density and viscosity of B30 palm biodiesel is 1.58% and 27.61% respectively, higher than diesel fuel. In general, all biodiesel blends regardless of the feedstock are denser and less compressible than diesel fuel due to their large molecular mass and chemical structure. Meanwhile, the heating value of the samples decreased with the increasing percentage of palm biodiesel. The heating value of B30 palm biodiesel fuel is 10.13% lower than diesel fuel. Lower heating value of fuel is due to the presence of oxygen content in the biodiesel molecules [42]. Additional oxygen elements have led to a reduction in carbon-hydrogen ratio in biodiesel blends which contributes to lower heating values compared to more carbon-hydrogen ratio on diesel fuel [43,44].

Table 4
Fuel property of diesel and palm biodiesel blends

Fuel property	B0	B10	B20	B30
Density (kg/m^3)	825	830	834	838
Kinematic viscosity (mm^2/s)	4.02	4.52	4.81	5.13
Heating value (MJ/kg)	48.26	46.33	44.67	43.37

2.3 Cyclic Variation Equations

Among the most used parameters in cyclic variation or cycle-to-cycle variation analysis are the peak in-cylinder pressure (P_{max}), indicated mean effective pressure (IMEP) and coefficient of variation (COV). P_{max} value is obtained through the actual reading of the combustion pressure over a certain cycles duration. IMEP is average pressure acting on an engine piston over one revolution and it is also defined as the work output per unit displacement volume. This parameter is independent of the size, speed and number of cylinders on the engine. The IMEP can be computed in accordance to the Eq. (1) and Eq. (2)

$$IMEP = \frac{W_c}{V_d} \tag{1}$$

$$W_c = \int P\,.dv \tag{2}$$

where W_c is the work performed for one cycle, V_d is engine displacement volume and P is the measured in-cylinder combustion pressure. The V_d at any instantaneous crank angle position was calculated using engine geometry parameters, as stated in Eq. (3) and Eq. (4) [23]

$$V_d = V_c + \frac{\pi B^2}{4}(l + a - s) \tag{3}$$

$$s = a\cos\theta + (l^2 - a^2\sin^2\theta)^{\frac{1}{2}} \tag{4}$$

where V_c refers to the clearance volume, *B* is the bore diameter, *a* is the crank radius, *l* is the length of connecting rod, *s* is the distance between the crank axis to piston pin axis, and θ is the instantaneous crank position in radian unit.

COV is a measurement of the event dispersion and frequently used indicator in the engine cyclic variation studies [34]. It can be computed by adhering to Eq. (5) and Eq. (6) [23]

$$COV = \frac{\sigma}{\bar{x}} \times 100\% \tag{5}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{n-1}} \tag{6}$$

where σ is the standard deviation, $\bar{x}$ is the average value and *n* refers to the total number of cycles in the study.

The wavelet spectrum analysis is a tool that is commonly used to analyses the dominant periodic signal in time series of data sets. Transformation of the time series data into the time-frequency domain will give simultaneous information about how the frequency and amplitude vary within certain time duration. The wavelet method has been widely applied in the internal combustion engine research [35,37,39,41,45,46]. The continuous wavelet transformation (CWT) used in this study is based on the findings by Torrence and Compo [47], but with some modifications according to the needs of this study. The main steps include the selection of the mother wavelet and its convolutions in the time series. The Morlet wavelet order six was chosen for this work because it provides a good balance between time and frequency resolutions. The Morlet wavelet consists of a plane wave modulated by a Gaussian function and can be derived according to Eq. (7)

$$\psi(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2} \tag{7}$$

where $\psi$is the non-dimensional wavelet, $\eta$is the time parameter, $\pi$is the normalization factor and $\omega_0$is the wave number.

In order to change the overall size, and to slide the entire wavelet within a certain time frame, the scaling parameter (*s*) must be included. The final wavelet transformations (W_n) for a given time series (*x*) can be simplified by Eq. (8)

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \rightleftarrows\rightleftarrows \psi^* \left[\frac{(n'-n)\delta t}{s}\right] \tag{8}$$

where *n* is the translation parameter, *N* is the cycle number, δt refers to the time interval, *n* denotes the time index and the asterisk (*) indicates the complex conjugate values. The wave power spectrum (WPS) energy at the specific scale of "s" is defined by the Eq. (9)

$$P(s) = |W_n(s)|^2 \tag{9}$$

The WPS is plotted on a time-frequency plane, with the cycle number on x-axis and the band period on y-axis. The WPS surface contour provides a good description of engine cyclic variation at different periodic scales. Another useful parameter derived from WPS is the global wavelet spectrum (GWS). The GWS is the average of the WPS at each scale over all engine cycles and it is identical to the smoothed Fourier power spectrum. The dominant periodicities in time series can be identified from the peak locations in the GWS plot. The GWS over a certain period can be computed by Eq. (10)

$$W_s^2 = \frac{1}{N_c} \sum_{n=1}^{N} |W_n(s)|^2 \tag{10}$$

3. Results and Discussion

This section discusses the effects of diesel fuel and palm biodiesel blends on the combustion cyclic variations in low compression marine diesel engine. The cyclic variation analysis was focussed at constant engine load and torque rated speed of 1400 rpm. The analysis consists of variation in the peak cylinder pressure and indicated mean effective pressure parameters. In addition, the wavelet power spectrum simulation was also provided to present the IMEP variations in the graphic form of the time-frequency domain.

3.1 Cyclic Variation in Peak Cylinder Pressure (P_{max})

Maximum pressure or p_{max} is an important aspect that needs to be addressed during the design process because it relates to the output power generated by the engine. The magnitude of p_{max} depends on the phasing and speed of combustion process. Higher p_{max} value is normally generated from faster fuel burning rate. Figure 2 illustrates the cycle-to-cycle variation of p_{max} for 100 consecutive cycles running using diesel fuel and palm biodiesel blends in low compression marine diesel engine. The value of p_{max} was spread over the range of 4.9–5.6 MPa for all tested fuels.

The maximum, minimum, average and standard deviation values of p_{max} are listed in Table 5. The average of p_{max} was noticed as 5.35 MPa, 5.33 MPa, 5.32 MPa and 5.32 MPa for B0, B10, B20 and B30 respectively. The use of palm biodiesel blends has slightly reduced the peak of p_{max} by 0.25–1.00% compared to diesel fuel. The variation of p_{max} is reduced when running with palm biodiesel blends as indicated by lower standards deviation value compared to diesel fuel.

Meanwhile the COV p_{max} for B0, B10, B20 and B30 was calculated as 1.47%, 1.15%, 1.29% and 1.11%, respectively as shown in Figure 3. The use of palm biodiesel blends has reduced the dispersion of p_{max} in low compression marine engine. Effects of slow burning rate by palm biodiesel in low compression marine engine have contributed to this occurrence and results in more stable combustion. More viscous of biodiesel property has contributed to slow burning during the combustion process [48]. This indicates that the overall cyclic variation of P_{max} on low compression marine diesel engines is minimal when operated with palm biodiesel.

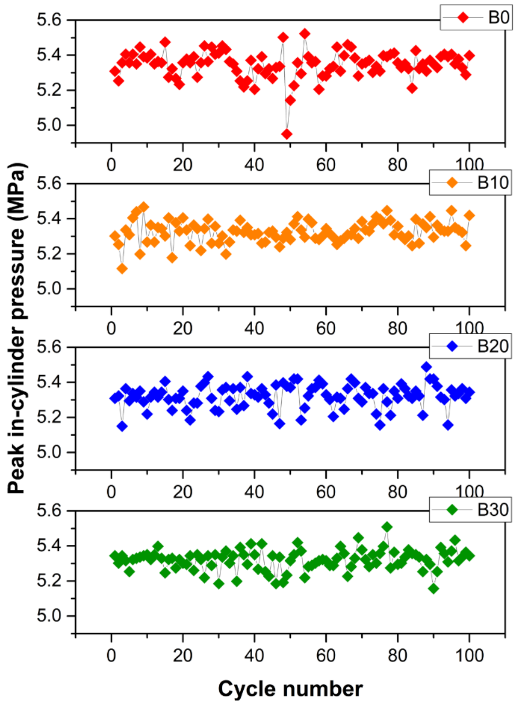


Fig. 2. Cyclic variation in p_{max} of diesel fuel and palm biodiesel blends

Table 5
Detailed variations in p_{max} of diesel fuel and palm biodiesel blends

Parameter	B0	B10	B20	B30
Maximum (MPa)	5.52	5.47	5.49	5.51
Minimum (MPa)	4.95	5.12	5.15	5.16
Average (MPa)	5.35	5.33	5.32	5.32
Standard Deviation	0.78	0.61	0.69	0.59
Maximum (MPa)	5.52	5.47	5.49	5.51

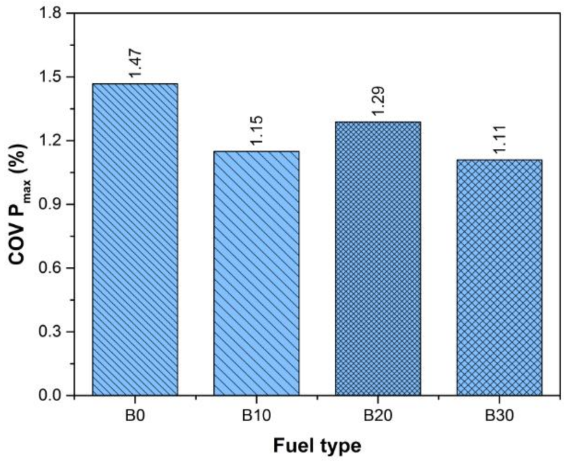


Fig. 3. COV p_{max} of diesel fuel and palm biodiesel blends

The p_{max} frequency distributions of diesel fuel and palm biodiesel blends are illustrated in Figure 4. The graph indicates scattered distribution of peak pressure where most of the readings concentrated in the region of 5.4-MPa, which comprises of 58%, 58%, 62% and 64% for B0, B10, B20 and B30 fuel, respectively. Meanwhile, at the 5.5-MPa range, the B0 fuel dominates with 19%

frequency distribution, leaving behind B10, B20 and B30 at 11%, 10% and 5%, respectively. At the region of 5.6-MPa, the p_{max} distribution is only occupied by the B0 and B30 fuel with 2% and 1%, respectively. The p_{max} of B0 fuel is also located at the lower region within 5.0–5.2 MPa.

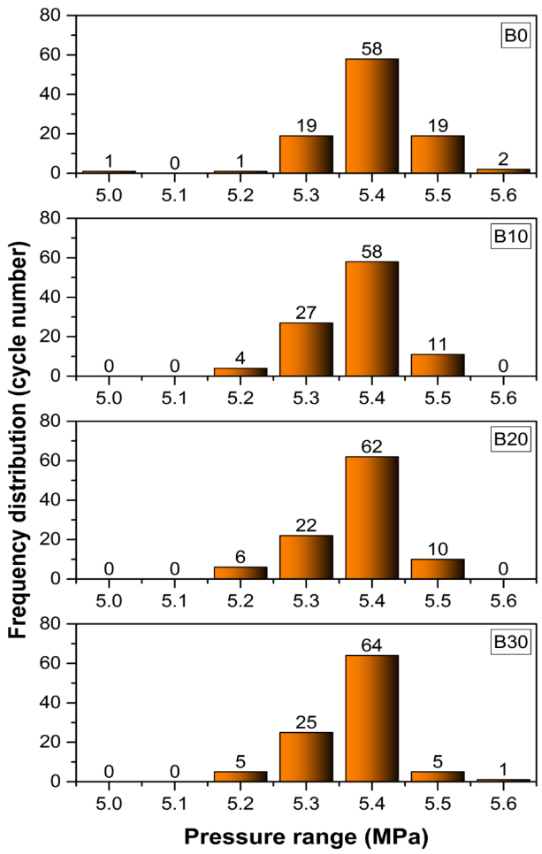


Fig. 4. Frequency distribution in p_{max} of diesel fuel and palm biodiesel blends

3.2 Cyclic Variation in IMEP

The IMEP is a measure of engine work output and is defined as the average pressure acting on the engine piston during engine combustion cycle. It is a common parameter used in assessing the stability of fuel combustion inside the engine cylinder. Faster combustion rate is directly proportional to higher IMEP output value. Figure 5 displays the fluctuations of IMEP in low compression marine diesel engine operating with diesel fuel and palm biodiesel blends. The maximum values of IMEP are 0.74 MPa, 0.74 MPa, 0.72 MPa and 0.72 MPa for B0, B10, B20 and B30, respectively. Lower IMEP values for palm biodiesel blends correspond to slow burning rate of biodiesel as discussed in Section 3.1.

The IMEP frequency distributions for diesel fuel and palm biodiesel blends are illustrated in Figure 6. The plot indicates that the IMEP values are scattered within the region of 0.65 to 0.75 MPa. Most of the fuel has frequency distribution of IMEP at 0.70-MPa region, recorded at 49%, 41%, 55% and 61% of B0, B10, B20 and B30 fuel, respectively. At the upper region of 0.75-MPa, the IMEP dispersion was only recorded by B0 and B10 fuels with 2% and 4% frequency, respectively. Meanwhile, the frequency of B0 IMEP also occurs at 0.65-MPa region with 3% spread. The range of IMEP distribution of palm biodiesel blends is lower compared to diesel fuel.

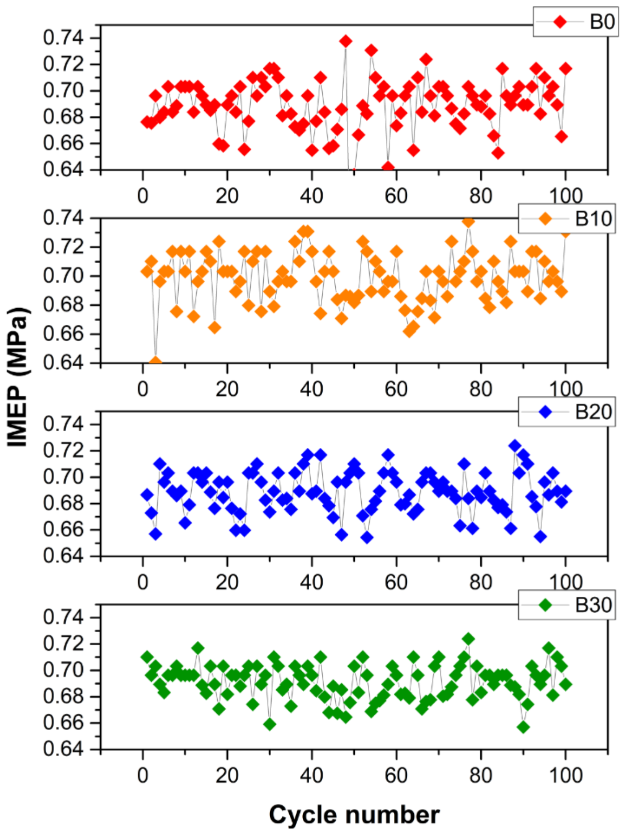


Fig. 5. Cycle-to-cycle variation in IMEP of diesel fuel and palm biodiesel blends

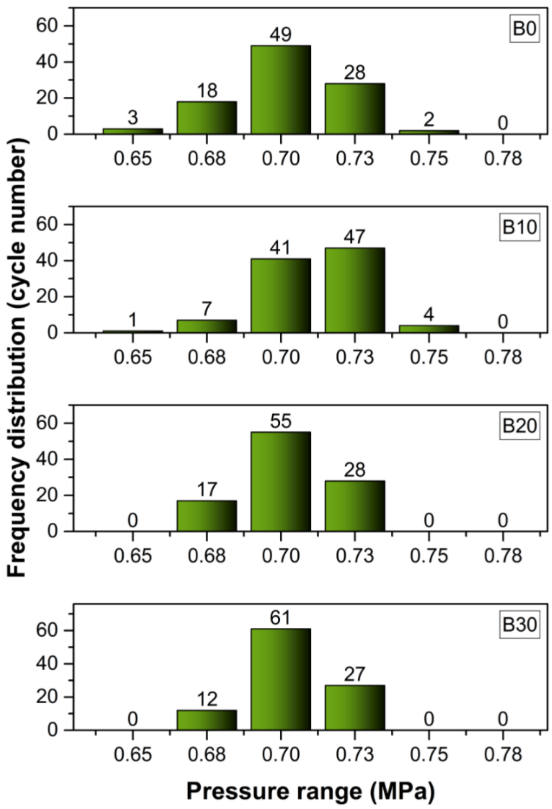


Fig. 6. Frequency distribution in IMEP of diesel fuel and palm biodiesel blends

The trends of COV_{IMEP} in low compression marine diesel engine are shown in Figure 7. The B0, B10, B20 and B30 readings are 3.16%, 2.50%, 2.27% and 1.91%, respectively. The use of palm biodiesel blends has reduced the COV_{IMEP} values up to 39.56% compared to diesel fuel. Lower variations of IMEP for palm biodiesel fuel are due to slow fuel combustion speed coupled with low compression of marine engine that produces more combustion stability. Overall, the cyclic variation inside the marine diesel engine is at the lower level – a previous study suggested that the COV_{IMEP} should be less than 10% to avoid vehicle driveability problems [23]. The details of IMEP variations in low compression marine diesel engine are summarised in Table 6.

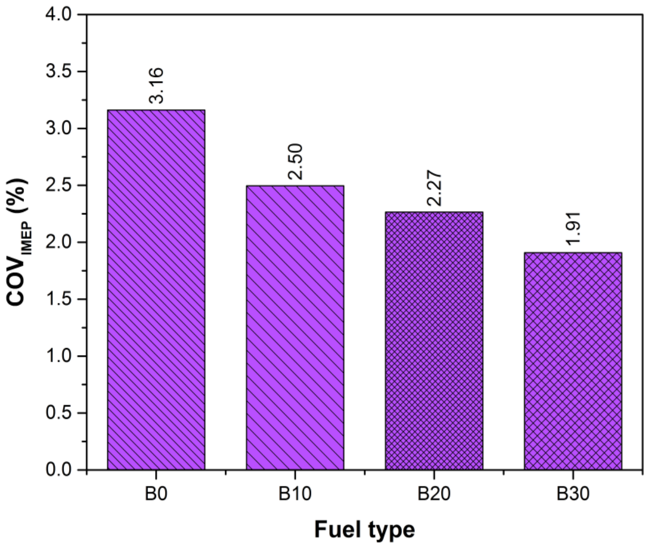


Fig. 7. COV_{IMEP} of diesel fuel and palm biodiesel blends

Table 6
Detail variations in IMEP of diesel fuel and palm biodiesel blends

Parameter	B0	B10	B20	B30
Maximum (MPa)	0.74	0.74	0.72	0.72
Minimum (MPa)	0.58	0.64	0.65	0.66
Average (MPa)	0.69	0.69	0.69	0.69
Standard Deviation	0.22	0.17	0.16	0.13
Maximum (MPa)	0.74	0.74	0.72	0.72

3.3 Wavelet Spectrum Analysis

In this section, the IMEP time series of 100 consecutive engine cycles were analysed using the continuous wavelet transform (CWT) method. The wavelet power spectrum (WPS) and global wavelet spectrum (GWS) were plotted to investigate the effects of different palm biodiesel blends on IMEP variations in terms of frequency and amplitude. The confidence level of WPS analysis was set at 95% with null hypothesis below 5% level. WPS peak that exceeds the set confidence level will appear as a red-noise background spectrum in the plot. In order to avoid errors due to finite-length of data, the WPS time series was padded with zeroes at both ends during the simulation process. In addition, the region in which these edge effects become important is called the cone of influence (COI). The result below the COI line is considered invalid for evaluation. The wavelet spectrum simulation models were run using the MATLAB software (Version: R2017b, License number: 40641886).

Based on the 100 cycle's duration of the IMEP time series, the wavelet analysis was confined to periodicities within the 64-band periods. Figure 8 illustrates the WPS and GWS of B0 IMEP time series with several fluctuations results. A strong and higher intensity of IMEP variation appears between the 2–16 band periods and spanning over 45–55 cycle number. The less strong periodic bands are also found within 2–16 band periods but widely spreading along 30–70 cycle numbers. Several short-term periodicities were observed along the whole time period of B0 fuel. The wavelet analysis of B10 IMEP time series are shown in Figure 9. As seen in this figure, IMEP variation occurs at multiple time scales. A persistent strong oscillation obviously appears at 16–18 band periods spreading from 35–70 cycle numbers. Furthermore, moderate short-term periodicities also occur at low frequency as indicated within 2–8 and 16–18 band periods.

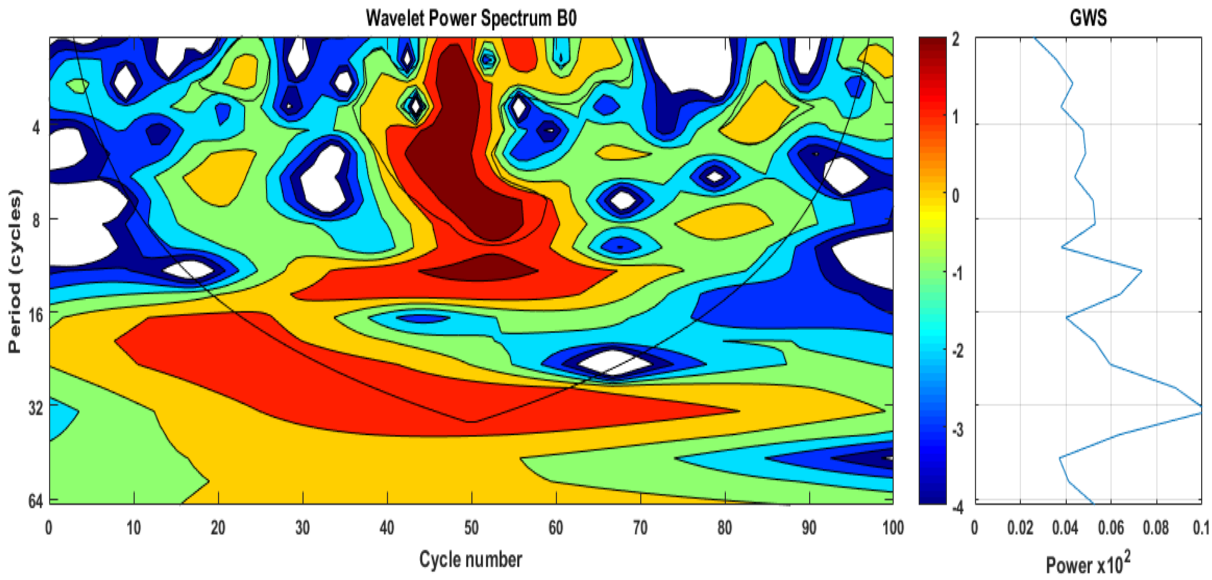


Fig. 8. Wavelet power spectrum and global wavelet spectrum of the B0 IMEP time series

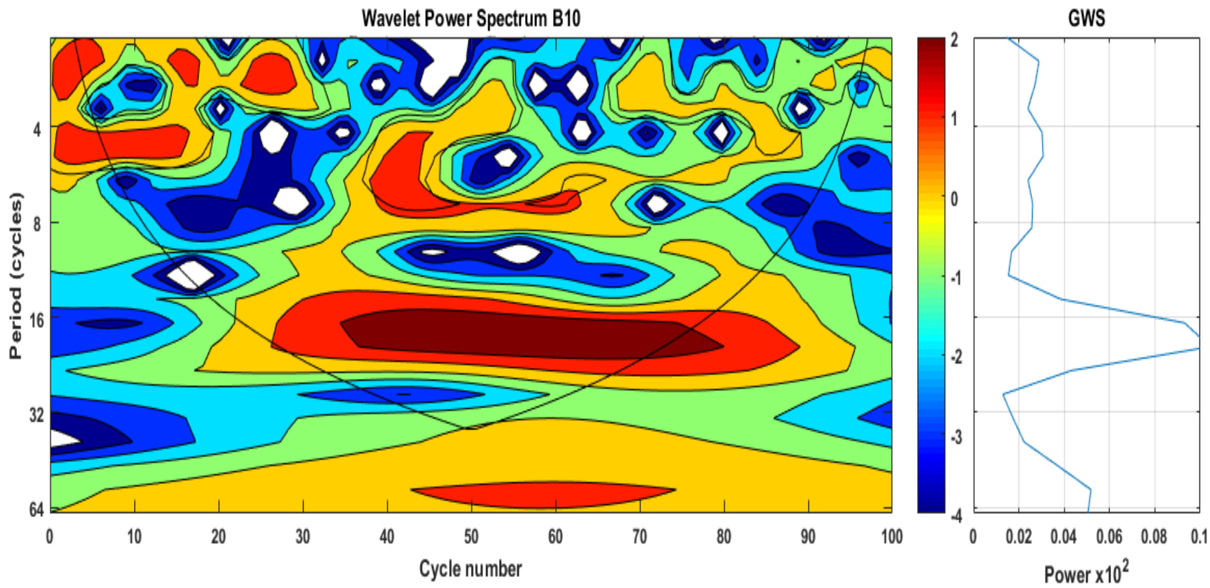


Fig. 9. Wavelet power spectrum and global wavelet spectrum of the B10 IMEP time series

Meanwhile, Figure 10 depicts the WPS and GWS of IMEP time series of B20 fuel. As the palm biodiesel content increases in the blend, the intensity of variation also decreases. A strong periodicity is observed at 8–10 band periods over 45-65 cycle durations, while the moderate periodicities occurs at 4-16 band periods which widely extends over 10–90 cycles numbers. A few weaker short-term periodicities are also found at low frequency region of B20 fuel. The WPS and GWS of IMEP time series for B30 fuel is illustrated in Figure 11. The plot demonstrates a strong and narrow periodicity only occurring for five cycle numbers at low frequency of 5 to 7-band periods. However, the moderate periodicities are seen at 8 to 10-band periods, which continuously span over 40–80 cycle numbers. Many short-term intermittent oscillations occur below the 4-band periods.

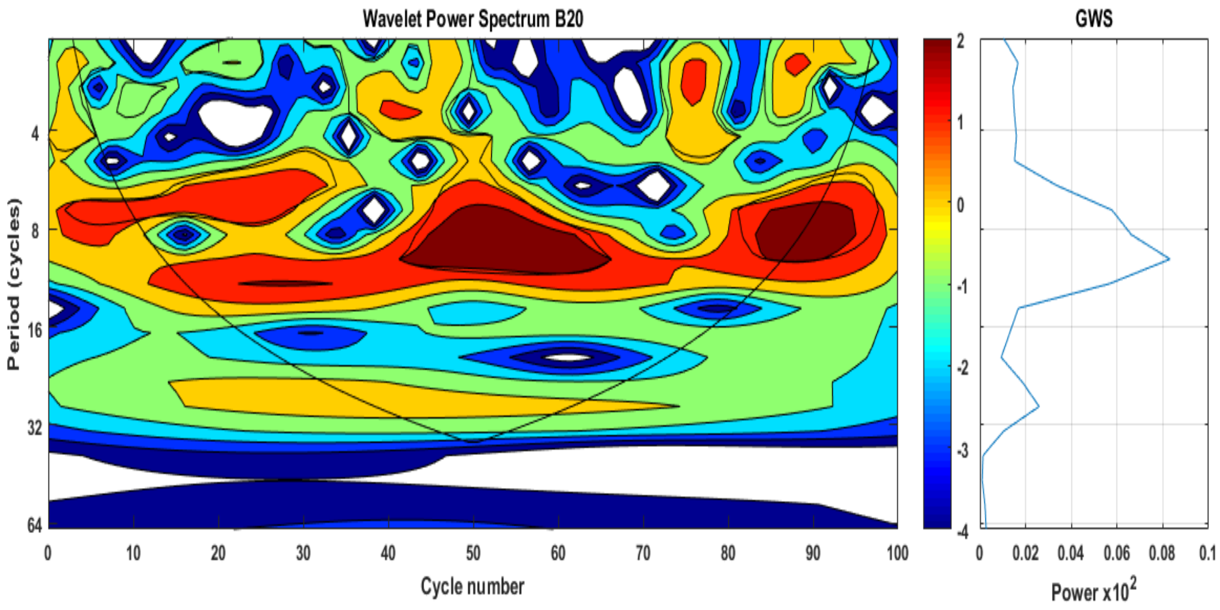


Fig. 10. Wavelet power spectrum and global wavelet spectrum of the B20 IMEP time series

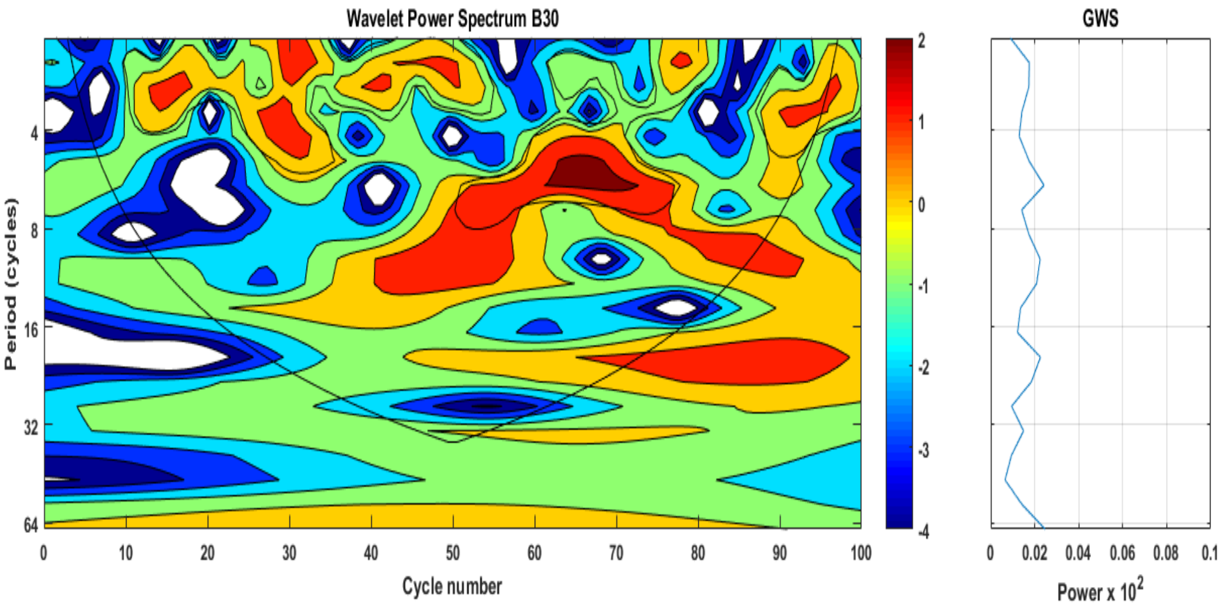


Fig. 11. Wavelet power spectrum and global wavelet spectrum of the B30 IMEP time series

It is noted that the use of palm biodiesel blends has reduced the IMEP frequency oscillation especially in the case of B30 fuel. Short and intermittent period oscillations appeared in palm biodiesel blends compared to long and intermediate oscillations in diesel fuel. In addition, the spectral power also decreased with the increase of palm biodiesel percentage in the test fuels as illustrated in the plots (Figure 8 to Figure 11). The GWS was recorded as 0.10, 0.10, 0.08 and 0.02 for B0, B10, B20 and B30 fuels, respectively. Again, the B30 has the lowest GWS among other fuels, which means that it has the minimum average wavelet power spectrum at each scale of the overall engine cycles. This result corresponded to the lower COV_{IMEP} value when run using the B30 palm biodiesel blend.

4. Conclusions

This study has investigated the effect of palm biodiesel blends on the combustion cyclic variations of a low compression marine engine. The study employed statistical and continuous wavelet spectrum methods. The engine tests were conducted using four types of fuels such as B0, B10, B20, and B30 at maximum torque speed of 1400 rpm. The engine cyclic variation was derived based on the 100 cycles of peak in-cylinder and the indicated mean effective pressure data. Increased palm biodiesel percentage in the blend has lowered the engine cyclic variations during the combustion process of low compression marine diesel engine. The B30 palm biodiesel blend produces the minimum cyclic variations among the tested fuels. The cyclic variations of palm biodiesel blends were at a low level between 1.91–2.50% compared to 3.16% obtained with that of diesel fuel. Low cyclic variations are a result from slow premixed combustion speed generated by palm biodiesel blends which consequently stabilize the engine combustion cycle. The wavelet spectrum analysis was employed to provide interactive information about how the IMEP frequency and amplitude varied within the certain time series. The result revealed that the use of palm biodiesel blends had reduced the IMEP oscillation frequency as exhibited by the short and intermittent signal periodicities on the interactive WPS plot. Meanwhile, the average wavelet spectral power was also reduced with more percentage of palm biodiesel in the blends. The B30 palm biodiesel has a minimum GWS of 0.02 compared to 0.10 of diesel fuel. This finding agreed with the lower COV_{IMEP} value when operated with B30 fuel. In short, the B30 palm biodiesel blend has produced the most stable combustion among the tested fuels.

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