Analysis of cylinder pressure cyclic variability operating with butanol blends in a diesel engine

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Abstract. Butanol is a second-generation biofuel which obtained from the biomass feedstock sources to improve the fuel properties and performance of the recent fuels. However, there are certain grey aspects in the combustion characteristics of butanol blends in various operating speeds and loads. This work investigates the use of mineral diesel (D), palm biodiesel (B), butanol (10%)-diesel (90%) (DBu10) and butanol (10%)-palm biodiesel (90%) (BBu10) fuels. The objectives of this study are to investigate the cyclic combustion variations of cylinder pressure profiles and peak cylinder pressure, $P_{\text{max}}$ and analyse the combustion stabilities using recurrence plot (RP) on tested fuels using a diesel engine. The results showed that higher peak cylinder pressures were observed for butanol blends with full load at 1100 rpm. Higher cylinder pressure cyclic variability occurred at high load and speed for all test fuels, especially DBu10 with higher COVP$_{\text{max}}$ values. Thus, in this case, DBu10 produced the most chaotic combustion irregularities and higher cyclic variations for the time series in those conditions. In conclusion, cylinder pressure variations in the time series were found to be affected by the fuel composition of butanol in the blends and types of fuel in engine operation.

1. Introduction

In-cylinder pressure has always been considered an important experimental diagnostic parameter in engine research and development due to its direct relation to fuel combustion [1]. The analysis of thermodynamic for the measured in-cylinder pressure data is a significant tool to quantify the combustion parameters of both compression and spark-ignition engines. Furthermore, the in-cylinder pressure measurement could provide useful information regarding cylinder torque variability, cyclic fuelling variability, thermal efficiency, intake and exhaust tuning, combustion phasing, cylinder balance, detonation, and structural loading. Regarding the studies for the purposes described above, in-cylinder pressure data is averaged at each crank angle to obtain the mean at desired accuracy and used to obtain average indicated engine performance characteristics including indicated work, indicated power and IMEP.

In-cylinder pressure cyclic variations can easily be seen by plotting the pressure data for each cycle on one figure. However, the mean measured in-cylinder pressure in the experimental work is computed averagely from the numbers of the cyclic variation at a specified period. Through the measurements of the pressure-time history of consecutive cycles in the combustion chamber in the
engine, the changes from one cycle to another do exist and can be easily seen. Since the in-cylinder pressure rate is exclusively related to the combustion, the pressure variations are caused by both chemical and physical phenomena variations that occur cyclically in the combustion process. Those and physical phenomena are considered as the fuel composition, the fuel-air ratio, the changes in the residual gas fraction and the motion of unburned gas in the closed cylinder. Three identified sources that contribute to the development of cyclic variations in the cylinder are mixture composition [2,3], cyclic cylinder charging [4,5], and in-cylinder mixture motion [6]. The factors which belong to the mixture composition and cyclic cylinder charging are influence mostly the main stage of the combustion, while the other sources play a regular role at any stage of fuel combustion.

The significance of recurrent or frequent behaviours, including heart rate and seasonality, in natural processes has been studied and presented for decades [7–9]. However, these recurrent behaviours are hardly visualized in the time-domain analysis. Thus, to solve this restraint, recurrence plot (RP) was first introduced into the dynamical system study by Eckman et al. in their distinguished 1987 paper which its function as an experimental time-series data analysing tool [10]. However, this method was first proposed by Maizel and Lenk in year 1981 for visualizing the substantial array patterns of genetic nucleotides [11]. Recurrence plots (RP) are two-dimensional representations of a single trajectory were used to visualize the quantification of recurrence patterns in a time series or sequence into a graphical presentation form to analyse the experimental data [10,12]. Interestingly, these recurrence plots often reveal the correlations between the data which are not easily determined by the normal time series methods. Then, based on the RP proposal by Eckmann et al., considerable efforts have been taken to develop quantification schemes for the plots and for the patterns within them from that time [10]. This recurrence plot (RP) tool allows the above assumptions testing which gives substantial useful information and describes whether the assumptions are satisfactory or otherwise. According to Eckmann et al., recurrence plots were used to visualize time-dependent behaviour of orbits $x_i$ in phase space, which represent the recurrence of the phase space trajectory to a state [10]. The recurrence of states is a fundamental property of deterministic dynamical systems. Deterministic dynamical models mean the substantial mathematical objects involving larger population size that been used to model the physical phenomenon whose state changes over time. Recurrence quantification analysis (RQA) was developed by Zbilut and Webber [13] and then a further study was conducted by Marwan et al. [14–17] to provide quantitative and statistical measures of recurrence plot (RP) analysis. Several RQA parameters include recurrence rate (RR), the maximal length of the diagonal or vertical lines ($L_{\text{MAX}}$ or $V_{\text{MAX}}$), determinism (DET), laminarity (LAM), trapping time (TT), entropy (ENTR) and the recurrence trend (TREND) used for analyzing quantitatively the in-cylinder pressure time series. This approach is paralleled with literature works on the cycle-to-cycle variations in the engine operation [18–23].

The objectives of this study are to investigate the cyclic combustion variations of cylinder pressure profiles and peak cylinder pressure, $P_{\text{max}}$ and to analyse the combustion stabilities in-cylinder pressure using recurrence plot (RP) fuelled with mineral diesel (D), palm biodiesel (PB), palm biodiesel-butanol (BBu10), and mineral diesel-butanol (DBu10) blends. These investigations were conducted at full load with a specific engine speed of 1100 rpm for 200 consecutive cycles are further analysed and discussed in details.

2. Material and methods

In this research work, palm biodiesel (B) and butanol were blended at 10% by volume of butanol for each 1 liter of palm biodiesel and mineral diesel, which denoted as DBu10 (90% mineral diesel+10% butanol) and BBu10 (90% palm biodiesel+10% butanol). Both butanol and ethanol blends were prepared by pouring anhydrous (99.9% purity) butanol and ethanol into the neat mineral diesel (D) and palm biodiesel (B) beaker in 10/90 proportions by volume and mixing them together to ensure the fuel blends were in homogeneous conditions. During the mixing process, the fuel blends were stirred using an electric magnetic stirrer at 200 rpm for a duration of 20 minutes. Then, the fuel blends were stirred continuously for an additional 20 minutes and left for 30 minutes to ensure the fuel blends reached an
equilibrium state at room temperature before the fuel blends were subjected to further fuel testing. The use of butanol and ethanol also have some limitations, such as lower lubricity, reduction in ignitability, low cetane number and miscibility but higher in volatility and cooling effects which may lead to increased unburned hydrocarbon emissions. Therefore, butanol and ethanol were added in small concentrations of 10% by volume to fuel blends, designated by DBu10 and BBu10 fuels. The fuel properties of the blends were tested according to the ASTM standards listed in table 1.

| Details                        | Testing Method (ASTM) | Mineral diesel (D) | Palm Biodiesel (B) | BBu10 | DBu10 |
|--------------------------------|-----------------------|--------------------|--------------------|-------|-------|
| Density @ 20 °C g/cm³          | D287                  | 0.826              | 0.867              | 0.858 | 0.824 |
| Viscosity @40 °C mm²/s         | D445                  | 5.144              | 7.495              | 6.026 | 3.5   |
| Cetane number                  | D613                  | 47.8               | 52.8               | 52.4  | 51    |
| Flash Point (°C)               | D93                   | 60                 | 80                 | 74.4  | 56.4  |
| Calorific value (MJ/kg)        | D240                  | 44.8               | 38.6               | 37.99 | 43.6  |

This research work was conducted on a Yanmar TF120-M single-cylinder diesel engine with a maximum power of 7.8 kW at 2400 rpm. The engine was coupled to a 15 kW eddy current, dump load dynamometer with a universal controller model DC5-10KW to control the engine speed and torque. The specifications of the engine are listed in Table 2. Two separate fuel tanks with thermocouples and a fuel valve system were used, one for biodiesel and the other for the blends. In the fuel delivery system, a burette was used to measure the fuel consumption of both fuels. Figure 1 illustrates the setup of the engine testing and specification of the test engine.

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Type                             | Horizontal, water-cooled 4 cycle diesel |
| Combustion system                | Direct injection       |
| Number of cylinder               | 1                      |
| Bore (mm)                        | 92                     |
| Stroke (mm)                      | 96                     |
| Compression ratio                | 17.7                   |
| Displacement (ℓ)                 | 0.638                  |
| Connecting rod length (mm)       | 150                    |
| Rated continuous output, hp / rpm (kW) | 10.5 / 2400 (7.8)   |
| Maximum torque, kgf.m / rpm       | 4.42 /1800            |
| Injection timing, deg            | bTDC 17.0              |
| Injection pressure, kg/cm²       | 200                    |
Figure 1. Engine testing set up.

Since this work focuses on the cyclic combustion of cylinder pressure, an Optrand AutoPSI-S model C22294-Q pressure transducer was used to measure the in-cylinder pressure. A magnetic crank encoder was used to obtain the signal of the crank angle degree (CA). The in-cylinder pressure recording and measurement for further analysis processes were executed using a TFX combustion analyser at the specific test condition. Each 200 consecutive cycles were analysed to evaluate the cyclic combustion using recurrence plot (RP) analysis.

3. Results and discussion
Density of the fuel is a function of the fuel chemical composition. Density increases with carbon chain number with a class of compounds. In general, palm biodiesel (B) and mineral diesel (D) have different densities, with B fuel having the highest density as compared to D fuel. This result is similar to the previous results from Chong et al. [24] and Phoon et al. [25]. The density of test fuels varies in the range of 0.826-0.867 g/cm³ for both D and B fuels. The density of B fuel is moderately higher than D fuel as listed in Table 1. Moreover, as a comparison, the difference in density is approximately a 4.8% increase when compared B fuel to D fuel. The density of biodiesel is influenced by different feedstock sources used in the biodiesel production process [26,27]. This requires addition of density reducer including alcohol to reduce the biodiesel density. Thus, it is obvious that the decrease in the density of the biodiesel blends are due to the additional butanol and ethanol content in the palm biodiesel. The use of alcohol is significantly well-diluted with the biodiesel as mineral diesel is diluted with biodiesel at different proportions [28–30]. The analysis shows that B achieved the highest density with 0.867 g/cm³, higher compared to that of other test fuels, namely BBu10 (1.02%), and DBu10 (4.50%), respectively, lower than that of B. These results provide further support for the hypothesis that various alcohol could reduce the density of the higher density fuels including biodiesel. Moreover, these results match those observed in earlier studies of butanol [31–33], ethanol [34–36], methanol [37] and propanol [38,39]. The present study contributes to existing knowledge of different fuel densities by providing significant findings on butanol and ethanol mixing with base fuels including palm biodiesel.
Kinematic viscosity mainly governs the lubricity of oil or fuel. It mainly relates to the molecular size and weight as well as the hydrocarbon class of oil or fuel. A number of studies have concluded that fuel viscosity and lubricity play a vital part in the lubrication of fuel injection system, for example, the rotary distributor injection pumps that rely on the fuel lubrication level in high pressure pumping mechanism [40–42]. Therefore, lower viscosity in the fuel contributes to maximum reduction in fuel delivery and decrease in the engine power output due to leakage occurring in the injector and pump. Moreover, fuel viscosity also affects fuel atomization and spray formation characteristics in the cylinder [43–46]. Hence, smaller Sauter mean droplet diameters are greatly attributed to the lower fuel viscosities, which causes an increase in droplet surface area and influences the duration of evaporation characteristics. The viscosity of the test fuels which varies in the range of 5.144 – 7.495 mm²/s for D and B fuels, respectively. The viscosity of the test fuels decreases as the alcohol amount increases in the blends. The viscosity of the B fuel is 7.495 mm²/s, which is 37.2% higher than that of D fuel with 5.144 mm²/s as listed in Table 1. Analysis has shown that B fuel possesses the highest density. Accordingly, the viscosity of other test fuels DBu10 and BBu10 are 70.8% and 21.7%, lower than that of B fuel, owing to the effect of alcohol blending. Results show that with a small proportion of 10% butanol in the blends, the test fuels have significant decrease in density and viscosity. Moreover, the densities of the butanol and ethanol blends are reduced to a lower value than that of B and D fuels because the butanol have considerable lower kinematic viscosities than B and D fuels respectively. These findings suggest that in general the use of butanol are succesfully reduced the viscosities of B and D fuels. The results of this study are consistent with those of other studies on butanol [47,48] and ethanol [36,49]. These results provide further support for the hypothesis that there are correlations between fuel properties and combustion cyclic variations of different fuels. In addition, these findings enhance the understanding on the effects of fuel viscosities on the combustion characteristics with different operating conditions.

Calorific value or heating value is one of the most significant parameters to characterise a fuel due to its energy content. Calorific value is the amount of heat energy released through combustion of a unit value of fuel per mass. In fact, higher calorific value of fuel is desirable for a combustion engine in terms of fuel economy [27]. Previous studies have found that the calorific values of biodiesel fuel from different feedstock sources are lower than that of diesel fuel [24,50,51]. A possible explanation for this might be that higher oxygen content (about 10 to 11%) is obtained for biodiesel as compared to that of mineral diesel. For the record, the calorific value is not specified in ASTM D6751 and EN 14214 biodiesel standards but it is stated in EN 14213 (biodiesel for heating purpose) standard with a minimum value of 35 MJ/kg. Different feedstock sources of biodiesel possess different calorific value as well as use different alcohol base fuels blending with base fuels.

The results in Table 1 clearly show that the measured calorific value for D fuel is 14.9% higher than B fuel. Moreover, the measured calorific value for DBu10 blend is higher than BBu10 blend by 13.7%, respectively due to the presence of the D fuel in the blends. This result may be explained by the fact that higher volume of D fuel improves the calorific values of the blends. It seems possible that these results are due to the observed decrease in calorific value could be attributed to the mixing of alcohol fraction in the blend fuels since alcohol has higher oxygen content than D fuel, reduces the carbon and hydrogen content [52–54]. Therefore, the analysis of calorific value undertaken here, has extended the knowledge on the important fuel properties in developing various combustion characteristics of different fuels with different operating conditions. Cetane number mainly indicates the quality of the fuel which significantly affects the fuel ignition time delay upon injection within the combustion chamber. Higher Cetane number produces shorter ignition delay period that results in easy cold start and low idling noise [27]. Conversely, when longer ignition delay period occurs in the expansion process, this event produces incomplete combustion, reduces in power output, creates fuel economic inefficiency and increases slightly the engine noise. In general, most of biodiesel fuel studies have found that biodiesel has a higher Cetane number than mineral diesel as biodiesel is
mainly composed from the groups of long chain hydrocarbon [36,45,55–57]. Interestingly, palm biodiesel has higher Cetane number compared to biodiesel from other feedstock sources due to the higher saturated fatty acid acting as the main component in the fuel composition [58] and its higher oxygen content which results in higher combustion efficiency [27]. The Cetane number of test fuels varies in the range between 47 – 52.8 for both D and B fuels. In consequence, the Cetane number of the test fuels decreases as an increase in alcohol amount dilutes with B and D fuels as listed in Table 1. The Cetane number for B fuel is 55.5, which is a 23.5% higher than that of D fuel, and surpassed the test fuels with 8.5% (DBu10) and 5.7% (BBu10), correspondingly. The observed correlation between Cetane number and oxygen content might be explained in this way with different results between B and D fuels. It was observed from the figure that the addition of butanol and ethanol in B and D blends have reduced the Cetane number of the butanol blends. It seems possible that these results are due to butanol possessing lower Cetane number than B fuel. These measured results are similar to the previous alcohol fuel studies involving butanol [47,59], ethanol [35,60] and methanol [55,61].

Figure 2. Comparison of cylinder pressure cyclic variations and mean cylinder pressure with a full load at 1100 rpm.

The analysis of test fuels comparison involving 200 cycles of cylinder pressure data and mean cylinder pressure are shown in Figure 2. It can be seen from the figure that the 200-cylinder pressure cycles and mean cylinder pressure diagrams do not show any appreciable difference in profile between mineral diesel (D), palm biodiesel (B), butanol (BBu10 and DBu10) blends. However, as expected, the pressures increase with load for all fuels at similar engine speed. The results reveal that higher combustion temperature is observed at high engine load for all fuels due to larger amount of fuel burnt in the cylinder which is mainly attributed to the increase in temperature for the residual gas and the cylinder wall. Also, lower cyclic variations in cylinder pressure are observed with the decrease in the
ignition delay [5]. The mineral diesel (D) fuel combustion in diesel engine is nearly steady with minimal cyclic variations existing for all loads at a similar engine speed. However, when alcohols including butanol and ethanol with lower Cetane number are combusted in diesel engine, though further improvement in NOx emission and smoke are observed, the combustion variations still exist and cause problems at low load condition. In Table 3, it is observed that higher applied load significantly increases the mean cylinder pressure for all test fuels at a constant engine speed. More fuel is delivered and burnt at this point, hence higher combustion temperature is achieved as well as cylinder pressure. Therefore, most of the test fuels achieve higher mean cylinder pressure at this point. Consequently, peak cylinder pressure, $P_{\text{max}}$ for all fuels elevates with an increase in engine load. Also, it can be clearly observed from Table 3 that addition of ethanol leads to a relatively higher COV of cylinder pressure cyclic variations, and as ethanol is absent, the COV of cylinder pressure cyclic variations decreases. This is because ethanol has a tendency to knock which can result in higher cylinder pressure cyclic differences [62].

**Table 3.** Statistical results and percentage of relative standard error, RSE% on cylinder pressure cyclic variations at full load (N=1100 rpm).

| Test fuels | Cylinder pressure, bar |  |  |  |
|------------|------------------------|---|---|---|
|            | Mean       | Max       | Min       | Std Dev, $\sigma$ | COV      | RSE, % |
| D          | 65.5       | 68.0      | 63.3      | 0.92            | 0.0144   | 0.099  |
| B          | 66.2       | 69.2      | 63.5      | 1.08            | 0.016    | 0.115  |
| BBu10      | 64.8       | 68.1      | 62.6      | 0.89            | 0.014    | 0.096  |
| DBu10      | 63.0       | 64.6      | 61.0      | 0.70            | 0.011    | 0.078  |

![Figure 3.](image_url)  
Time series of peak cylinder pressure cyclic variation values, $P_{\text{max}}(i)$ and $R_P$ with a full load at 1100 rpm.
Two-dimensional dynamical graphic patterns of the $P_{\text{max}}$ values from the recurrence plots (RP) are compared in Figure 3. It is observed from the figure that different graphical patterns are found corresponding to the magnitude of the $P_{\text{max}}$ data values representing all six fuels. As shown in the figure, the points in the state space are represented by the colour codes at the coordinates from blue to red. In RP, the points that are close to each other in the state space are represented by blue colour, whereas the red colour code represents the points that are located far from other points [63]. Note that the RPs of peak cylinder pressure, $P_{\text{max}}$ time series are inconsistent with that of pure random process whose RP describes a uniform distribution (all blue regions). The RP patterns for all fuels are more similar to the chaotic processes whose RPs are composed of red, yellow and blue regions. Analysing Figure 3, larger irregularities are observed in case of B fuel, while for other fuels; D, BBu10, and DBu10, smaller irregularities are found in the RPs. Note that at high load with constant engine speed, more fuel is delivered and burned at high temperature which leads to higher pressure in the cylinder. In addition, more chaotic combustion process are observed at this state with different fuel composition. Note that at high load with constant engine speed, more fuel is delivered and burned at higher temperature which leads to higher pressure in the cylinder. Also, more chaotic combustion process is observed at this state with different fuel composition. The summary of the corresponding recurrence quantification analysis (RQA) is listed in Table 4. Note that determinism (DET) and laminarity (LAM) are the corresponding ratios of points in diagonal and vertical lines. It is observed that larger DET and LAM values are observed for DBu10 at this operating condition which significantly lead to more deterministic structures. These quantities are connected to the stability on the engine operation in which lower cyclic variations are observed. On the other hand, other fuels; B is characterised by smaller values of DET and LAM which point to the more regular dynamics or irregularities.

| Test fuels | RQA parameters values |
|------------|------------------------|
|            | DET       | LAM                  |
| D          | 2.720     | 0                    |
| B          | 1.604     | 0                    |
| BBu10      | 3.671     | 0                    |
| DBu10      | 6.462     | 2.206                |

4. Conclusion
The conclusions for the work as follow:
- Adopting butanol with D and B blends further reduce the densities of the fuel blends since butanol have lower density than B and D.
- Blending of butanol in the base fuels could significantly reduce the Cetane number values of biodiesel and diesel blends, hence various combustion characteristics and cyclic variations are developed.
- For all four fuels, there was a significant increase of cylinder pressure with full load condition at 1100 rpm. However, lower peak cylinder pressure was observed for butanol blends especially DBu10 compared to that of D and B fuels.
- The COV value has an increasing trend in the presence of butanol in B and D fuels. Also, the COV values are found to be higher for butanol blends compared to that of D and Biodiesel fuels.
- Higher recurrence points are observed for DBu10 fuel compared to that of B and BBu10, which shows more engine stability is obtained at the operating condition.
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