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Cycle-to-Cycle Variation in Diesel Engines Using Water-Diesel-Butanol Blended Fuels

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Abstract
This study investigates the cycle-to-cycle variations in cylinder pressure. It indicates the mean adequate pressure (IMEP) of a single-cylinder diesel engine fueled with water-in-diesel-butanol (WDBu) emulsified blends at various engine loads. Experiments were conducted at a constant engine speed of 3,000 rpm under 50% load, using five different fuel types: pure diesel (D), water-in-diesel (W5D), and three WDBu blends: W5DBu5, W5DBu10, and W5DBu15. Results revealed that the highest peak cylinder pressure (Pmax) of 89.10 bar was recorded with W5DBu10, while the lowest (79.03 bar) was observed with W5DBu15. The maximum pressure variation was most stable for W5D, with a %RSD of 1.23%, and least stable for W5DBu10, with a %RSD of 2.21%. Notably, the W5DBu5 blend showed a moderate Pmax variability of 8.95 bar and produced the most inconsistent pressure across 100 cycles. Regarding IMEP cyclic variation, the coefficient of variation (COVimep) was used to assess combustion stability at engine loads of 20%, 35%, and 50%. At 50% load, W5DBu5 exhibited the lowest coefficient of variation (COV) of 1.10, indicating superior cyclic stability compared to diesel, which showed the highest COV of 1.26. The findings suggest that a WDBu5 blend offers an optimal balance between performance and stability, positioning it as a promising alternative fuel for compression ignition engines. This study contributes valuable insights for enhancing combustion consistency in alternative fuel applications.

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1. Introduction

The global demand for cleaner and more efficient energy systems has intensified research into alternative fuels that can reduce dependency on conventional fossil diesel while ensuring engine performance and environmental compliance. Compression ignition (CI) engines are widely used due to their high thermal efficiency and durability; however, their operation using fossil diesel contributes significantly to greenhouse gas emissions and particulate matter [1–4]. Researchers have explored various fuel modification techniques to address this issue, including emulsification and blending oxygenated fuels [5–8]. Water-in-diesel (W/D) emulsions have shown promise in reducing NOx and particulate emissions due to the micro-explosion phenomenon that enhances fuel atomization and combustion efficiency [9–12]. However, W/D emulsions may negatively affect engine stability and performance, particularly in terms of cycle-to-cycle variation. To compensate for this drawback, the incorporation of low-carbon alcohols such as butanol has been proposed. Butanol offers favourable physicochemical properties, including higher energy density than ethanol and better miscibility with diesel and water [13–16].

Combining water-diesel emulsions with butanol (WDBu) presents a novel multi-component fuel system that synergistically balances combustion stability, emission reduction, and fuel efficiency. Previous studies have reported conflicting outcomes regarding the combustion behaviour and pressure fluctuations of these blends [17–20], suggesting the need for further experimental validation under controlled conditions and diverse load settings. Cycle-to-cycle variation (CCV) is a critical indicator of combustion stability, directly linked to engine vibration, noise, and efficiency losses [21–23]. Parameters such as peak cylinder pressure (Pmax) and indicated mean adequate pressure (IMEP) are commonly analysed to assess the magnitude of CCV. However, literature on the detailed statistical and comparative assessment of WDBu blends on CCV in CI engines remains limited [24–26].

This study investigates the impact of different WDBu blend ratios (W5DBu5, W5DBu10, and W5DBu15) on the cyclic variations of cylinder pressure and IMEP at various engine loads, with a constant engine speed of 3,000 rpm. Specifically, we analyse peak pressure values, standard deviation, relative standard deviation (%RSD), and coefficient of variation (COVimep) to quantify combustion stability. The novelty of this work lies in its comparative analysis of cyclic pressure and IMEP variability for WDBu blends under controlled load conditions. The study provides new insights into the optimal blend ratio that maintains combustion stability while enhancing pressure characteristics. This area has not been extensively explored with these specific fuel formulations. The findings from this research are expected to contribute to the development of cleaner and more stable alternative fuels for diesel engines, offering a practical approach to reducing emissions without compromising performance. The results also aim to support policymakers and engine manufacturers in evaluating the viability of WDBu emulsions as sustainable fuel alternatives.

2. Methodology

This section provides a comprehensive description of the experimental facilities and instrumentation used in the study. The term 'experimental setup' encompasses the complete engine test rig configuration, including all integrated measurement systems and data acquisition components. Key instrumentation for performance and combustion analysis comprises a high-precision emission analyser, an in-cylinder pressure transducer, a fuel flow metering system, an engine speed encoder, and a torque measurement unit. Additionally, a detailed overview of the data acquisition system architecture and sensor integration methodology is presented to ensure the accuracy, synchronisation, and repeatability of experimental measurements.

Figure 1 illustrates the detailed schematic of the experimental setup utilised throughout this study. All experimental procedures and measurements were conducted at the Engine Performance Laboratory, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang. This laboratory features a comprehensive engine test rig system for analysing performance, combustion, and emissions under controlled conditions. The setup features a single-cylinder engine and a 150 kW eddy current dynamometer, providing precise torque and load control. The air intake and exhaust systems are configured to ensure consistent airflow and proper emission routing. A fuel flow meter is installed between the fuel tank and the engine to accurately monitor real-time fuel consumption rates. The engine is thermally regulated using an engine water cooler system linked to a dyno cooling tower, ensuring stable operating temperatures during extended testing periods.

The system integrates a robust data acquisition platform, including a combustion and temperature analyser, for capturing critical parameters such as in-cylinder pressure and thermal response. Emission outputs are quantified using a gas analyser, which records CO, CO_2, NOx, and unburned hydrocarbon concentrations. All sensor signals and performance data are collected and monitored via the dyno control panel and control room interface, enabling real-time data visualisation and storage. This highly instrumented setup ensures accurate and repeatable measurements, allowing for a rigorous evaluation of cycle-to-cycle variations and combustion behaviour across different fuel blends.

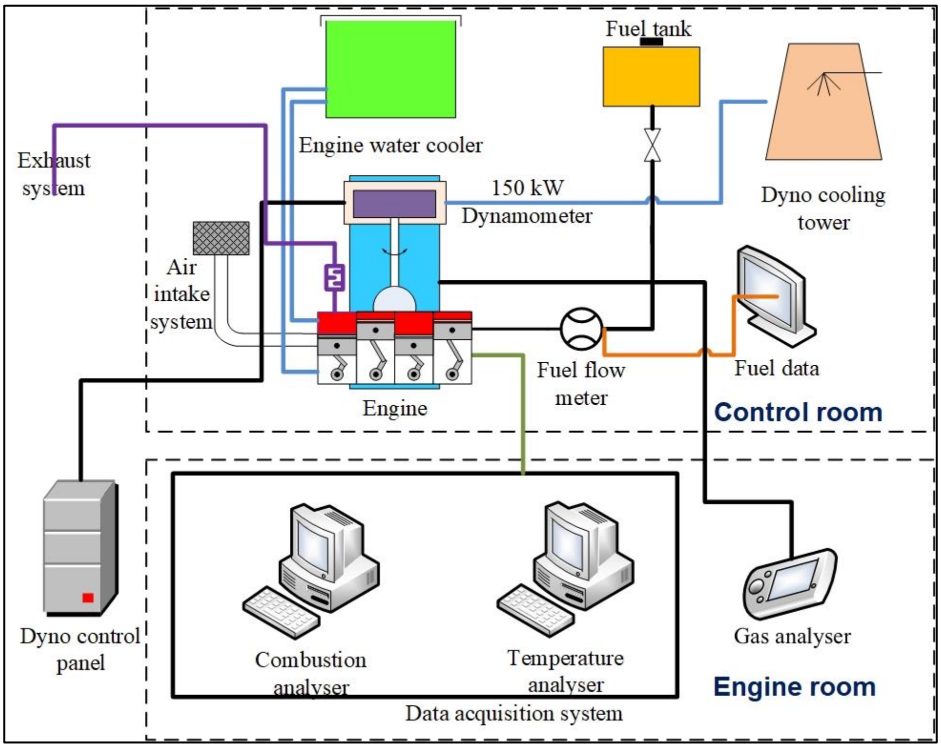

Figure 1: Schematic of the test cell for the experimental setup

Figure 2 shows the physical setup of the engine test rig, explicitly highlighting the eddy current dynamometer system used for torque loading and performance measurement. This setup is critical in controlling and simulating various engine load conditions during the combustion experiments. At the centre of the image is the eddy current dynamometer unit, characterised by its robust housing and mounted on a vibration-isolated base frame. The unit is mechanically coupled to the engine crankshaft to absorb and measure the engine's output in real-time. The arms extending laterally from the dynamometer are torque reaction arms connected to load cells (seen on the left and right sides). These load cells provide precise torque readings, essential for calculating brake power and evaluating thermal efficiency.

Figure 2: Eddy current dynamometer calibration.

On the right-hand side of the dynamometer, a network of cooling pipes and control valves is visible, which form part of the engine's water-cooling circuit. This system ensures the engine operates within its optimal temperature range, preventing thermal distortion or overheating during prolonged tests. The visible instrumentation and control modules located near the rig, including signal conditioning boxes and sensor hubs, enable real-time data acquisition, synchronisation, and interfacing with the central control system. Integrating this dynamometer with advanced sensors and measurement tools enables high-fidelity testing, making it suitable for accurately assessing combustion stability, fuel consumption, and emission behaviour. This physical configuration complements the schematic layout in **Figure 1** and demonstrates the practical realisation of a highly controlled experimental environment.

3. Result & Discussion

Cylinder Pressure Cycle to Cycle at Engine Load of 50%

Figure 3 presents the in-cylinder pressure traces over 100 consecutive combustion cycles and their corresponding average profiles for five fuel types: (a) Diesel, (b) W5D, (c) W5DBu5, (d) W5DBu10, and (e) W5DBu15 operated at 50% engine load and a constant speed of 3,000 rpm. The plots illustrate the pressure variation as a function of crank angle degree, with notable fluctuations observed during the compression and combustion phases. The addition of butanol to water-diesel emulsions leads to increased cycle-to-cycle pressure variability. Among the tested fuels, W5DBu10 exhibits the highest peak cylinder pressure (Pmax) of 89.10 bar, followed by W5DBu5 (88.43 bar) and W5DBu15 (88.35 bar). Despite its high Pmax, W5DBu10 also shows the most significant cyclic dispersion with a relative standard deviation (%RSD) of 2.21, indicating a decrease in combustion stability with the addition of 10% butanol.

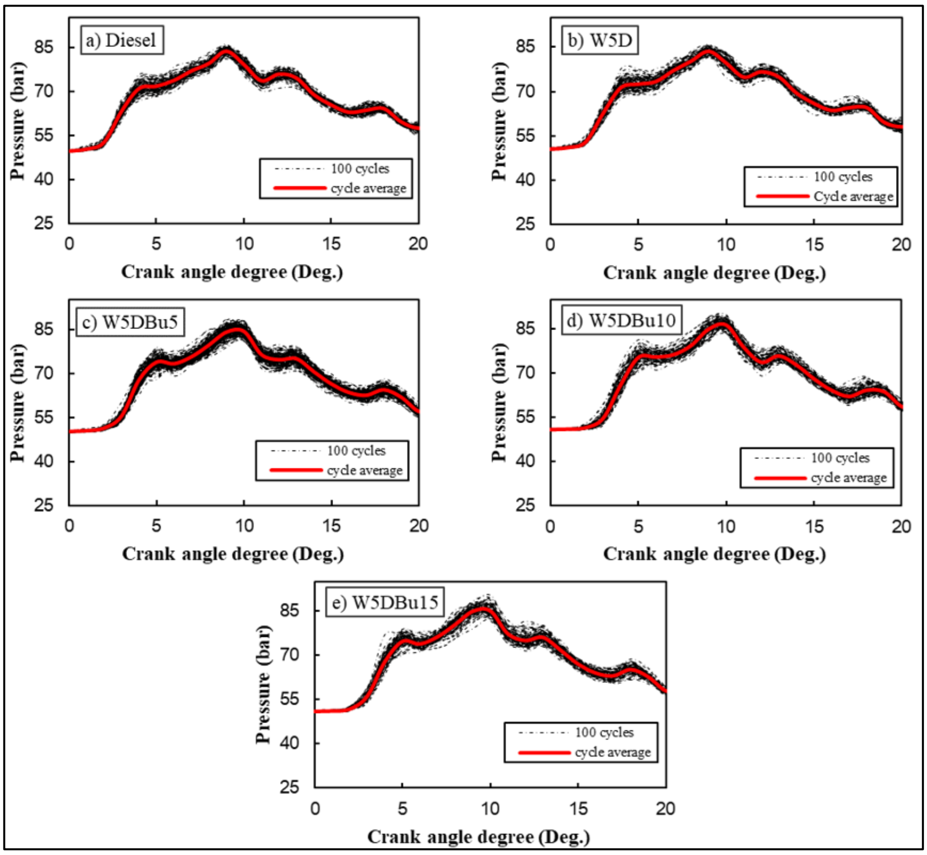

Figure 3: Peak cylinder pressure variation for (a) Diesel, (b) W5D, (c) W5DBu5, (d) W5DBu10 and (e) W5DBu15 at 50% load and speed of 3,000 rpm

Conversely, the W5DBu15 blend demonstrates improved consistency with a lower %RSD of 1.86, suggesting that a higher butanol ratio may contribute to partially stabilising combustion behaviour. W5DBu5, however, exhibits significant fluctuation in individual cycle traces, despite a slightly lower Pmax than W5DBu10, and records a %RSD of 2.07, confirming its role in generating the most inconsistent in-cylinder pressure profile among the 100 cycles. The baseline diesel fuel achieves a relatively lower Pmax of 85.97 bar with a %RSD of 1.28. At the same time, the W5D blend offers the most stable performance, with a %RSD of only 1.23%, emphasising the stabilising effect of water emulsion alone, without butanol enhancement. These findings underline the trade-off between peak pressure generation and cyclic stability, with W5DBu10 delivering the highest combustion intensity at the cost of increased variability, whereas W5DBu15 offers a better balance between performance and cycle stability.

Table 1: Statistical results on maximum pressure cyclic variations at 50% load and speed of 3,000 rpm

Fuel test	Pmax (bar)					Varian	SD	%RSD
	Min	Max	Range	Average	Mode			
D	81.06	85.97	4.92	83.65	83.66	1.14	1.07	1.28
W5D	81.39	86.02	4.63	83.66	83.72	1.06	1.03	1.23
W5DBu5	79.48	88.43	8.95	84.34	84.33	3.03	1.74	2.07
W5DBu10	80.71	89.10	8.40	85.12	85.24	3.54	1.88	2.21
W5DBu15	79.03	88.35	9.32	85.11	85.30	2.51	1.58	1.86

Table 1 summarises the statistical analysis of peak cylinder pressure (Pmax) variations for five fuel types under a constant engine speed of 3,000 rpm and 50% load. The parameters analysed include minimum and maximum pressure values, pressure range, average and mode of Pmax, variance, standard deviation (SD), and relative standard deviation (%RSD), which comprehensively understand combustion stability and cyclic consistency for each fuel blend. Among all tested fuels, W5DBu10 records the highest maximum Pmax of 89.10 bar, reflecting the most intense combustion phase, followed closely by W5DBu15 at 88.35 bar and W5DBu5 at 88.43 bar. In contrast, pure diesel fuel (D) demonstrates the lowest maximum pressure (85.97 bar) and narrowest range (4.92 bar), indicating more consistent combustion characteristics.

The highest-pressure fluctuation range is observed in W5DBu15 (9.32 bar), followed by W5DBu5 (8.95 bar) and W5DBu10 (8.40 bar), which shows that the addition of butanol increases combustion variability. This trend is further confirmed by the variance and standard deviation values, where W5DBu10 shows the highest variance (3.54) and SD (1.88), suggesting less stable combustion behaviour. From a combustion stability perspective, %RSD is a critical indicator. W5D (water-in-diesel without butanol) yields the most stable performance with the lowest percentage relative standard deviation (RSD) of 1.23%, even slightly better than diesel (1.28%). On the other hand, W5DBu10 exhibits the highest %RSD at 2.21%, indicating significant cycle-to-cycle pressure variability. Interestingly, W5DBu15 improves stability compared to W5DBu10, with a reduced percentage relative standard deviation (RSD) of 1.86%, suggesting that a higher butanol ratio may help suppress excessive fluctuations. In conclusion, adding butanol enhances the peak pressure output and tends to compromise cyclic stability, especially at moderate blend ratios. W5DBu5 and W5DBu10 offer higher combustion intensity at the expense of stability. Conversely, W5D and W5DBu15 present better control over pressure variations, making them more suitable for optimising engine smoothness and repeatability.

Figure 4 illustrates the distribution of maximum cylinder pressure (Pmax) across 100 consecutive combustion cycles for five fuel types: Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 operated at 50% engine load and 3,000 rpm. The graph illustrates the cyclic fluctuations in Pmax, facilitating a visual comparison of combustion stability among the tested fuels. W5DBu10 (purple) exhibits the highest fluctuation range and peak Pmax value, with pressure readings reaching up to 89.10 bar, as reported in **Table 1**. In contrast, W5DBu15 (green) records the lowest observed pressure, dropping to 79.03 bar, despite maintaining high combustion intensity. This variation suggests that the initial increase in butanol concentration introduces instability (as seen in W5DBu10), but may contribute to improved damping effects at higher concentrations (W5DBu15).

Among all blends, W5D (yellow) exhibits the most consistent pressure distribution across cycles, which aligns with its lowest relative standard deviation (%RSD) of 1.23%, indicating superior combustion stability. Conversely, W5DBu10 has the highest percentage relative standard deviation (RSD) of 2.21%, highlighting significant variability in pressure peaks from cycle to cycle. Diesel fuel (black) and W5DBu5 (red) display moderate fluctuations with %RSD values of 1.28% and 2.07%, respectively. These findings reinforce that while butanol enhances combustion intensity, it also increases pressure instability, particularly at mid-blend ratios, while W5D remains the most stable fuel option under the tested conditions.

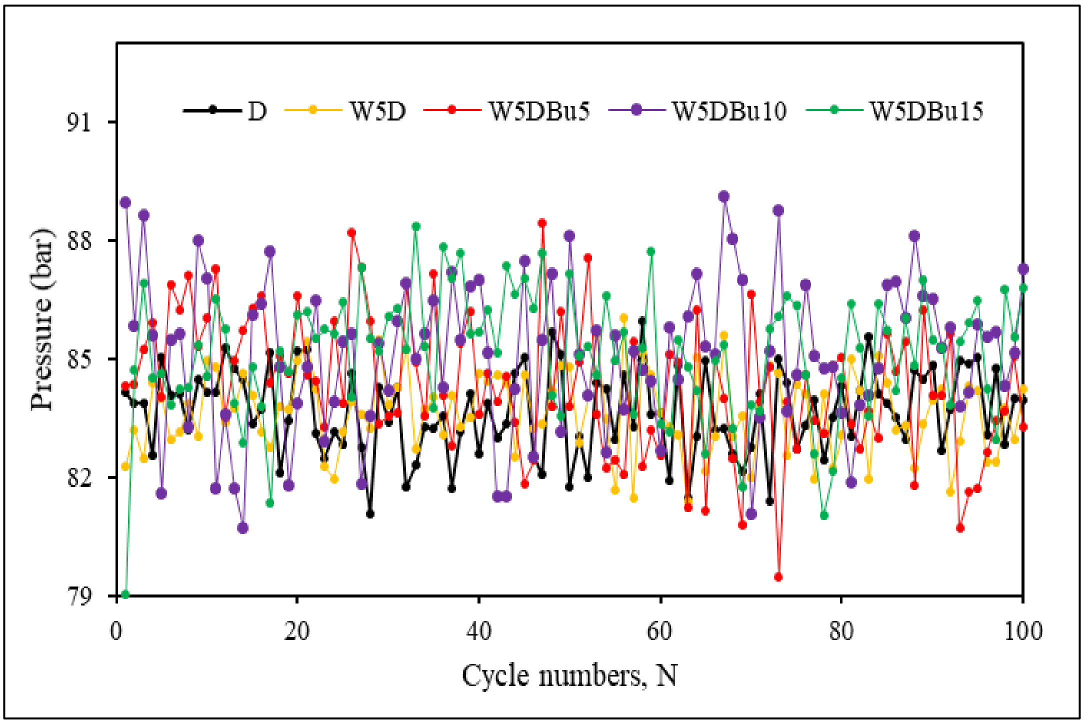

Figure 4: Pmax graph for a hundred cycles of tested fuel at 50% load and speed of 3,000 rpm

Cyclic Variation of IMEP

Cycle-to-cycle variation (CCV) during combustion remains one of the critical limitations in expanding the stable operating range of compression ignition engines. These variations can be characterised by key indicators such as in-cylinder pressure, combustion-related parameters, and emissions. One of the most reliable and commonly used statistical tools for evaluating combustion stability is the coefficient of variation (COV) of the indicated mean adequate pressure (IMEP), denoted as COVimep. This parameter reflects the relative fluctuation in indicated work per engine cycle, serving as a direct metric of cyclic stability. **Figure 5** illustrates the calculated COVimep for 100 consecutive engine cycles at an engine speed of 3,000 rpm and 20% load for all five fuel types: Diesel, W5D, W5DBu5, W5DBu10, and W5DBu15. Each subplot represents the evolution of COVimep values per cycle, along with the corresponding average trend line for each fuel.

The plots show that diesel fuel exhibits the highest variation throughout the cycles, with COVimep values frequently peaking above 3.5 and an average value near 1.8. In contrast, W5D demonstrates significantly lower cyclic variability, with COVimep consistently below 1.5 and an average around 1.2, indicating enhanced combustion stability due to water emulsification. The W5DBu5 blend exhibits relatively moderate fluctuations, with peak COVimep values reaching 3.0 but a more stable average near 1.5. W5DBu10 and W5DBu15 exhibit improved cyclic regularity compared to diesel, with their average COVimep values stabilising at approximately 1.4 and 1.3, respectively. However, W5DBu15 reveals more pronounced early-cycle fluctuations, suggesting potential instability during initial combustion phases before settling. These findings confirm that blended fuels, particularly W5D and W5DBu15, contribute to improved IMEP stability compared to conventional diesel. The reduction in COVimep with the inclusion of water and butanol suggests enhanced mixing and combustion uniformity, likely driven by the fuel blend's micro-explosion effect and increased oxygen content.

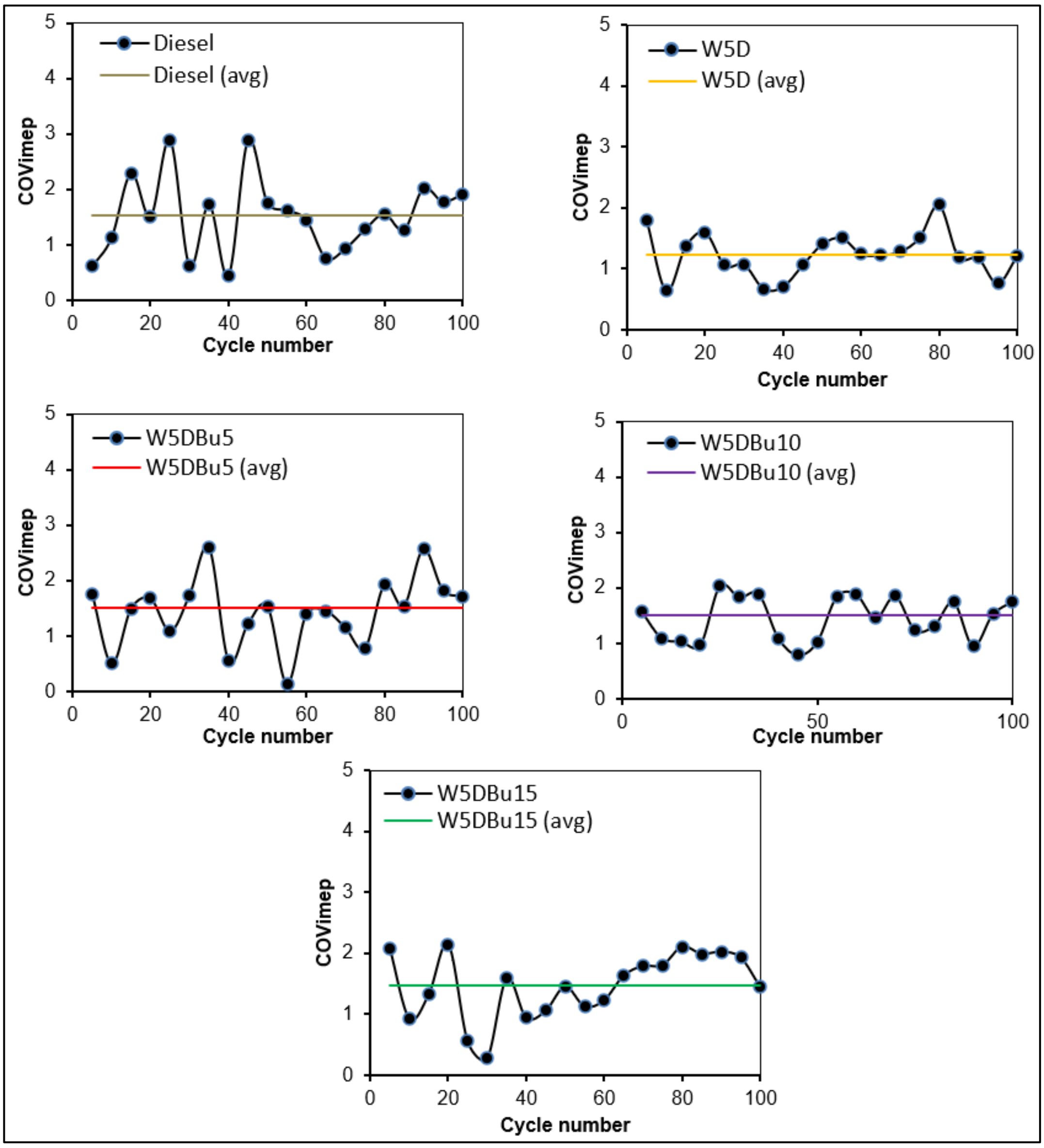

Figure 5: *COVimep* variation versus the cycle number over 100 sequential cycles for D, W5D, W5DBu5, W5DBu10 and W5DBu15 operate at 20% engine load and speed of 3,000 rpm

Figure 6 illustrates the variation of the coefficient of variation of indicated mean adequate pressure (COVimep) across 100 sequential engine cycles for Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15, operated at an engine speed of 3,000 rpm and 35% load. Compared to the results at lower load conditions (e.g., 20% load), the COVimep patterns exhibit better stability and convergence over the cycle range. Among all fuel types, W5DBu5 exhibits the most consistent and stable combustion behaviour, with minor fluctuations and an average COVimep near 1.1, reinforcing its role as the most stable blend under these conditions. W5D also shows a stable trend, with values generally maintained below 1.3 across all cycles, confirming the beneficial stabilising effect of water-in-diesel emulsification. On the other hand, W5DBu10 demonstrates relatively high fluctuation in the early cycles, with COVimep initially exceeding 3.0, before gradually stabilising to values near 1.2 beyond the 30th cycle.

A similar pattern is observed in W5DBu15, where early-cycle instability is evident. However, the later cycle values stabilise closer to an average of 1.3, indicating a delayed but eventual improvement in combustion uniformity. Diesel fuel, while generally more stable than at 20% load, continues to exhibit moderate variability across the cycle range, with an average coefficient of variation (COV) slightly above 1.4. This suggests that while increased engine load contributes to improved combustion consistency for all fuel types, blended fuels, particularly W5DBu5, still outperform diesel in minimising cycle-to-cycle variation. Overall, the data confirm that W5DBu5 offers optimal stability at mid-load operation, while higher butanol blends may require more engine cycles to achieve steady-state combustion performance. These results underscore the importance of both fuel formulation and operating conditions in influencing cyclic stability in compression-ignition engines.

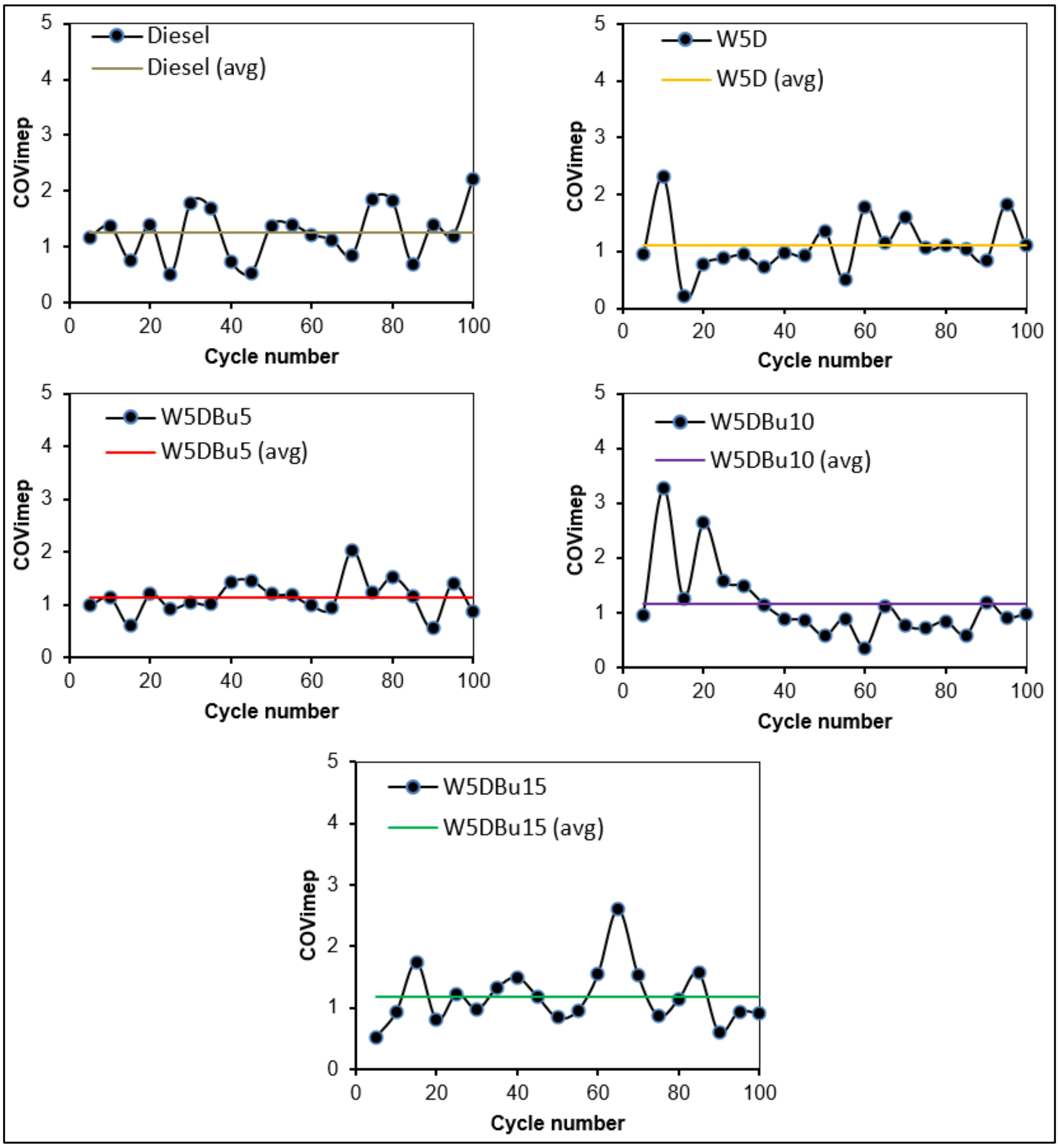

Figure 6: *COVimep* variation versus the cycle number over 100 sequential cycles for D, W5D, W5DBu5, W5DBu10 and W5DBu15 operate at 35% engine load and speed of 3,000 rpm

Figure 7 illustrates the variation in the coefficient of variation of indicated mean adequate pressure (COVimep) across 100 combustion cycles for Diesel, W5D, W5DBu5, W5DBu10, and W5DBu15, operated at 50% engine load and 3,000 rpm engine speed. The plots provide a clear comparative visualisation of combustion stability across different fuel types under higher load conditions. W5DBu5 exhibits the lowest average COVimep, approximately 1.10, indicating the most consistent and stable combustion process among all fuel types. Its relatively flat trend line and minimal dispersion throughout the cycles support this. In contrast, Diesel shows a higher average COVimep of 1.26, with noticeable fluctuations across the cycle range, suggesting less combustion stability than blended fuels.

While W5D and W5DBu10 also demonstrate good cyclic stability with average COVimep values around 1.23 and 1.19, respectively, their profiles display slightly more cycle-to-cycle oscillation than W5DBu5. Meanwhile, W5DBu15 shows moderate variation with an average COVimep of 1.30, indicating a balanced but less stable performance relative to W5DBu5. These findings reinforce that the W5DBu5 blend, combining 5% water and 5% butanol in diesel, delivers the most stable combustion under mid-to-high load conditions. The data support the viability of water-in-diesel-butanol emulsions as a promising alternative to conventional diesel, particularly in enhancing combustion uniformity and reducing cycle-to-cycle variability in compression ignition engines.

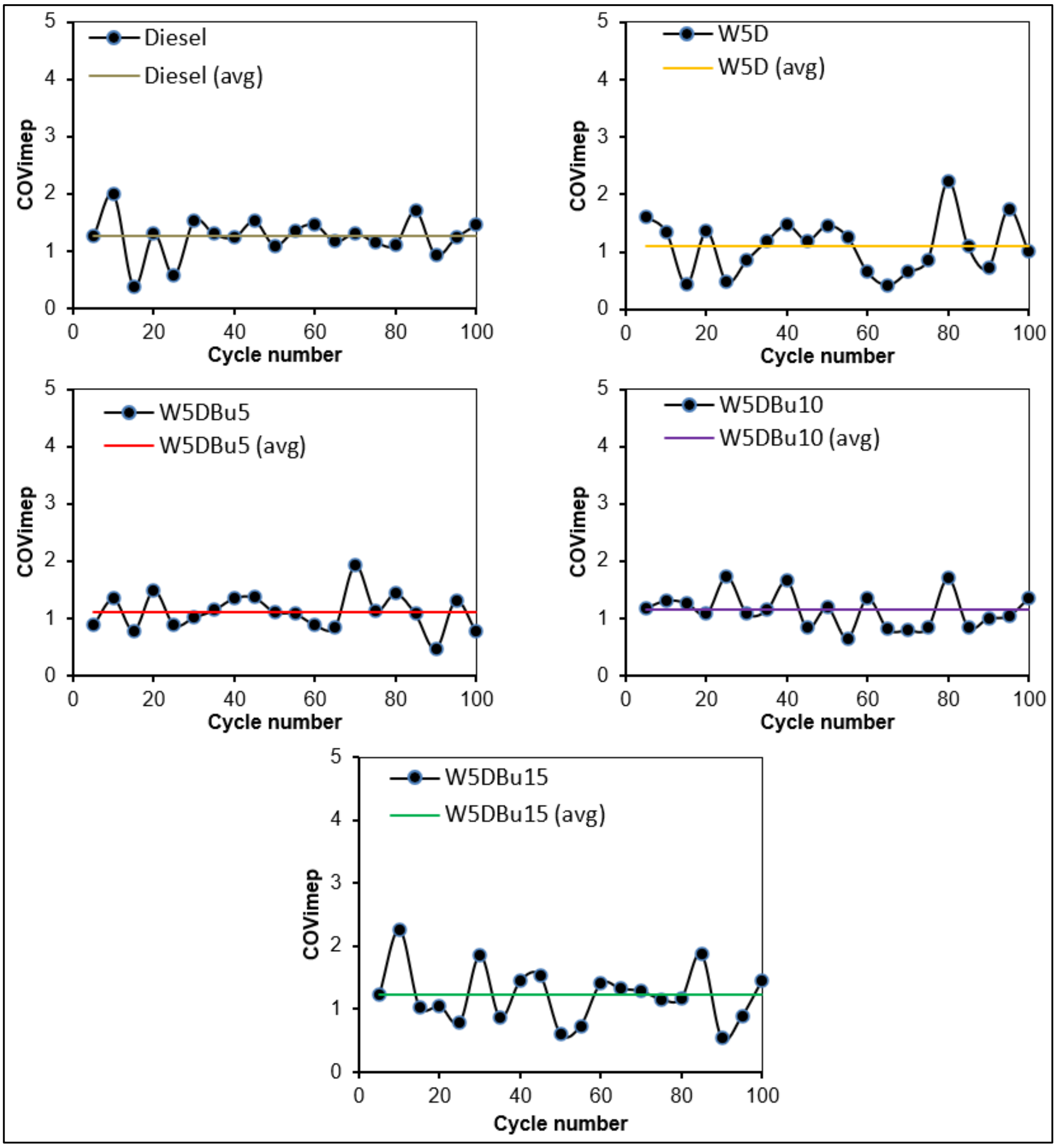

Figure 7: *COVimep* variation versus the cycle number over 100 sequential cycles for D, W5D, W5DBu5, W5DBu10 and W5DBu15 operate at 50% engine load and speed of 3,000 rpm

The novelty of this study lies in its integrated analysis of both pressure cyclic variation and IMEP stability under multi-load conditions using systematically formulated WDBu blends. While prior studies have explored water or alcohol blends independently, this work introduces a dual-emulsified system (water + butanol) and reveals that W5DBu5 offers an optimal balance between combustion intensity and stability. Furthermore, the study provides new experimental evidence that a moderate addition of butanol enhances pressure without significantly degrading cycle stability, contrary to common assumptions in single-emulsion systems. These insights expand current knowledge on alternative fuel formulation strategies for compression ignition engines and provide a practical pathway for reducing emissions while maintaining optimal combustion performance.

4. Conclusion

This study comprehensively evaluated the cyclic variations of cylinder pressure and IMEP in a diesel engine operated with water-in-diesel-butanol (WDBu) emulsified fuels at 3,000 rpm under various load conditions. The results demonstrate that fuel composition has a significant impact on combustion stability and pressure characteristics. At 50% engine load, the W5DBu10 blend achieved the highest peak cylinder pressure (Pmax) of 89.10 bar, while W5DBu15 recorded the lowest at 79.03 bar. However, W5DBu10 also exhibited the highest cycle-to-cycle pressure variation with a %RSD of 2.21, indicating reduced combustion stability. Conversely, W5D presented the most stable pressure cycles with the lowest %RSD of 1.23 and a pressure range of only 4.63 bar. Regarding IMEP cyclic variation, W5DBu5 emerged as the most stable fuel blend with the lowest coefficient of variation (COVimep) of 1.10 at 50% load, outperforming pure diesel (COVimep = 1.26). Despite the high Pmax of W5DBu10, its increased pressure fluctuation and COVimep (1.19) indicate less reliable performance. These findings confirm that W5DBu5 offers an optimal trade-off between combustion pressure and cyclic stability, making it a viable and stable alternative to conventional diesel in compression ignition engines. Future studies should investigate long-term engine wear and emission performance using WDBu blends to validate their practical applications further.

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