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# Cycle-to-Cycle Pressure Analysis of Butanol-Water-Diesel Blends at Varying Engine Loads

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## Abstract

This study investigates the cycle-to-cycle variation (CCV) in-cylinder pressure for an internal combustion engine fueled with various butanol–water–diesel blends at a constant engine speed of 3,000 rpm and different engine loads (20% and 35%). The primary aim is to assess the combustion stability and performance of the tested emulsified fuels by analysing in-cylinder pressure and coefficient of variation (COV) of the indicated mean adequate pressure (IMEP). Five fuel types were tested: pure diesel (D), water-emulsified diesel (W5D), and three water–diesel blends with 5%, 10%, and 15% butanol additions (W5DBu5, W5DBu10, W5DBu15). At 20% engine load, the W5DBu5 blend showed the lowest relative standard deviation (%RSD) of maximum pressure at 2.80%, indicating superior combustion stability compared to diesel (5.58%) and W5D (4.77%). The maximum pressure (Pmax) ranged from 47.68 bar (D) to 67.30 bar (W5DBu15). At 35% load, W5DBu10 exhibited the highest Pmax of 81.34 bar and a higher variation (%RSD of 2.93%), while diesel had a significantly lower variation at 1.45%. The results demonstrate that small additions of butanol, especially in W5DBu5, improve pressure stability and combustion performance at partial load. However, increased butanol concentration beyond 10% tends to elevate cyclic pressure fluctuations. These findings offer insight into optimizing biofuel blends for improved engine efficiency and reduced emissions.

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## 1. Introduction

Internal combustion engines (ICEs) remain the backbone of the transportation and automotive industries due to their high energy density and mature technology. However, the pursuit of cleaner combustion and improved efficiency has driven researchers to explore alternative fuels and combustion enhancement techniques. One major challenge in ICE performance is the cycle-to-cycle variation (CCV) of in-cylinder pressure, which affects engine stability, emissions, and drivability [1–4]. Cycle-to-cycle variation refers to the fluctuation in combustion parameters from one engine cycle to another under identical operating conditions. These variations are mainly influenced by changes in the combustion process, air-fuel mixing, ignition delay, and residual gas concentration [5–8]. Minimizing CCV can lead to more consistent engine power output, reduced emissions, and smoother engine operation [9–12].

Recent studies have shown that blending oxygenated biofuels such as butanol into diesel can positively influence combustion characteristics by promoting more complete combustion and reducing soot emissions. It was observed that butanol's low cetane number and high latent heat of vaporization could modify the ignition behaviour and temperature profile within the cylinder [10,13–15]. Furthermore, emulsified fuels containing water have been shown to reduce NOx and particulate matter emissions by lowering peak combustion temperatures through the micro-explosion phenomenon. While both butanol and water emulsification offer advantages, their combined effect on CCV and combustion stability remains an underexplored domain. Some researchers have reported that higher alcohol content may worsen ignition delay and increase pressure variability under certain engine conditions [16–19]. However, the balance between improved atomization and thermal cooling provided by butanol–water–diesel blends has yet to be fully quantified concerning cycle pressure uniformity.

This study focuses on the effect of varying butanol content (5%, 10%, and 15%) in water-emulsified diesel fuel on the cycle-to-cycle pressure variation of a single-cylinder engine operated at 3,000 rpm under partial load conditions (20% and 35%). The coefficient of variation (COV) of maximum cylinder pressure and in-cylinder pressure traces over 100 consecutive cycles were used to evaluate combustion stability. The novelty of this research lies in its systematic evaluation of combined water–butanol emulsification on diesel combustion using a statistical analysis of pressure fluctuations, which has rarely been addressed comprehensively in prior literature. Most previous studies have independently analyzed the effects of either water or butanol addition, but seldom in conjunction with an under-controlled CCV observation across engine loads.

This work aims to determine the optimal proportion of butanol in water-emulsified diesel blends that can minimize cycle-to-cycle pressure variation while maintaining desirable combustion characteristics. This study contributes to the growing research on developing cleaner and more stable alternative fuels, especially for daily partial-load engine operations in urban driving conditions.

## 2. Methodology

The different components of the experimental engine test rig are shown in **Figure 1**. The test setup consists of a single-cylinder diesel engine (center-left) mounted securely on a rigid frame to minimize vibration during operation. The engine is directly coupled to an eddy current dynamometer (foreground), which provides precise control over engine load and speed conditions during testing. A blue drive shaft connects the engine output to the dynamometer input, ensuring accurate torque transmission. To the left side of the engine, a fuel supply system equipped with transparent fuel lines and a calibrated burette is installed for fuel consumption measurement and visualization. As mentioned in the methodology, the in-cylinder pressure is monitored using a piezoelectric pressure transducer integrated into the cylinder head via the glow plug port.

Additionally, multiple thermocouples and pressure sensors are visibly connected to the engine for real-time monitoring of key parameters such as exhaust temperature, intake air pressure, and cooling water temperature. The test cell also has instrumentation panels and data acquisition systems (visible in the background) to record engine performance parameters and combustion characteristics. A water-cooling circuit is implemented to maintain engine thermal stability, as indicated by the flexible coolant hoses leading to and from the engine and dynamometer. This comprehensive setup allows for controlled and repeatable testing of alternative fuel blends under variable load conditions.

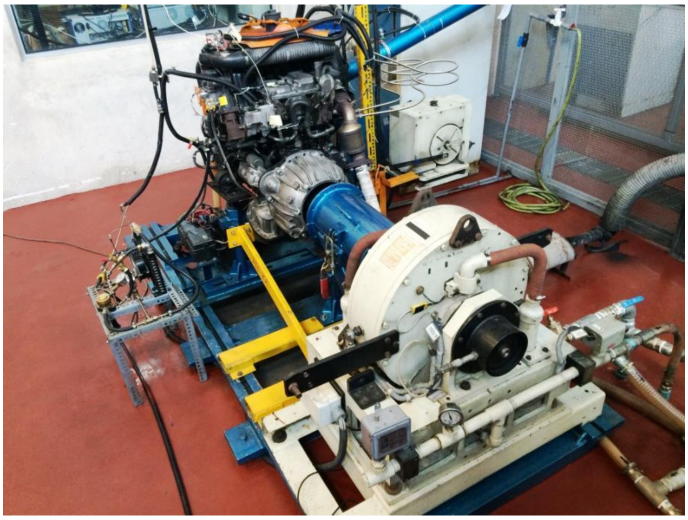

**Figure 1**: Engine test rig of 4JJ1 Diesel engine 3.0 litre with a turbocharger.

A Kistler 6041A ThermoComp water-cooled piezoelectric pressure transducer was employed for accurate in-cylinder pressure measurement. This sensor enables real-time acquisition of pressure traces within the combustion chamber. As illustrated in **Figure 2**, the transducer was installed in cylinder one by replacing the original glow plug port. A tap water-based cooling system was integrated into the setup to prevent excessive thermal loading on the sensor due to direct exposure to combustion gases. The technical specifications and operating parameters of the pressure transducer are detailed in **Table 1**.

**Table 1**: Pressure sensor specifications

| Description | Specifications |
|---|---|
| Make and model | Kistler ThermoComp 6041A |
| Range | 0-250 bar |
| Linearity | ≤ ± 0.5 % FSO |
| Operation temperature range | -50 ˚C to 350 ˚C |
| Natural frequency | 70 kHz |
| Sensitivity shift with cooling | 50 ± 35 ˚C      < ± 0.5 % |

**Figure 2**: In-cylinder pressure transducer

## 3. Result & Discussion

Evaluation of the Cycle-to-Cycle Variation for Different Butanol Ratios on Emulsified Water-Diesel
When testing outstanding engine performance characteristics, the most essential factors are cycle-to-cycle variations (CCV) or cyclic variations. The smaller the variation, the better the performance of the tested engine. A simple method of detecting the stability of engine variations is to test the indicated mean adequate pressure (IMEP). Most researchers named the coefficient of variation (*COVimep*) [20,21]. Several studies have been developed using COV to analyze cycle variations in internal combustion engines. Cycle-to-cycle variation is a practical statistical method used to compare the level of variation between two situations. This is useful even if the mean value of each data is entirely different [22]. It does this by providing a single numerical measure that can be used in any given time series to characterise the erratic variability present in the data [23]. The standard deviation divided by the mean value of the time series data produces the coefficient of variation. The in-cylinder pressure traces are most significant to the engine output since they are affected by several elements, such as the heat release rate from fuel burning and the cylinder volume change over the cycle. Indicated means adequate pressure. Various studies have proposed various limitations for the COVimep. These limitations are determined by the number of cylinders in the engine, the number of cylinders that are monitored, and the collecting data system.
This section focuses on the effects of different test fuels on an engine when the engine is working at a constant speed of 3,000 revolutions per minute. Cyclic cylinder pressure fluctuations are of particular interest in this section. In this part, the examination of test fuels' cyclic cylinder pressure changes is discussed, and the existence of butanol-water-in-diesel blends is shown and validated.

**Cycle-to-cycle analysis of In-Cylinder Pressure**
Among the main engine metrics that characterise the engine's performance is the cylinder pressure cyclic variation (CV), also known as the cylinder pressure cycle-to-cycle variation (CCV). A significant component of the combustion issue that has been found is the fluctuation in cylinder pressure that occurs from cycle to cycle and is caused by many different causes [22–24]. Because of this, the usage of lean mixes is restricted, the levels of pollutant emissions are raised, and the idle pace of operation is sped up. As a result, the cyclic variation effect might be eliminated or reduced, which would result in an increase in the power output of the engine as well as a decrease in the noise and vibration produced by the engine [25]. Additionally, cyclic variation is the source of torque variations and poor drivability in the vehicle [26]. The research on the cyclic fluctuations of the engine produced a single statistical measure for a regular specified time series. This measure was used to characterise the periodic variation of the data values (Heywood, 1988).
Additionally, cyclic variation research can measure and indicate the degree to which the mean values repeat themselves across the cycles. This section presents and discusses the findings of cylinder pressure cyclic variations based on 100 consecutive cycles, as well as the coefficient of variation (COV) resulting from the effects of zero, partial, and full loads on cyclic variations based on cylinder pressure at three distinct engine loads (20%, 35%, and 50%). This section provides more information on the impact of butanol on water-in-diesel blends with reference to the changes in engine cycle pressure.

**Cylinder Pressure Cycle to Cycle at Engine Load of 20%**
The effect of cylinder pressure variation for diesel, W5DBu5, W5DBu10, and W5DBu15 is shown in **Figure 2** for 20% load and 3,000 rpm. As expected, the cylinder pressure variations are comparable among all fuels. This figure shows that most of the cylinder pressure practically starts at the same point for W5DBu5, W5DBu10, and W5DBu15 (for the same engine load). This is attributed to similar fuel injection conditions, as there is no significant decrease in their ignition delay values due to comparable cetane numbers. Diesel contains the highest cetane number, which provides the fastest injection, while W5DBu15 was ranked worst. Based on visual observations, it was found that the variation of change on W5D was greatest before reaching the first pressure peak. This may be due to the inconsistent burning process of water molecules at this time. This condition is reduced when butanol is added to the

water-diesel fuel mixture. As expected, all butanol blend diagrams show slightly lower maximum pressures than diesel fuels. The explanation for this behaviour is mainly attributed to the fuel spray characteristics containing butanol droplets of smaller size and the higher cooling effect of alcohols with the aid of water, lowering the combustion temperature. These findings are paralleled with the study conducted by [27].

The superimposed traces in **Figure 3** reveal that the tightest clustering of pressure curves around the cycle average (red line) occurs in the W5DBu5 case, suggesting superior combustion repeatability under low-load conditions. This consistent pressure evolution indicates stable ignition and flame propagation, facilitated by the synergistic effect of butanol and water emulsification. In contrast, W5D shows more significant deviation, especially in the compression and early combustion phases (crank angle 5°–10°), likely due to uneven vaporization and delayed micro-explosions of water droplets. This instability manifests as a broader spread in the pressure traces, emphasizing the destabilizing effect of water when unaccompanied by an oxygenated additive such as butanol.

On the other hand, W5DBu10 and W5DBu15 present more scattered pressure patterns beyond the 10° crank angle, particularly during the expansion stroke, which may be attributed to the excessive cooling effect and prolonged ignition delay caused by the higher butanol content. The dual peaks in some traces further suggest uneven combustion phases, potentially indicating split or delayed combustion events. The overall trend confirms that although butanol blends can reduce peak pressure due to lower combustion temperatures, only moderate concentrations (e.g., 5%) yield a balanced compromise between pressure stability and combustion efficiency. At the same time, higher proportions tend to undermine cycle uniformity.

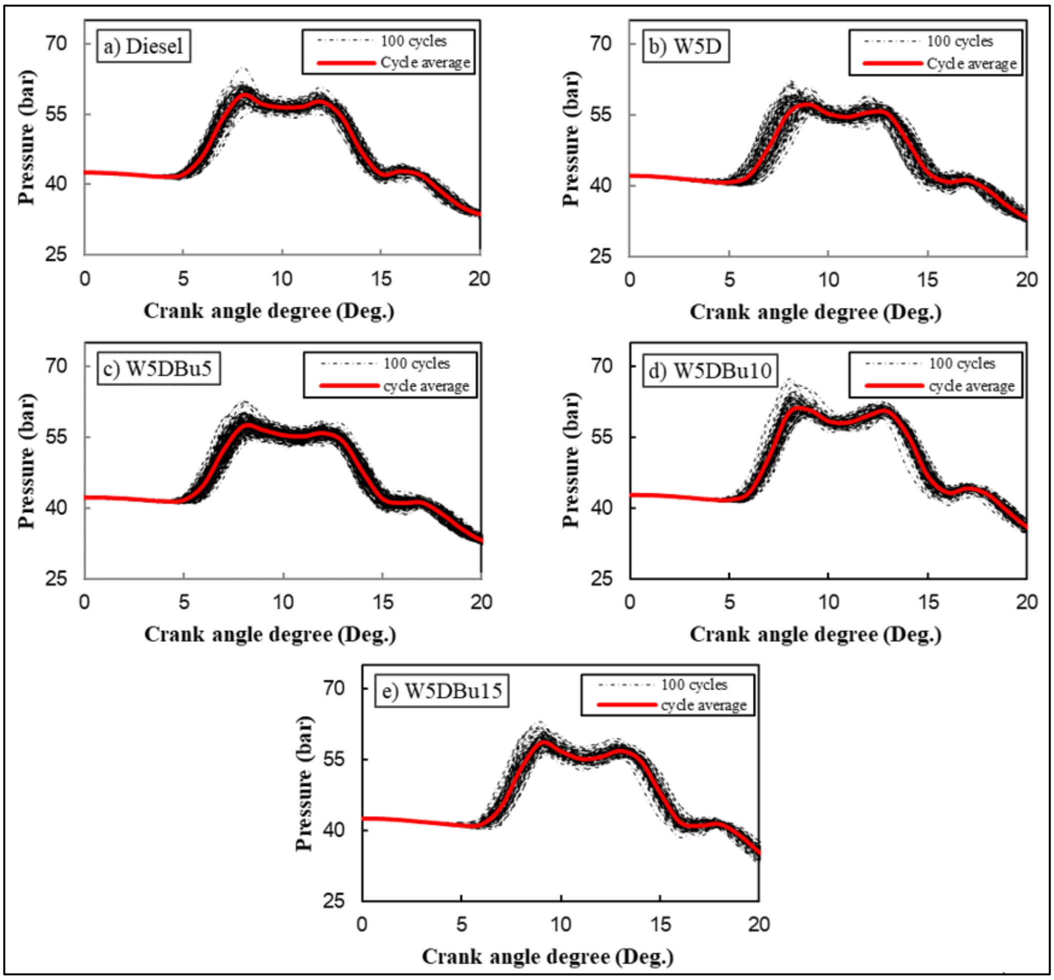


**Figure 3**: Cylinder pressure variation for (a) Diesel, (b) W5D, (c) W5DBu5, (d) W5DBu10 and (e) W5DBu15 at 20% load and speed of 3,000 rpm

**Figure 4** shows the maximum pressure ($P_{max}$) for a hundred cycles of diesel, W5D, W5DBu5, W5DBu10, and W5DBu15 at 20% load and speed of 3,000 rpm. The figure is assisted by Table 4.6 to explain the data in more detail. The data in the figure show the mean variability of the maximum pressure ($P_{max}$) on the five fuel types tested. W5DBu15 recorded the highest Pmax value at 67.37 bar, while W5D recorded the lowest Pmax value at 47.83 bar. Among all fuel types, diesel (D) showed the most significant $P_{max}$ difference range of 14.38 bar compared to W5DBu5 at only 8.74 bar. This is evidenced when the smallest percentage of W5DBu5 standard deviation is only 2.80%. This small %RSD difference indicates a more stable W5DBu5 fuel consumption at 20% load. This aligns with **Figure 3,** where the W5DBu5 graph shows a smaller pressure variation line than the others.
The visual representation in **Figure 4** highlights the cyclic stability behaviour of each fuel type. The W5DBu5 curve (red) exhibits relatively narrow oscillations with minimal abrupt peaks or dips, reinforcing the statistical findings in **Table 2**, where W5DBu5 had the lowest standard deviation (1.61) and %RSD (2.80%). This consistency confirms that the 5% butanol addition effectively dampens fluctuations in combustion pressure by promoting more uniform ignition and burn rates. In contrast, pure diesel (black) and W5D (yellow) demonstrate more erratic behaviour, with W5D especially showing frequent and sharp downward spikes below 50 bar, indicative of unstable combustion likely due to uneven water droplet vaporization and delayed ignition.
Furthermore, the trends observed for W5DBu10 (purple) and W5DBu15 (green) illustrate a progressive increase in variability with higher butanol content. W5DBu15, while achieving the highest peak pressures approaching 67 bar, also shows the widest dispersion across the 100 cycles, indicating increased cycle-to-cycle inconsistency. These erratic fluctuations may stem from the excessive latent heat of vaporization and lower cetane index of butanol at higher concentrations, which can extend ignition delay and result in uneven combustion phasing. Therefore, while higher butanol content enhances peak pressure output, it does so at the expense of combustion stability, particularly under low-load conditions.

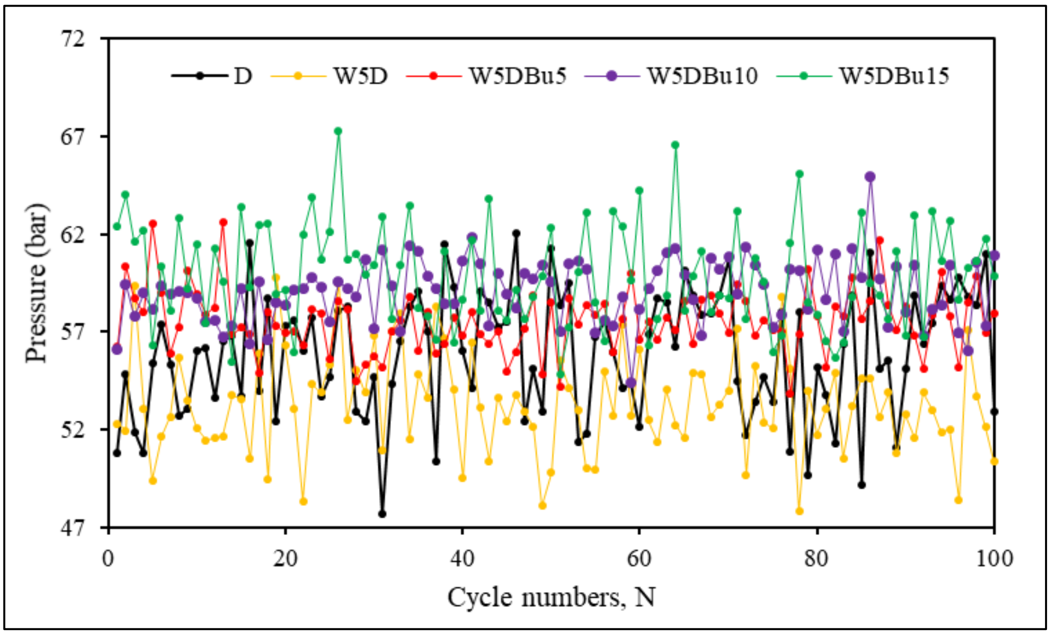


**Figure 4**: Pmax graph for hundred cycles of tested fuel at 20% load and speed of 3,000 rpm

**Table 2** summarizes the statistical variation of maximum cylinder pressure (Pmax) across 100 consecutive cycles for five fuel types under a 20% engine load. This low-load condition is susceptible to combustion instabilities due to incomplete combustion and lower in-cylinder temperatures, making it an ideal regime for assessing the impact of fuel blending on pressure consistency. Among the tested fuels, W5DBu5 exhibited the most stable combustion performance, with the lowest standard deviation

(SD = 1.61), variance (2.59), and relative standard deviation (%RSD = 2.80%). Its pressure range was the narrowest (8.74 bar), and the average Pmax reached 57.55 bar. These results suggest that a 5% butanol addition effectively suppresses cyclic pressure fluctuations, likely due to enhanced fuel atomization and more homogeneous air-fuel mixing. The slightly higher average pressure than diesel (55.91 bar) indicates improved combustion energy release.

In contrast, pure diesel (D) presented the highest variation, with a wide pressure range of 14.38 bar and the largest %RSD of 5.58%, suggesting greater instability in combustion. This may be attributed to the absence of water-induced micro-explosions and the lack of oxygenated components, which can enhance mixing and reduce ignition delay. W5D, while showing reduced combustion variability compared to diesel (%RSD = 4.77%), still demonstrated significant pressure deviation, likely due to inconsistent vaporization and localized cooling effects from emulsified water droplets. As butanol concentration increased beyond 5%, W5DBu10 and W5DBu15 showed a mixed effect. While both blends achieved higher average Pmax values (59.06 and 59.94 bar, respectively), their %RSD values increased slightly to 2.73% (W5DBu10) and 4.33% (W5DBu15). The increase in variability, particularly in W5DBu15, may be linked to the cumulative effects of higher latent heat and lower cetane number from butanol, which delays ignition and introduces irregular combustion phasing. This supports findings from prior studies where excessive alcohol blending has been associated with elevated CCV at low-load conditions [28–31].

These results affirm that moderate butanol addition (5%) in water–diesel emulsions delivers a favourable trade-off between combustion efficiency and stability at light engine loads. However, increasing the butanol content beyond 10% can undermine these benefits significantly when ignition timing is already compromised.

**Table 2**: Statistical results on maximum pressure cyclic variations at 20% load and speed of 3,000 rpm

| Fuel test | Maximum pressure (bar) | | | | | Varian | SD | %RSD |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Range | Average | Mode | | | |
| D | 47.68 | 62.06 | 14.38 | 55.91 | 56.21 | 9.72 | 3.12 | 5.58 |
| W5D | 47.83 | 59.78 | 11.95 | 53.32 | 53.09 | 6.47 | 2.54 | 4.77 |
| W5DBu5 | 53.87 | 62.60 | 8.74 | 57.55 | 57.64 | 2.59 | 1.61 | 2.80 |
| W5DBu10 | 54.42 | 64.94 | 10.52 | 59.06 | 59.19 | 2.61 | 1.61 | 2.73 |
| W5DBu15 | 54.84 | 67.30 | 12.46 | 59.94 | 59.73 | 6.73 | 2.59 | 4.33 |

**Cylinder Pressure Cycle to Cycle at Engine Load of 35%**

**Figure 5** shows the plot of 100 times cylinder pressure variation against the crank angle degree at 35% engine load applied to the engine at a constant engine speed of 3,000 rpm for all test fuels. From **Figure 5**, the variation of the cylinder pressure curve for test fuel shows a growing trend as the total percentage of butanol content in the fuel increases. This engine experiences a more significant difference in cycle variations when driven with a content of water-diesel emulsification with butanol as an additive, especially the W5DBu10 (4.94). In Figure 4.56 (d), the engine exhibits a higher rate of variation of the cylinder pressure curve, especially around power stroke and exhaust when the fuel used is W5DBu10. Compared to diesel-based, the variant is the lowest at 1.20. In fact, with the addition of butanol, a higher cylindrical pressure is achieved in the emulsified water-diesel mixture along with butanol. These findings have the same opinion as the studies conducted by [27].

A closer inspection of Figure 4 reveals that the Diesel and W5DBu5 fuels display relatively narrow bands of pressure fluctuation around the red cycle-averaged line, especially during the compression and power stroke regions (approximately 5° to 15° crank angle). This reflects a more stable and consistent combustion event, supporting the low %RSD values observed in Table 2 for both fuels (1.45% for diesel and 1.87% for W5DBu5). The W5DBu5 trace also exhibits an improved peak pressure distribution compared to W5D, suggesting that the 5% butanol addition helps enhance mixture homogeneity and reduces erratic combustion phasing, even under increased load.

On the other hand, W5DBu10 and W5DBu15 demonstrate a broader scatter among the 100 cycle traces, particularly around the peak pressure zone (~10° crank angle) and expansion stroke, indicative of elevated cycle-to-cycle variation. This is consistent with their higher standard deviations (2.22 bar) and %RSD values (2.93% and 2.83%, respectively). The greater instability may be caused by the delayed ignition and uneven vaporization effects of higher butanol content, which interfere with consistent combustion development. Although these blends achieved the highest average pressures, the increased cyclic dispersion could contribute to combustion harshness and torque irregularities, which are undesirable for engine durability and drivability. Thus, the visual analysis in Figure 4 confirms that excessive butanol addition, while enhancing peak pressure, may compromise combustion stability, especially under moderate engine loads.

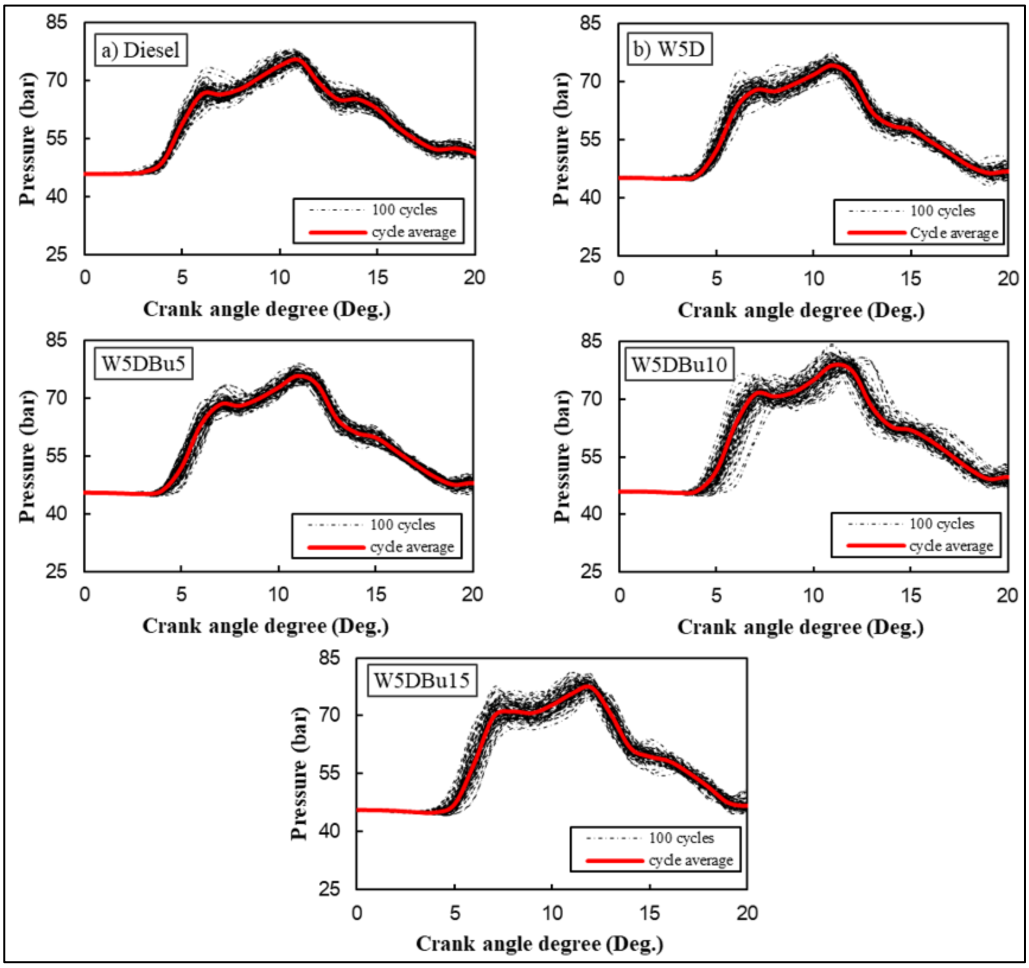


**Figure 5:** Cylinder pressure variation for (a) Diesel, (b) W5D, (c) W5DBu5, (d) W5DBu10 and (e) W5DBu15 at 35% load and speed of 3,000 rpm

**Figure 6** shows the maximum pressure ($P_{max}$) for a hundred cycles of diesel, W5D, W5DBu5, W5DBu10, and W5DBu15 at 35% load and speed of 3,000 rpm. The figure is assisted by **Table 3** to explain in detail the data involved. The data in the figure show the mean variability of the maximum pressure ($P_{max}$) on the five fuel types tested. W5DBu15 recorded the highest Pmax value at 67.37 bar, while W5D recorded the lowest Pmax value at 47.83 bar. Among all fuel types, diesel (D) showed the most significant Pmax difference range of 14.38 bar compared to W5DBu5 at only 8.74 bar. This is evidenced when the smallest percentage of W5DBu5 standard deviation is only 2.80%. This small %RSD difference indicates a more stable W5DBu5 fuel consumption at 35% load. This aligns with **Figure 6,** where the W5DBu5 graph shows a smaller pressure variation line than the others.

A visual analysis of **Figure 6** reveals that W5D and Diesel exhibit relatively clustered data points with limited amplitude fluctuations across the 100 cycles, indicating relatively stable combustion behaviour. Diesel, despite having the highest cetane number, still shows minor fluctuations likely due to fuel spray dynamics at low-to-moderate load. However, W5D, which lacks oxygenated additives, displays occasional low-pressure dips, suggesting incomplete combustion phases possibly triggered by inconsistent water vaporization. These localized pressure drops in W5D reinforce the importance of a stabilizing additive to reduce the cyclic dispersion seen in water-emulsified fuels.
In contrast, the curves for W5DBu10 and W5DBu15 display a noticeably more erratic pattern with frequent high-pressure spikes reaching above 82 bar and sharp drops approaching 70 bar. These irregularities are symptomatic of higher cycle-to-cycle variation, which may be induced by longer ignition delays and greater thermodynamic instability caused by increased butanol content. Interestingly, although W5DBu15 achieves the highest peak pressures, its increased amplitude spread reflects a trade-off between power output and combustion stability. Meanwhile, W5DBu5 maintains a more consistent trend with moderate peak pressures and tightly packed fluctuations, highlighting its effectiveness in balancing performance and pressure uniformity under partial engine load conditions.

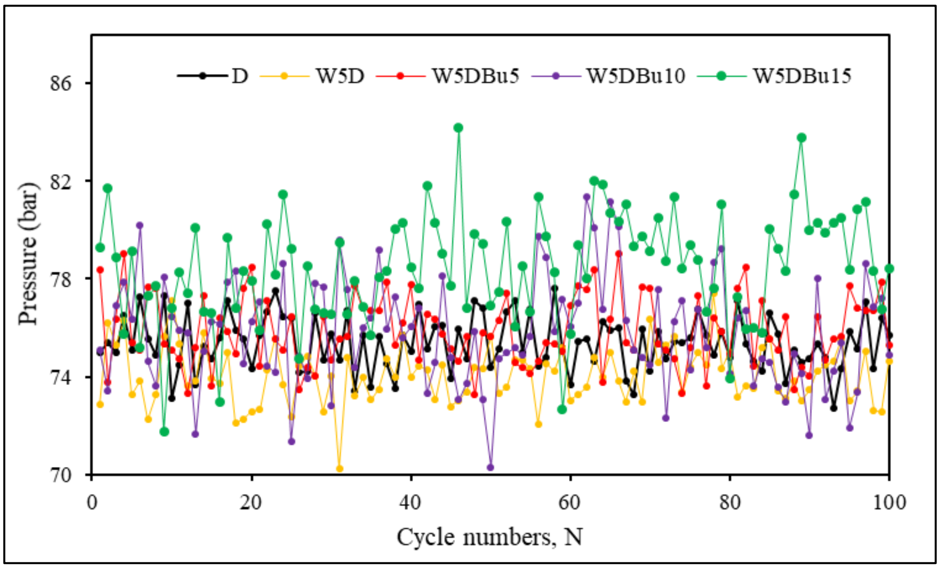


**Figure 6** Pmax graph for a hundred cycles of tested fuel at 35% load and speed of 3,000 rpm

The graphical trend in Figure 5 further illustrates the influence of butanol concentration on the pressure uniformity over 100 consecutive cycles. Diesel (D) and W5DBu5 curves exhibit relatively tight pressure fluctuations, oscillating within a narrower vertical band between 73–78 bar. This aligns with their lower standard deviation and %RSD values shown in **Table 3**. In contrast, W5DBu10 and especially W5DBu15 exhibit visibly broader and more erratic oscillations, frequently exceeding 80 bar and dipping below 72 bar, highlighting their poorer combustion stability. The green curve representing W5DBu15 demonstrates the highest scatter, suggesting that excessive butanol concentration disrupts the combustion process consistency, likely due to prolonged ignition delays and uneven fuel-air mixing under emulsified conditions. Moreover, the W5D (water-diesel without butanol) curve shows frequent abrupt dips, particularly in the first half of the cycle range. These fluctuations may be attributed to incomplete vaporization of water droplets, leading to localized cooling and misfire-prone conditions during early combustion cycles. The introduction of 5% butanol effectively mitigates this issue, as seen in the smoother W5DBu5 curve, confirming its role as a combustion stabilizer in moderate concentrations. Overall, the visual evidence from **Figure 5** reinforces the statistical findings: moderate butanol addition enhances cycle stability, whereas higher concentrations compromise combustion regularity despite higher average Pmax values.

**Table 3**: Statistical results on maximum pressure cyclic variations at 35% load and speed of 3,000 rpm

| Fuel test | Cylinder Pressure (bar) | | | | | Varian | SD | %RSD |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Range | Average | Mode | | | |
| D | 72.69 | 77.61 | 4.92 | 75.38 | 75.41 | 1.20 | 1.10 | 1.45 |
| W5D | 70.24 | 77.41 | 7.17 | 74.07 | 74.00 | 1.36 | 1.17 | 1.58 |
| W5DBu5 | 73.25 | 79.03 | 5.78 | 75.87 | 75.62 | 2.02 | 1.42 | 1.87 |
| W5DBu10 | 70.29 | 81.34 | 11.06 | 75.83 | 75.87 | 4.94 | 2.22 | 2.93 |
| W5DBu15 | 71.76 | 84.18 | 12.42 | 78.49 | 78.45 | 4.92 | 2.22 | 2.83 |

**Table 3** presents the statistical results of maximum cylinder pressure (Pmax) over 100 consecutive cycles for different fuel blends at 35% engine load. The variation in Pmax is a key indicator of combustion stability, with lower relative standard deviation (%RSD) values suggesting more consistent combustion behaviour. Among the tested fuels, pure diesel (D) recorded a Pmax range of 4.92 bar (72.69–77.61 bar), with an average of 75.38 bar and the lowest variance of 1.20, resulting in a %RSD of 1.45%. This indicates a relatively stable combustion process for diesel under partial load conditions. W5D, the water-emulsified diesel without butanol, exhibited a wider range of 7.17 bar and a slightly higher %RSD of 1.58%, highlighting the destabilizing effect of water emulsification on pressure consistency due to micro-explosion behaviour during combustion.

Introducing 5% butanol (W5DBu5) improved pressure stability, as evidenced by a reduced range of 5.78 bar, moderate variance (2.02), and %RSD of 1.87%. Although higher than pure diesel, W5DBu5 showed more uniform combustion than W5D. This may be attributed to the improved atomization and fuel-air mixing provided by the butanol additive, which enhances evaporation and combustion homogeneity. However, further increases in butanol concentration led to notable pressure instability. The W5DBu10 and W5DBu15 blends demonstrated wider Pmax ranges of 11.06 bar and 12.42 bar, respectively, and shared the highest standard deviation (SD = 2.22) and variance (~4.9). Their corresponding %RSD values were 2.93% and 2.83%, indicating increased cycle-to-cycle fluctuation. While both blends achieved the highest average pressures (78.49 bar for W5DBu15), their elevated pressure variability may lead to adverse effects such as engine knock, vibration, and drivability issues. These results suggest that a moderate butanol content (5%) in water-diesel emulsions balances enhanced combustion efficiency and pressure stability. Conversely, higher butanol levels (≥10%), despite increasing Pmax, compromise combustion consistency under partial load. The findings corroborate prior studies, which indicate that excessive alcohol content, due to its lower cetane number and higher latent heat, can prolong ignition delay and induce unstable combustion phasing [28–31]. In summary, W5DBu5 emerges as the optimal blend under 35% load conditions, offering superior pressure stability compared to other emulsified blends while maintaining performance close to pure diesel. These insights are critical for optimizing alternative fuel formulations targeted for partial-load engine operations.

## 4. Conclusion

This study comprehensively investigated the cycle-to-cycle pressure variation characteristics of a diesel engine operating at 3,000 rpm under partial loads (20% and 35%) using various water–diesel–butanol blended fuels. The analysis focused on statistical variation in maximum cylinder pressure (Pmax) over 100 combustion cycles, supported by visual and numerical interpretation. The results indicate that adding 5% butanol (W5DBu5) to a 5% water–diesel emulsion significantly improves combustion stability across both load conditions. At 20% load, W5DBu5 achieved a relatively high average pressure of 57.55 bar with the lowest %RSD of 2.80%, compared to diesel's %RSD of 5.58% and W5D's 4.77%, reflecting enhanced pressure uniformity. Similarly, at 35% load, W5DBu5 demonstrated the lowest cyclic variation among all tested fuels, with a %RSD of 1.87%, outperforming diesel (1.45%) and notably better than higher butanol blends such as W5DBu10 (2.93%) and W5DBu15 (2.83%). Higher butanol concentrations (10% and 15%) led to elevated peak pressures—up to 67.30 bar (W5DBu15 at 20% load) and 84.18 bar (W5DBu15 at 35% load)—but at the cost of increased combustion instability and cycle-to-cycle variability. These results suggest that excessive butanol levels can undermine water emulsification's combustion control advantages. In conclusion, the W5DBu5 blend presents the most balanced formulation. It offers both combustion stability and consistent pressure development under partial engine loads, making it a promising candidate for cleaner and more efficient alternative fuel applications in compression ignition engines.

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