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Combustion and Pressure Rise Characteristics of Butanol–Diesel Blends in a Multi-Cylinder Engine at Varying Loads and Speeds

MK Akasyah[1,2], Norazmira Awang[2], Che Zawiyah Che Hasan[3]

[1]Automotive Technology Center (ATeC), Politeknik Sultan Mizan Zainal Abidin, Malaysia
[2]Department of Mechanical Engineering, Politeknik Sultan Mizan Zainal Abidin KM 8 Jalan Paka, 23000, Dungun Terengganu, Malaysia
[3]Department of Electrical Engineering, Politeknik Ungku Omar, Ipoh, Malaysia

Corresponding author: akasyah@psmza.edu.my

Abstract

This study investigates the combustion characteristics, and in-cylinder pressure rise behaviour of a single-cylinder diesel engine fueled with various diesel–butanol–water blends. Five fuel types were tested: pure diesel (Diesel), diesel with 5% water (W5D), and W5D further blended with 5%, 10%, and 15% butanol, labelled W5DBu5, W5DBu10, and W5DBu15, respectively. Experiments were conducted at a constant engine speed of 3,000 rpm under varying load conditions of 20%, 35%, and 50%. Results show that W5DBu10 produced the highest pressure rise at 20% load, reaching 11.9 bar at 6° after the top dead centre (ATDC), approximately 21% higher than pure diesel (9.8 bar). At 35% load, W5DBu15 demonstrated the highest rate of pressure rise (RoPR) with a peak of 16.25 bar at 5° ATDC, compared to 13.48 bar for diesel. Under 50% load, W5DBu15 again showed the highest RoPR at 14.84 bar (2.5° ATDC). The mass fraction burned (MFB) analysis revealed that W5DBu15 completed combustion slightly later but demonstrated higher thermal efficiency, especially at medium and high loads. Moreover, ignition delay tended to increase with higher butanol content. These findings suggest incorporating butanol into diesel–water blends can enhance in-cylinder pressure characteristics and combustion performance. However, the optimal blend ratio must be carefully selected to balance ignition delay and pressure rise behaviour.

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1. Introduction

The global automotive industry has experienced increasing pressure to reduce greenhouse gas emissions and dependence on fossil fuels. Diesel engines, widely used for their efficiency and durability, are also a significant source of nitrogen oxide (NOx) and particulate matter (PM) emissions. Alternative fuels and advanced combustion strategies have been actively researched to enhance fuel efficiency while minimizing environmental impact [1–4]. Among the alternative fuels, alcohol-based blends such as ethanol and butanol have gained attention due to their renewability and favourable combustion characteristics. Butanol offers several advantages over ethanol, including higher energy content, lower vapour pressure, and better miscibility with diesel (Lapuerta et al., 2008). Previous studies have demonstrated that butanol–diesel blends can improve combustion efficiency and reduce emissions, especially under low to medium engine loads [5–8].

Adding water into diesel or alcohol–diesel mixtures has also been investigated to suppress peak temperatures and reduce NOx formation. Water emulsions or water–fuel blends prolong ignition delay and promote complete combustion through micro-explosion phenomena [9–12]. However, the combined effects of water and butanol in diesel fuel, particularly on pressure rise rate and mass fraction burned at varying engine loads, remain underexplored. The rate of pressure rise (RoPR) and the mass fraction burned (MFB) are critical indicators of in-cylinder combustion quality. A higher RoPR can enhance thermal efficiency but may lead to engine knocking or increased mechanical stress. Previous research has shown that oxygenated fuels accelerate the premixed combustion phase, thus affecting the RoPR profile [13–16]. MFB analysis, on the other hand, provides insight into combustion phasing and the duration of energy release within the engine cycle.

This study aims to fill the knowledge gap by investigating the effects of blending butanol and water with diesel on engine combustion characteristics, focusing on RoPR and MFB under different engine loads. Specifically, the blends tested include diesel with 5% water (W5D) and W5D further blended with 5%, 10%, and 15% butanol (W5DBu5, W5DBu10, and W5DBu15). Tests were conducted at a fixed engine speed of 3,000 rpm under 20%, 35%, and 50% load conditions.

The primary objective of this study is to evaluate how different proportions of butanol in diesel–water blends affect the pressure development and combustion phasing within the engine cylinder. The analysis includes quantitative comparisons of peak RoPR, ignition delay, and MFB progression among the fuel blends. The study also aims to determine the optimal blend that balances combustion efficiency and mechanical safety. The novelty of this research lies in the combined application of water and butanol in diesel blends and in assessing their impacts on RoPR and MFB over multiple load conditions. While numerous studies have examined butanol–or water–diesel blends independently, limited literature addresses their synergistic effects on engine performance. This study provides new insight into optimizing oxygenated and hydrated fuel blends for improved combustion in compression-ignition engines.

2. Methodology

This section provides a detailed description of the key facilities and experimental equipment utilized in the study. The term 'experimental setup' encompasses the engine test rig and the main instruments employed for data acquisition. These include the emission analyzer, cylinder pressure sensor, fuel flow meter, engine speed sensor, and torque measurement device. Additionally, this chapter offers a brief overview of the data acquisition system and the integration of various sensors.

Figure 1 illustrates a detailed schematic of the experimental setup, highlighting the major components involved in the engine performance evaluation process. The experimental work was conducted at the Engine Performance Laboratory, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang. The setup comprises two main sections: the engine and control rooms. In the engine room, a 150-kW dynamometer is coupled to the engine to simulate various load conditions. The engine is supported by essential subsystems, including an air intake system, exhaust and cooling systems (linked to a dyno cooling tower), and a fuel delivery system connected to a fuel tank and fuel flow meter. Engine cooling is managed via an engine water cooler to maintain thermal stability during operation. Meanwhile, in the control room, a data acquisition system is interfaced with several analyzers: a combustion analyzer, a temperature analyzer, and a gas analyzer. These instruments monitor and record critical engine parameters such as in-cylinder pressure, temperature, emissions, fuel consumption, engine speed, and torque. All systems are managed through a dyno control panel, ensuring accurate control and synchronization of the experimental procedures.

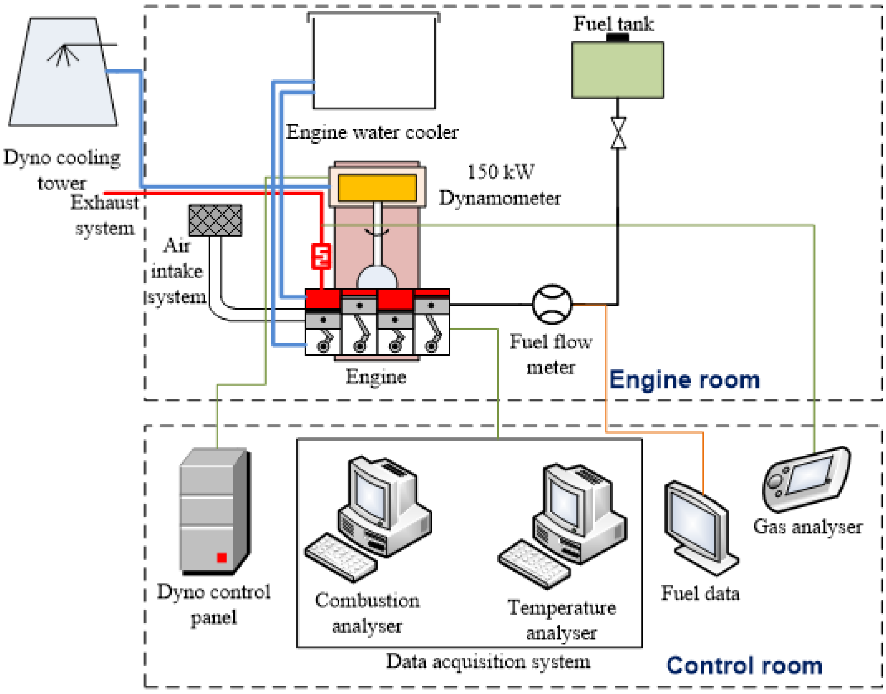

Figure 1: Schematic of the test cell for the experimental setup

Table 1: Isuzu 4JJ1 diesel engine specifications

Description	Specifications
Engine Model	ISUZU 4JJ1E4C-L
Type	Turbocharged, water-cooled, overhead valve
Bore (mm)	95.4
Stroke (mm)	104.9
Displacement (L)	2.999 L
Number of cylinders	4 in-line
Compression ratio	17.5
Connecting rod length (mm)	150.0
Piston pin offset (mm)	1.0
Rated output	103 kW/ 3600 rpm
Maximum torque	294 Nm/ 1400 – 3400 rpm
Fuel system	Common rail
Low idle speed	800±10 min^{-1}
Ignition system	Direct injection

The Isuzu 4JJ1E4C-L diesel engine was selected as the primary power unit for this experimental study. This engine is a turbocharged, water-cooled, overhead valve (OHV) type with four in-line cylinders and a total displacement of 2.999 litres. Detailed technical specifications are provided in **Table 1**. The engine features a bore of 95.4 mm and a stroke of 104.9 mm, resulting in a compression ratio 17.5, which is typical for high-efficiency diesel combustion. The connecting rod length is 150.0 mm, and the piston pin offset is 1.0 mm, influencing the engine's mechanical dynamics and combustion timing. The rated power output is 103 kW at 3600 rpm, while the maximum torque of 294 Nm is achieved across a wide speed range from 1400 to 3400 rpm, allowing for stable performance under various load conditions. This engine has a standard rail fuel injection system and uses direct injection for fuel atomization and combustion efficiency. Its idle speed is maintained at approximately 800 revolutions per minute, tolerating ±10 rpm, ensuring steady low-load operation. Although the engine includes an Exhaust Gas Recirculation (EGR) system for emission control, the EGR was deactivated during the experiments to maintain a consistent combustion environment and to isolate the effect of other variables under study.

3. Result & Discussion

Analysis of pressure rise rate

Figure 1 presents the rate of heat release (ROHR) versus crank angle degree for five different fuel types Diesel (D), W5D, W5DBu5, W5DBu10, and W5DBu15 operated at 50% engine load and a constant speed of 3,000 rpm. The graph illustrates the dynamic combustion behaviour of each fuel blend throughout the engine cycle, particularly highlighting the premixed and diffusion combustion phases. As shown in the figure, all fuel blends exhibit a sharp increase in ROHR near the top dead centre (TDC), indicating the onset of premixed combustion. Notably, the W5DBu15 blend demonstrates the highest peak heat release rate, exceeding 1,700 kJ/s around 1–2° after TDC. This increase can be attributed to the elevated oxygen content and improved volatility of butanol, which facilitate a more intense and rapid combustion during the premixed phase. In contrast, the baseline diesel fuel (D) exhibits a comparatively lower peak ROHR, suggesting slower combustion kinetics and limited oxygen availability.

The blended fuels (W5DBu5 and W5DBu10) display intermediate behaviour, with peak ROHR values slightly lower than W5DBu15 but higher than diesel and W5D. The presence of water in the W5D blend appears to moderate the heat release rate, likely due to the thermal diluting effect and higher heat of vaporization, which prolong ignition delay and reduce combustion intensity. Overall, the ROHR profiles reflect the combined influence of fuel oxygenation and ignition delay on combustion intensity. The increased peak values in W5DBu blends, particularly W5DBu15, suggest improved combustion efficiency, although this may also raise concerns about engine knocking and mechanical stress due to rapid pressure rise. These findings align with previous studies indicating that oxygenated fuels enhance premixed combustion but require careful optimization to maintain engine durability and performance [17–20].

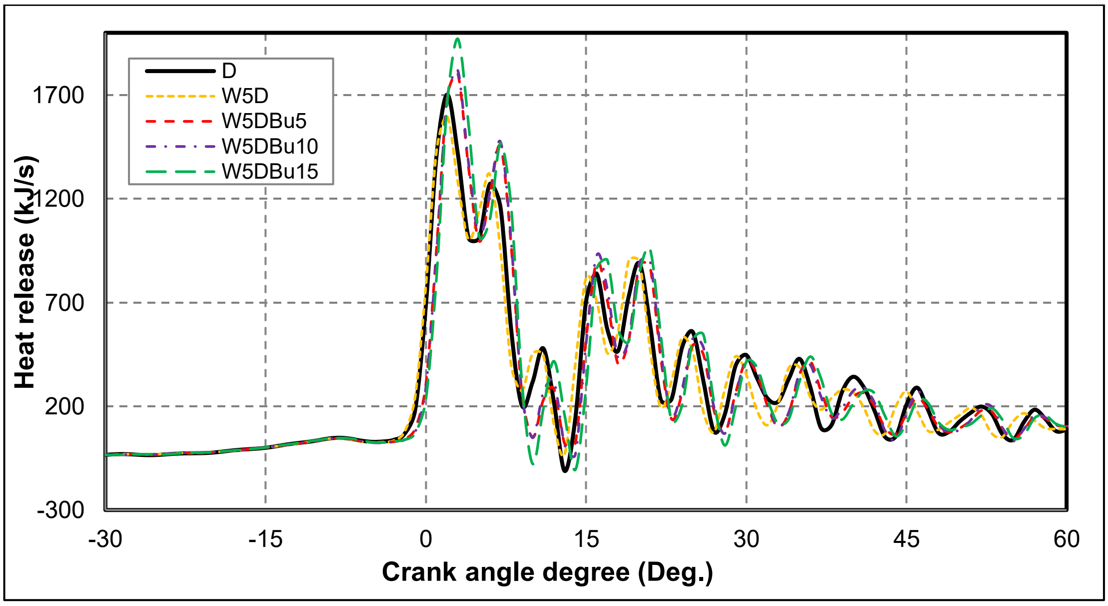

Figure 1: Rate of heat release for various blends of fuel operated at 50% load and speed of 3,000 rpm

Figure 2 illustrates the variation in the rate of pressure rise (RoPR) for diesel and various diesel–butanol–water blends (W5DBu5, W5DBu10, and W5DBu15) at a constant engine speed of 3,000 rpm and 20% load, averaged over 100 consecutive combustion cycles to ensure data consistency. The results are derived from the first derivative of in-cylinder pressure concerning crank angle, offering insights into combustion phasing and intensity. W5DBu10 exhibited the highest peak RoPR among the tested fuels, reaching 11.9 bar at 6° after the top dead centre (ATDC). In contrast, the baseline diesel fuel recorded a lower peak RoPR of 9.8 bar at the same crank angle, indicating a relative increase of approximately 21% with W5DBu10. This enhancement is primarily attributed to the increased oxygen availability and reduced specific heat capacity of butanol-containing blends, which promote more vigorous premixed combustion. The elevated RoPR observed with W5DBu10 suggests enhanced combustion efficiency; however, it also implies a more aggressive pressure development within the cylinder, which may lead to higher mechanical stress. The results confirm that the blend composition is critical in shaping the combustion profile, particularly under low-load conditions where ignition delay and mixture reactivity significantly influence pressure dynamics.

Furthermore, a comparative analysis of all fuel blends indicates a clear trend in peak RoPR values: W5DBu10 (11.9 bar) > W5DBu5 (11.2 bar) > W5DBu15 (10.7 bar) > Diesel (9.8 bar) > W5D (9.1 bar), all occurring within the range of 5° to 7° ATDC. The sharp pressure rise associated with W5DBu10 reflects an optimal balance between ignition delay and fuel reactivity, allowing for efficient energy release during the premixed combustion phase. Interestingly, although W5DBu15 contains a higher proportion of butanol, its peak RoPR was slightly lower than W5DBu10, likely due to excessive ignition delay and incomplete mixture preparation. In contrast, W5D recorded the lowest RoPR, confirming the retarding influence of water on combustion aggressiveness. These quantitative differences underscore the sensitivity of RoPR to butanol concentration, highlighting W5DBu10 as the most promising candidate among the tested blends for enhancing combustion performance without compromising pressure stability.

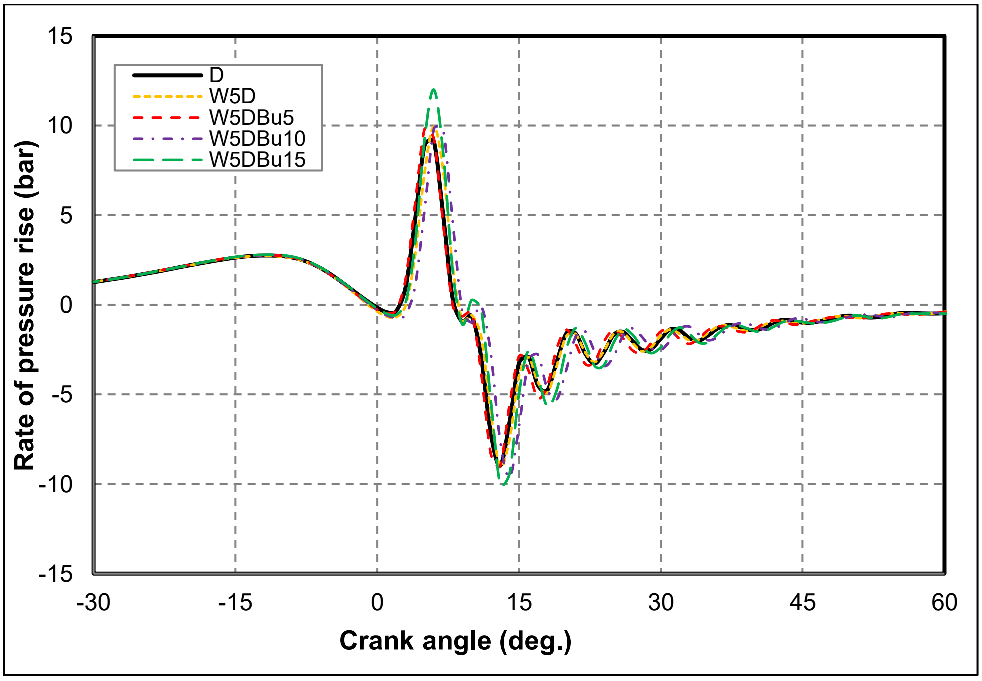

Figure 2: Rate of pressure rise for various blends of fuel operated at 20% load and speed of 3,000 rpm

Figure 3 presents the rate of pressure rise (RoPR) for various fuel blends Diesel, W5D, W5DBu5, W5DBu10, and W5DBu15 at an engine speed of 3,000 rpm and a load condition of 35%. The figure reveals distinct combustion characteristics among the fuel types, with significant variations in peak RoPR values, primarily arising during the premixed combustion phase. This phase is marked by rapid fuel oxidation following ignition delay, resulting in steep pressure gradients. The highest peak RoPR was recorded for the W5DBu15 blend, reaching 16.25 bar at 5° ATDC, followed by W5DBu10 (14.81 bar at 5° ATDC), W5DBu5 (14.08 bar at 4° ATDC), Diesel (13.48 bar at 4° ATDC), and finally W5D

(12.52 bar at 4° ATDC). These results demonstrate a positive correlation between butanol concentration and combustion intensity at mid-load operation. The improved volatility and oxygen content of butanol promotes more complete premixed combustion, thereby elevating RoPR values. However, a higher butanol ratio (as in W5DBu15) may also prolong ignition delay, contributing to increased fuel accumulation and a sharper pressure rise upon ignition. Interestingly, W5D, which lacks butanol, showed the lowest RoPR, confirming the dampening effect of water addition due to its high latent heat and inert thermal behaviour [21]. These findings underscore the dual role of butanol in enhancing pressure development while influencing combustion timing, highlighting the importance of optimizing blend ratios to maintain engine stability and performance.

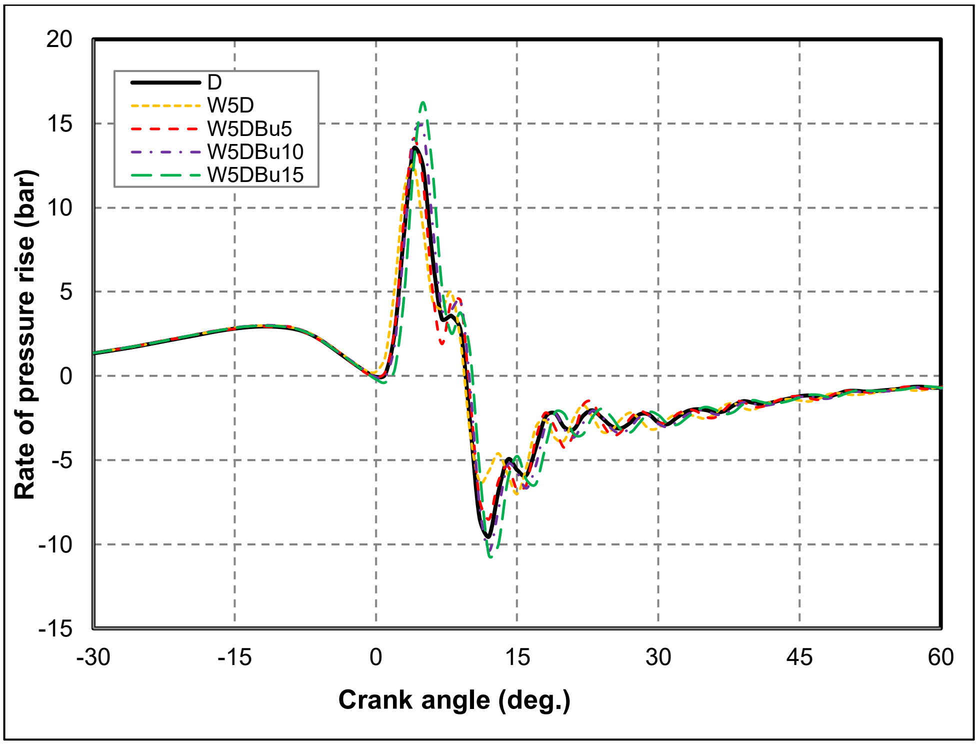

Figure 3: Rate of pressure rise for various blends of fuel operated at 35% load and speed of 3,000 rpm

Figure 4 illustrates the pressure rise (RoPR) rate for various fuel blends at a fixed engine speed of 3,000 rpm and a 50% load condition. The results indicate that increasing the proportion of butanol in diesel–water mixtures have a notable impact on peak RoPR values. Among all tested fuels, W5DBu15 exhibited the highest peak RoPR, reaching 14.84 bar at 2.5° ATDC, followed sequentially by W5DBu10 (13.53 bar at 3° ATDC), W5DBu5 (13.40 bar at 3° ATDC), Diesel (13.23 bar at 2° ATDC), and W5D (12.34 bar at 2° ATDC). These findings suggest that butanol-containing blends enhance the premixed combustion phase, resulting in a steeper pressure rise due to increased oxygen content and better vaporization characteristics. Notably, the RoPR values at 50% load are generally higher than those observed at lower loads, likely due to the increased fuel quantity injected per cycle. The higher butanol content in W5DBu15 extends the ignition delay, allowing more fuel to accumulate in the combustion chamber before ignition. This stored fuel undergoes rapid combustion upon ignition, producing a sharper pressure gradient and explaining the higher RoPR observed [22]. Despite the benefits in combustion intensity, elevated RoPR may raise concerns regarding combustion harshness and potential engine wear. Therefore, while W5DBu15 demonstrates superior combustion vigour, it must be considered considering engine durability and operational limits. The results reinforce the need to carefully balance fuel reactivity and ignition delay in designing optimal butanol–diesel–water blends for high-load engine operation.

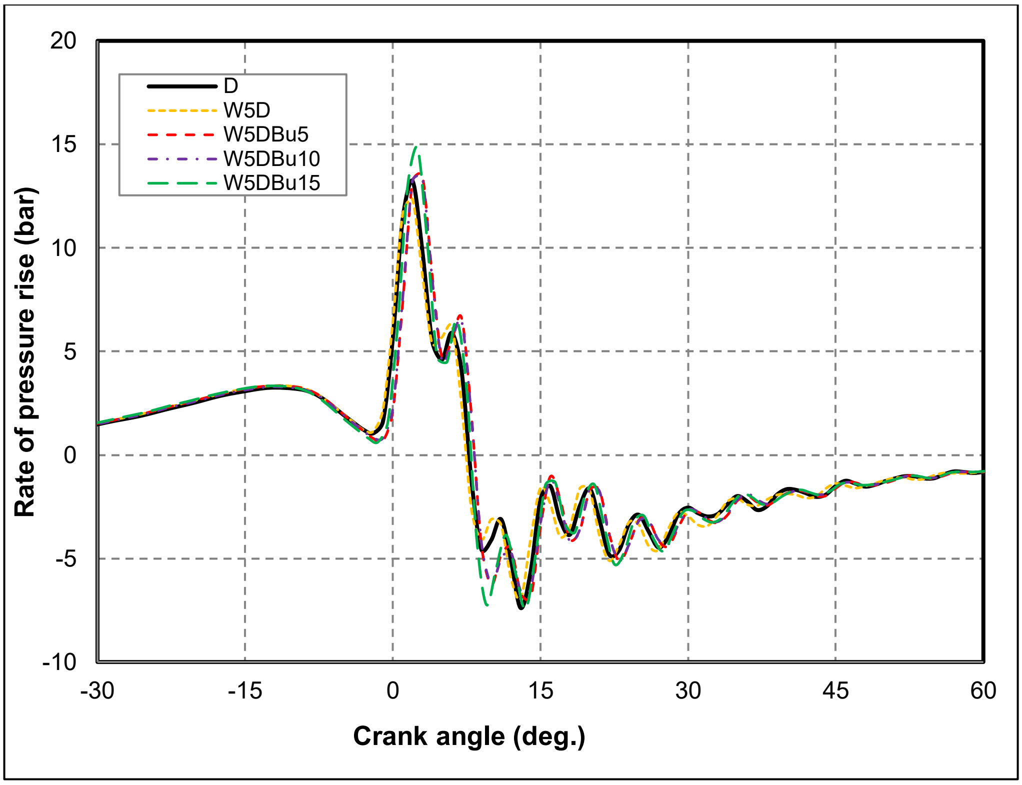

Figure 4: Rate of pressure rise for various blends of fuel operated at 50% load and speed of 3,000 rpm

Analysis of mass fraction burn

The mass fraction burned (MFB) is a critical parameter for characterizing the combustion process in internal combustion engines, as it reflects the cumulative energy release throughout the crank angle cycle. The combustion duration is typically evaluated between 1% and 99% of MFB, accounting for the ignition delay interval, which generally ranges from 1.5% to 5% of the total cycle duration [23]. However, this study adopted a narrower range of 3% to 97% to avoid inaccuracies at the endpoints caused by signal fluctuations and measurement sensitivity. Overall, the MFB profiles for all tested fuels demonstrated broadly similar trends, indicating comparable combustion efficiency. However, slight variations were observed in ignition timing and burn rates, particularly for blends with higher butanol content.

Figure 5 illustrates the mass fraction burned (MFB) profiles as a function of crank angle degree for various diesel–butanol–water blends, evaluated at 20% engine load and 3,000 rpm. The MFB curve characterizes the cumulative progress of combustion, from ignition onset to the complete energy release phase. The data are normalized on a percentage scale (0–100%) to enable direct comparison among all tested fuels. All fuel blends followed a similar MFB trend, exhibiting rapid combustion between 5° and 20° crank angles after the top dead centre (ATDC). However, minor deviations are observed in the combustion phasing and burn duration, particularly among the butanol-containing blends. The ignition is initiated approximately 4° before TDC, with the most rapid heat release occurring shortly after TDC. W5DBu15 exhibited a slightly delayed combustion completion compared to other fuels, suggesting a prolonged burn duration. This delay is primarily attributed to the higher latent heat of vaporization and lower cetane number associated with butanol, which increases ignition delay and reduces early combustion reactivity. Conversely, W5D and Diesel achieved earlier combustion completion, indicating more compact and timely energy release. The observed variations in MFB phasing highlight the influence of fuel oxygenation and volatility on combustion dynamics. While butanol enhances oxygen availability, its thermal properties introduce longer ignition delays at low-load conditions, which must be carefully considered for optimal combustion control.

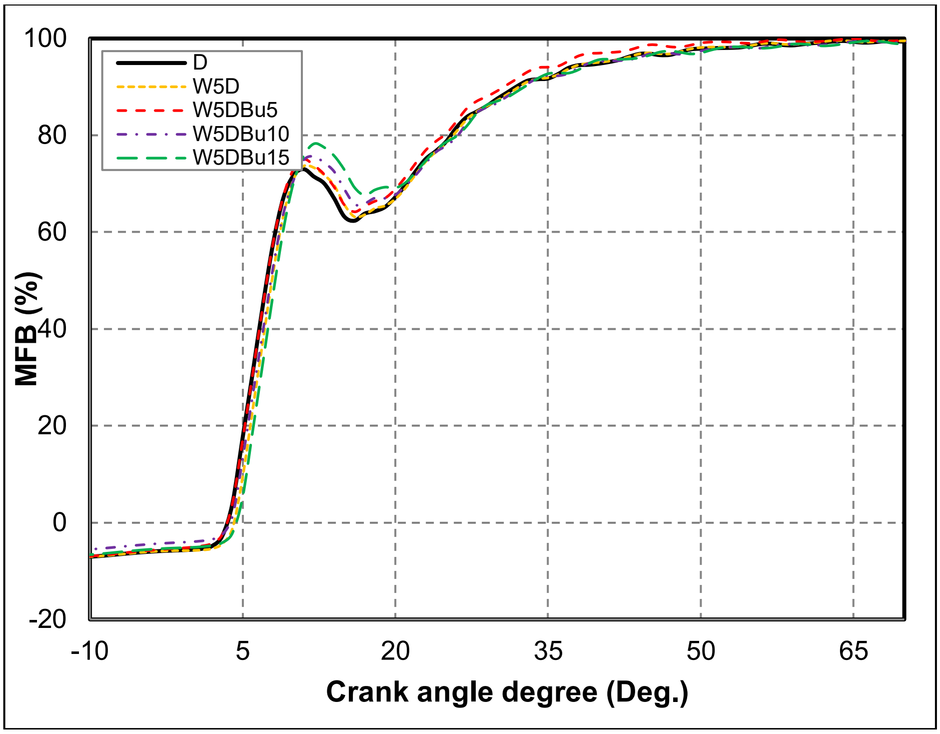

Figure 5: Mass fractions burn for various blended fuels operated at 20% load and speed of 3,000 rpm

Figure 6 presents the mass fraction burned (MFB) profiles for different diesel–butanol–water blends at 35% engine load and a constant speed of 3,000 rpm. The MFB curves reflect the rate and completeness of fuel combustion throughout the crank angle cycle. At this mid-load condition, a clear distinction is observed among the fuel blends, with W5DBu15 exhibiting the highest MFB progression across the entire crank angle range, followed by W5DBu10, W5DBu5, Diesel, and W5D. The more rapid and extensive combustion behaviour of W5DBu15 suggests that it enables more incredible in-cylinder energy conversion, consistent with previous findings regarding its higher thermal efficiency. The increased oxygen content and improved premixing associated with butanol contribute to a more complete and efficient combustion process. In contrast, W5D showed the slowest MFB evolution, indicating delayed combustion phasing and lower combustion efficiency.

Although the differences in MFB trends become less pronounced at higher crank angles, the ordering of fuel blends in terms of combustion completeness remains consistent, with butanol-containing fuels outperforming both pure diesel and water-diesel blends. These findings further affirm that the inclusion of butanol, particularly at higher concentrations, positively influences combustion characteristics under moderate engine loading.

Figure 7 presents the mass fraction burned (MFB) curves as a function of crank angle degree for five different fuel blends at a 50% engine load and a constant speed of 3,000 rpm. The MFB profiles represent the cumulative combustion progress, normalized on a 0–100% scale, and help analyze ignition timing, burn duration, and overall combustion completeness. Across all tested fuels, Diesel, W5D, W5DBu5, W5DBu10, and W5DBu15, the MFB curves show a nearly identical trend, indicating similar combustion behaviour under high load conditions. Combustion initiation occurs approximately at 11° before the top dead center (BTDC), with ignition delays measured at 12.5° CA for Diesel and W5DBu10, 12° CA for W5DBu5 and W5DBu15, and 11.5° CA for W5D. These slight variations reflect the combined effects of fuel properties on ignition delay and flame development, particularly cetane number and latent heat of vaporization.

Despite these initial differences, all fuel blends eventually converge toward similar MFB values beyond the 80° crank angle, suggesting complete combustion is achieved for all cases. The minimal divergence among blends at 50% load implies that higher fuel mass and cylinder pressure at this operating point promote more consistent combustion across different fuel compositions [24]. This observation confirms that the influence of butanol and water content on combustion characteristics becomes less significant under high-load conditions, likely due to enhanced turbulence and improved in-cylinder mixing.

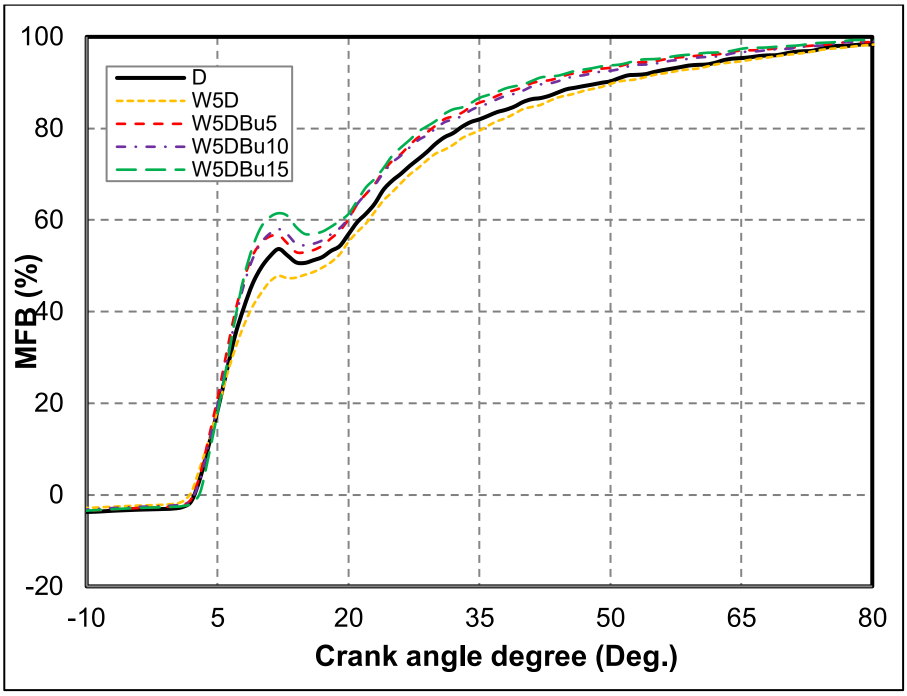

Figure 6: Mass fractions burn for various blends of fuel operated at 35% load and speed of 3,000 rpm

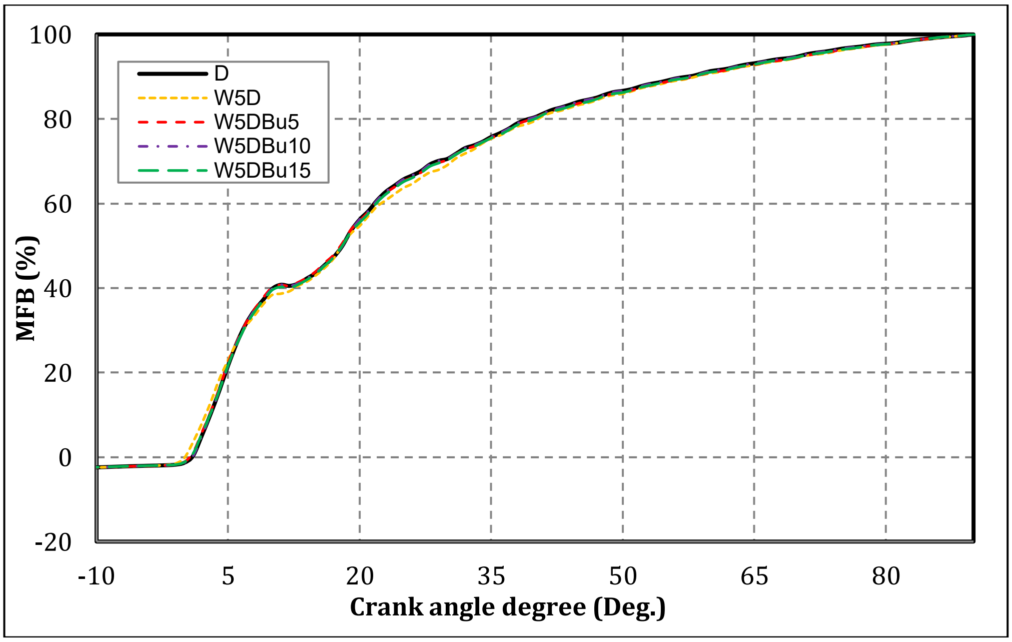

Figure 7: Mass fractions burn for various blends of fuel operated at 50% load and speed of 3,000 rpm

The comparative analysis of the diesel–butanol–water blends across varying engine loads and speeds revealed clear trends in combustion behaviour, particularly regarding the rate of pressure rise (RoPR), heat release, and mass fraction burned (MFB). W5DBu15 consistently demonstrated the most aggressive combustion profile among the tested blends, with the highest RoPR values observed across all load conditions. At 20% load, W5DBu10 exhibited the highest RoPR (11.9 bar at 6° ATDC), while at 35% and 50% load, W5DBu15 reached 16.25 bar and 14.84 bar, respectively. These results highlight the role of butanol concentration in enhancing the premixed combustion phase due to improved oxygen availability and volatility. Heat release analysis further corroborated the RoPR findings. Blends with higher butanol content—particularly W5DBu10 and W5DBu15—showed elevated peaks in heat release rate, indicating more intense energy liberation near TDC. This aligns with the higher thermal efficiency reported in similar oxygenated fuel studies. However, while increased RoPR and heat release are desirable for power output, they also raise concerns regarding combustion harshness and mechanical stress, especially at higher loads. Therefore, optimizing blend composition is critical for balancing performance and durability.

The MFB profiles provided insight into each blend's ignition timing and burn duration. At 20% load, butanol-rich blends like W5DBu15 displayed delayed combustion completion compared to diesel, attributed to extended ignition delay and the higher latent heat of butanol. At 35% load, W5DBu15 demonstrated the fastest combustion completion, supporting the claim of higher energy conversion efficiency. At 50% load, all blends exhibited nearly identical MFB trends, suggesting that higher load conditions help homogenize combustion behaviour due to more significant in-cylinder pressure and turbulence. In summary, incorporating butanol into diesel–water blends positively affects combustion characteristics by enhancing peak pressure development and promoting complete combustion, particularly under low to medium load conditions. However, the effects diminish at higher loads where combustion uniformity improves regardless of fuel type. Among the tested blends, W5DBu10 offers the best compromise between ignition stability and combustion intensity at low loads, while W5DBu15 performs best under moderate loads. These findings provide valuable guidance for selecting and optimising biofuel blends in compression-ignition engines.

4. Conclusion

This study evaluated the effects of diesel–butanol–water blends on the combustion behaviour and in-cylinder pressure characteristics in a single-cylinder diesel engine operating at 3,000 rpm under various load conditions. The results revealed that fuel blends containing butanol significantly influence the rate of pressure rise (RoPR) and mass fraction burned (MFB). At 20% load, the W5DBu10 blend produced the highest peak pressure rise of 11.9 bar at 6° ATDC, approximately 21% higher than pure diesel (9.8 bar). For 35% load, W5DBu15 recorded the highest RoPR of 16.25 bar at 5° ATDC, while diesel showed 13.48 bar. Similarly, at 50% load, W5DBu15 again led with 14.84 bar at 2.5° ATDC, outperforming diesel at 13.23 bar. These increases are attributed to the higher oxygen content and improved volatility of butanol, which enhanced premixed combustion. MFB analysis showed that higher butanol content, particularly in W5DBu15, delayed the completion of combustion but improved thermal efficiency at medium and high loads. Ignition delay was also observed to increase with butanol concentration, with delays of 12.5° CA for Diesel and W5DBu10, 12° CA for W5DBu5 and W5DBu15, and 11.5° CA for W5D. In conclusion, diesel–butanol–water blends, especially W5DBu15, can enhance combustion characteristics and pressure development, but optimal blending is crucial to balance performance and ignition behaviour.

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