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Cylinder Pressure and Heat Release Analysis of Diesel-Butanol Blends at High Engine Load

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Abstract
This study evaluates the combustion characteristics of diesel-butanol-water blends in a diesel engine operating at 3,000 rpm under 20%, 35%, and 50% load conditions. The tested emulsions W5DBu5, W5DBu10, and W5DBu15 contain increasing butanol concentrations. At 35% load, W5DBu15 recorded the highest peak cylinder pressure of 82.5 bar, a 7.4% increase over base diesel (76.8 bar), indicating enhanced combustion due to better air-fuel mixing. At 50% load, all blends reached peak in-cylinder gas temperatures of approximately 1,860°C, with W5DBu15 being the highest, yet slightly lower than the base diesel (1,880°C), suggesting potential NOx mitigation from water cooling effects. Heat release rate analysis showed that W5DBu15 achieved the highest peak (2,150 kJ/s at ~8°CA ATDC), a 29.5% increase compared to diesel (1,660 kJ/s), attributed to the longer ignition delay resulting from butanol's lower cetane number. Despite these changes, combustion phasing remained consistent with diesel, confirming operational safety. Overall, W5DBu15 offers improved thermal efficiency and combustion performance without compromising engine integrity, making it a promising alternative fuel under medium to high load conditions.

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1. Introduction

The global push towards cleaner and more sustainable energy sources has intensified the search for alternative fuels that reduce reliance on fossil fuels, such as diesel. Among various biofuels, butanol has emerged as a promising candidate due to its higher energy content, better miscibility with diesel, and lower volatility than ethanol. Blending butanol with diesel can improve combustion characteristics and reduce emissions, especially when emulsified with water, to form a micro-explosive mixture that enhances atomization during combustion. Previous studies have shown that butanol-diesel blends can increase peak cylinder pressure and improve combustion efficiency [1–4]. These studies also highlight the role of water emulsion in enabling micro-explosion phenomena, which enhances fuel atomization and leads to better mixing of air and fuel. However, excessive water content can negatively impact ignition and lead to combustion instability. Therefore, an optimal balance of water and butanol in diesel blends is necessary to achieve performance benefits without engine damage.

Further research has emphasised the thermal and emission characteristics of biofuel blends [5–8]. They found that oxygenated fuels, such as butanol, improve the premixed combustion phase due to better evaporation and increased oxygen availability, resulting in a more efficient combustion process. However, the effect of these blends at various engine loads and high speeds has not been comprehensively examined, particularly in terms of heat release and in-cylinder pressure dynamics. In-cylinder pressure and heat release rate are critical indicators of combustion efficiency and engine performance. Variations in these parameters are influenced by fuel properties, load conditions, injection timing, and combustion chamber geometry [9–12]. Yet, limited data exist for high-speed (3,000 rpm) diesel engine operations using butanol-water-diesel emulsions under varying load conditions.

The combustion process in diesel engines involves both premixed and diffusion phases, where the heat release rate is primarily governed by the ignition delay and the rate of fuel-air mixing [13–16]. Recent advancements in fuel formulation have aimed to enhance the premixed phase, improving combustion stability and reducing harmful emissions, such as NOx. However, most existing studies focus on single-speed or low-load scenarios, which do not represent practical engine operating conditions in many industrial or transportation sectors. The novelty of this study lies in its detailed experimental investigation of diesel-butanol-water blends across three different engine load levels (20%, 35%, and 50%) at a high engine speed of 3,000 rpm. The study provides comprehensive data on in-cylinder pressure profiles, gas temperature fluctuations, and heat release characteristics. Notably, the W5DBu15 blend exhibited a peak cylinder pressure increase and a gas temperature of nearly 2,000°C at 50% load, with improved premixed combustion and heat release compared to the base diesel.

This research aims to quantitatively assess how diesel-butanol-water blends influence key combustion parameters, namely cylinder pressure, in-cylinder temperature, and heat release rate, under high engine speed (3,000 rpm) and variable load conditions. The study hypothesises that increasing butanol concentration, particularly in the W5DBu15 blend, will enhance premixed combustion and thermal efficiency without compromising engine stability. By providing experimental data across a range of loads, this work contributes to the advancement of clean biofuel applications, demonstrating that W5DBu15 is a feasible and efficient alternative to conventional diesel with added benefits in combustion performance and potential emission reduction.

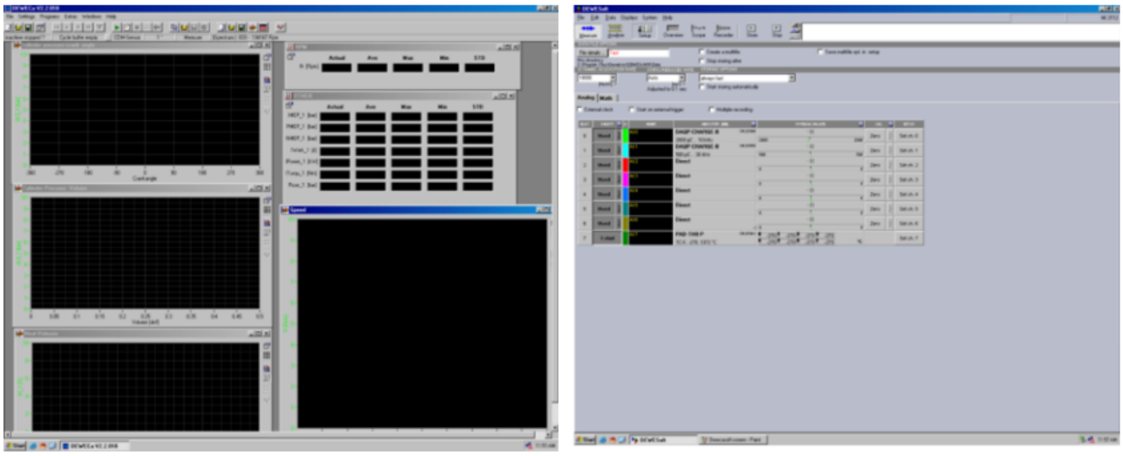
2. Methodology

As illustrated in **Figure 1**, an in-cylinder pressure transducer was attached to the combustion chamber and combined with a crank angle decoder to provide the combustion timing in terms of crank angle degrees (CAD). During the combustion process, a crank angle encoder is employed to indicate the location of the crankshaft, and comparisons are then made to the various cylinder pressures. At the side of the engine, in alignment with the pulley of the crankshaft, a Kistler CAM crank angle encoder type 2613B1 has been fitted. It was linked to the signal conditioner type 2613B2 via a 1.5-metre-long cable, allowing the analogue signal from the encoder to be converted into digital crank angle pulses. The characteristics of the pressure sensor are shown in **Table 1**. Appendix D1 lists the technical specifications for the Kistler CAM crank angle encoder.

The conditioned in-cylinder pressure signals arrived simultaneously at a signal conditioning amplifier model DAQ-AIN, which was then transferred to a DEWETRON Orion 1624 data acquisition system DEWE-800 PC. These signals originated from the channel of the charge amplifier that corresponded to the signal from the shaft encoder that indicated the position of the engine crankshaft. DEWECa and DEWESoft are the application software programmes pre-installed on the ORION data acquisition card that DEWETRON supplies to its customers. The DEWECa programme is used to gather pressure data and analyse combustion properties. **Figure 2a** illustrates an example of the graphical user interface

(GUI) used by DEWECa. In this application, the input channels, crank angle degree, pressure transducer characteristics, and engine parameters have been modified to conform to the requirements of a multi-cylinder diesel engine. The second program, DEWESoft software, acquires the engine's temperature using 19 K-type thermocouple probes fastened in various locations. The graphical user interface for DEWEsoft is shown in **Figure 2b** (GUI). The placement of the thermocouples is carefully deliberated before the tests are carried out to ensure their precision. These data were included in the combustion modelling and the real-time monitoring to stay within the parameters of the testing and engine limitations.

Figure 1: Kistler CAM crank angle encoder type 2613B1



(a) (b)

Figure 2: (a) DEWECa graphical user interface (GUI), (b) DEWEsoft graphical user interface (GUI).

The experimental setup involved a single-cylinder, direct-injection diesel engine operating at a constant speed of 3,000 rpm. The test fuel blends W5DBu5, W5DBu10, and W5DBu15 were prepared using a high-shear emulsification process to ensure uniform dispersion of butanol and water in diesel.

Instrumentation and Data Acquisition: A high-precision Kistler 6056A piezoelectric pressure sensor was installed in the cylinder head to record in-cylinder pressure, synchronised with a Kistler 2613B1 crank angle encoder (resolution: 0.1° CAD). The pressure signal was conditioned using a Kistler 5011B charge amplifier and digitised via a DEWETRON DEWE-800 data acquisition system, operating at 100 kHz sampling frequency to capture rapid pressure transients during combustion.

Calibration Procedures: Before testing, all pressure sensors were statically calibrated using a dead-weight calibration system to ensure linear response across the 0–200 bar range. Dynamic calibration was performed using a reference cylinder under known pressure conditions. The crank angle encoder was calibrated by aligning TDC with a dial indicator and verified through pressure rise analysis during motoring. Thermocouples (Type K) used for temperature measurements were calibrated against a dry-block calibrator (with a ±0.5°C accuracy) up to 1,200°C.

Uncertainty Analysis: Uncertainty estimates were computed using the root-sum-square method for multi-instrument measurements. The combined uncertainty in cylinder pressure was estimated to be ±0.8 bar (±1.0%), and for temperature measurements, it was ±15°C (±1.2%). The calculated uncertainty for derived parameters, such as heat release rate and in-cylinder temperature, was ±3.5%, accounting for pressure sensor nonlinearity, crank angle synchronisation, and heat capacity approximations. To minimise experimental variation, each fuel test was repeated three times, and the average values were reported. The standard deviation of peak pressure and temperature measurements across trials remained within ±2%, confirming the repeatability and reliability of the data.

3. Result & Discussion

Figure 3 presents the in-cylinder pressure profiles of various diesel-butanol-water blends (W5DBu5, W5DBu10, W5DBu15) compared to base diesel (D) and water-diesel (W5D) under a 35% engine load at a constant speed of 3,000 rpm. The data clearly show that increasing the proportion of butanol in the blend leads to a rise in peak cylinder pressure. The W5DBu15 blend recorded the highest peak pressure at approximately 82.5 bar, followed by W5DBu10 at around 80.2 bar and W5DBu5 at approximately 78.5 bar. In contrast, the peak pressure for base diesel (D) was about 76.8 bar. This incremental rise in peak pressure with higher butanol content is attributed to the improved combustion characteristics associated with butanol's higher oxygen content and superior volatility. These properties promote more efficient atomization and air-fuel mixing, particularly during the premixed combustion phase, leading to a more rapid and complete combustion process.
Additionally, the observed delay in ignition due to butanol's lower cetane number allows a more significant premixed charge to accumulate before ignition, resulting in a sharper and more intense pressure rise. Despite these changes, the general shape and position of the pressure curves remain consistent across all fuel blends, indicating stable combustion phasing. These findings suggest that using diesel-butanol-water emulsions, W5DBu15, can significantly enhance thermal efficiency and in-cylinder combustion pressure without compromising engine stability under medium-load and high-speed operating conditions.

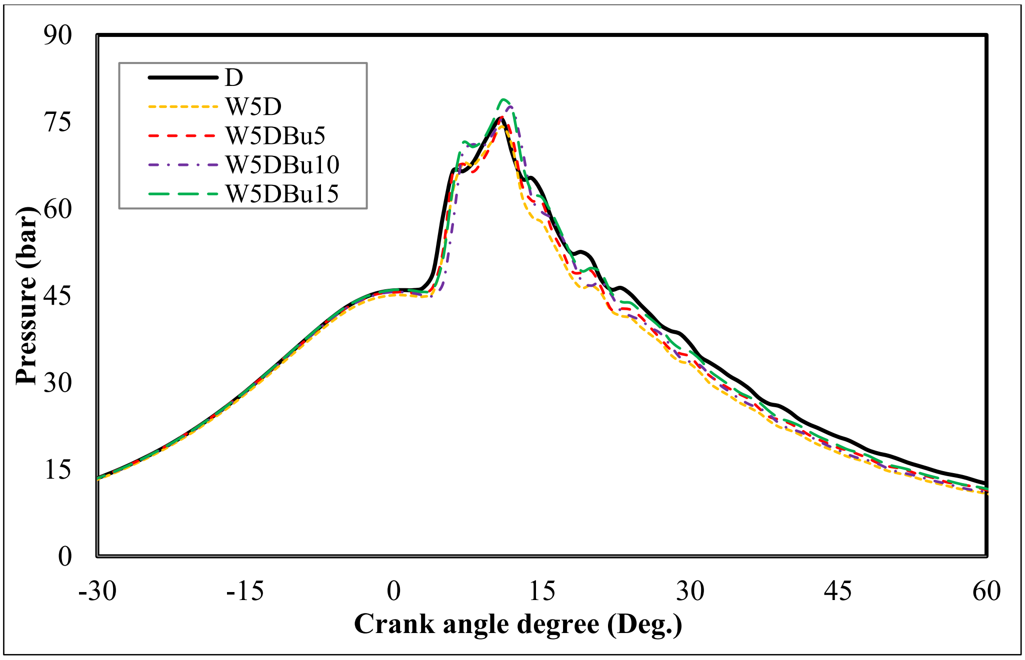


Figure 3: In-cylinder pressures for various blends of fuel operated at 35% load and speed of 3,000 rpm

The analysis of in-cylinder pressure data is crucial for gaining a comprehensive understanding of the combustion phenomena and the dynamic events that occur within the combustion chamber. In this study, pressure profiles were evaluated across various diesel-butanol-water fuel blends. Particular attention was given to the crank angle at which the peak pressure occurred, allowing for a comparative assessment with base diesel regarding the magnitude and timing of the pressure peak. Several parameters, such as engine load, volumetric efficiency, fuel properties, combustion chamber geometry, and heat transfer behaviour, affected in-cylinder pressure dynamics [17].

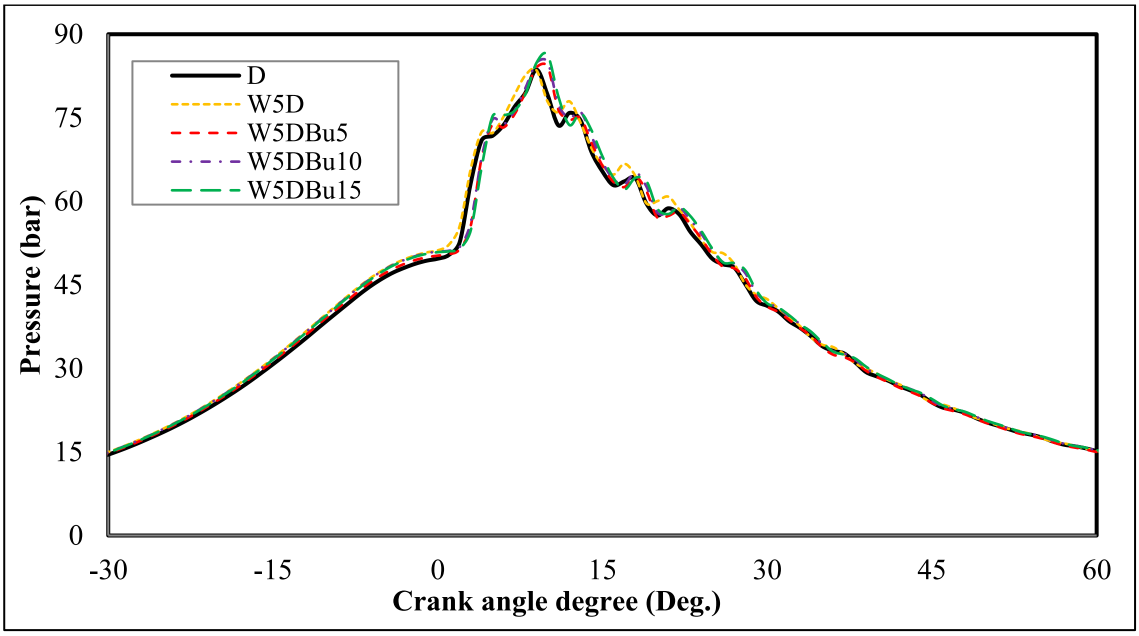


Figure 4: In-cylinder pressures for various blends of fuel operated at 50% load and speed of 3,000 rpm.

To describe the influence of butanol in diesel emulsion fuel blends, the characteristics of the additive, as indicated by the in-cylinder pressure versus crank angle during combustion [18–20]. **Figure 4** shows the trend of combustion for the parameters tested at 50% load and a speed of 3,000 rpm. It shows that the fuels were injected into the combustion chamber after TDC at all load tests. The peak pressure for all the fuel blends resembled the shape of the base diesel graph, and the peak pressures were higher than those of the base diesel. This lower pressure ratio exerted on the piston can benefit the engine as it does not harm it and adds value to its durability and performance. It cannot be denied that the properties of the fuel blends also played a role in such situations. These differences also reflect the reason for the poor atomisation of fuel during the combustion phenomena [21–23]. Despite all the disadvantages, specific properties tend to give an advantage, such as a low flash point temperature value for the dispersed phase rather than the continuous phase, which can lead to the dispersed phase causing a destructive explosion due to rapid nucleation during atomization.

The dispersed droplets break off from the parent droplet. This phenomenon is called a microexplosion and causes the temperature to rise distinctly up to a certain peak, which also contributes to the rise of pressure in the combustion chamber. The cetane number for W5DBU15 is slightly lower compared to base diesel, which has caused a delay in ignition duration and degraded engine combustion efficiency [24]. The trends are evident in the case of the engine operating at 3,000 rpm for 50% of the loads, as shown in Figure 4, which represents a similar shape to that of the base diesel for all blended fuels. The peak pressure for all blended fuels, except for W5DBu15, indicates that the engine operated within the performance of base diesel and was safe. However, the crank angle degrees for these cases are shifted after TDC. The different results for W5DBU15 do not significantly harm the engine, as there is only a slight difference in value. The same explanation also suitably describes what happened to fuel blends at high speed. With these findings, it can be said that using butanol in blended fuels to operate the diesel engine from lower to high speeds at various loads does not harm the engine, despite providing better performance compared to base diesel.

Analysis of in-cylinder temperature

The average in-cylinder gas temperature is a key indicator of diesel engine combustion behaviour and thermal efficiency. It can be derived from in-cylinder pressure data using the ideal gas law and reference conditions such as the intake valve closure. Both temperature and pressure evolve concurrently during the combustion process. Fuel composition significantly affects them, especially the oxygen content and latent heat of vaporisation in oxygenated fuels, such as butanol. **Figure 5** presents the in-cylinder gas temperature profiles for diesel and diesel-butanol-water emulsions (W5D, W5DBu5, W5DBu10, W5DBu15) under a 35% engine load at 3,000 rpm. The results indicate that all butanol-containing blends produce higher peak temperatures than base diesel (D). The W5DBu15 blend achieves the highest peak temperature of approximately 1,325°C, followed by W5DBu10 at 1,290°C, W5DBu5 at 1,270°C, and W5D at 1,260°C, while base diesel reaches a peak of only 1,250°C.

The elevated temperatures observed in the butanol blends are attributed to improved air-fuel mixing and enhanced premixed combustion characteristics. The oxygen molecules present in butanol facilitate more complete combustion, resulting in a higher energy release over a shorter duration. This is particularly evident near the crank angle of 13° ATDC, where W5DBu15 reaches its temperature peak, noticeably ahead of other blends. Post-combustion, the gas temperatures gradually decline. However, W5DBu15 consistently maintains a higher temperature curve throughout the expansion stroke, remaining above 1,050°C up to around 50° ATDC, whereas diesel drops below that threshold at around 35° ATDC. This sustained thermal energy indicates more complete fuel utilisation and slower heat losses, which may lead to improved overall thermal efficiency.

Furthermore, water in the emulsified blends induces micro-explosion effects, where secondary droplet breakup enhances atomization and flame propagation. This contributes to more homogeneous combustion and reduced formation of particulate matter. Despite the higher peak temperatures, the water content also moderates NOx formation by temporarily absorbing heat during vaporisation, potentially offsetting the thermal NOx increase typically associated with high combustion temperatures.

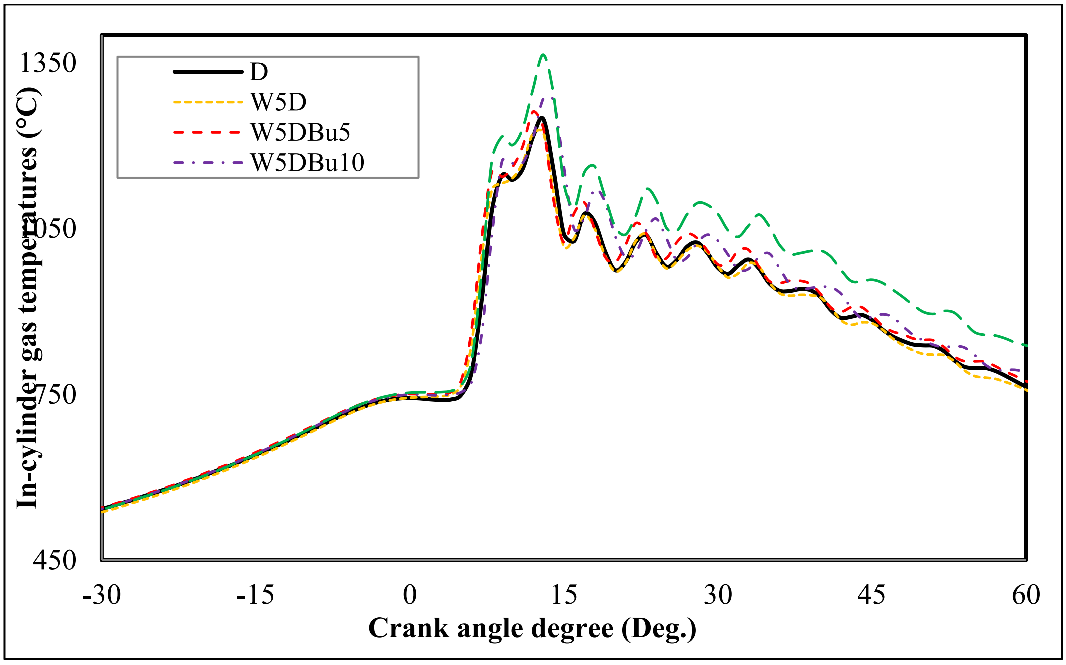


Figure 5: In-cylinder temperature for various blends of fuel operated at 20% load and speed of 3,000 rpm

Figure 6 depicts the in-cylinder gas temperature profiles for various diesel-butanol-water blends (W5D, W5DBu5, W5DBu10, W5DBu15) in comparison to pure diesel (D) under a high engine load condition of 50% at a speed of 3,000 rpm. Before the top dead centre (TDC), i.e., at crank angles less than 10°, all fuel blends, including diesel, exhibit similar combustion behaviour, with temperatures rising gradually to approximately 820°C, indicating consistent compression heating during the pre-combustion phase. Following TDC, combustion occurs rapidly, and all fuel blends experience a sharp temperature rise. The W5DBu15 blend reaches a peak in-cylinder temperature of approximately 1,625°C, the highest among all tested fuels. This is followed by W5DBu10 at around 1,590°C, W5DBu5 at 1,570°C, and W5D at 1,550°C. Interestingly, base diesel (D) produces a peak temperature of about 1,610°C, slightly lower than W5DBu15 but higher than the other blends.

Despite W5DBu15 showing the highest peak, the combustion temperatures of all butanol-based blends remain slightly lower than those of diesel during the expansion stroke, particularly after 20° ATDC. For instance, at 30° ATDC, diesel maintains a temperature of around 1,500°C, whereas W5DBu15 drops to 1,450°C, and W5DBu5 falls below 1,400°C. This indicates that although peak temperatures are high due to enhanced premixed combustion, the post-combustion gas temperatures are effectively moderated, primarily due to the water content in the emulsion blend. Water in these emulsified fuels facilitates micro-explosion phenomena during atomization, promoting rapid droplet disintegration and improved air-fuel mixing. Concurrently, the latent heat of vaporisation of water absorbs part of the thermal energy released during combustion, thereby reducing sustained high temperatures. This contributes to better fuel utilisation and potential NOx reduction, as NOx formation is highly temperature-sensitive and typically accelerates above 1,600°C.

These findings suggest that the W5DBu15 blend achieves a beneficial balance between peak combustion temperature for efficient burning and lower residual heat levels that may suppress NOx emissions. Therefore, diesel-butanol-water blends demonstrate promising thermal performance under high-load conditions, while offering the additional benefit of partial emission mitigation.

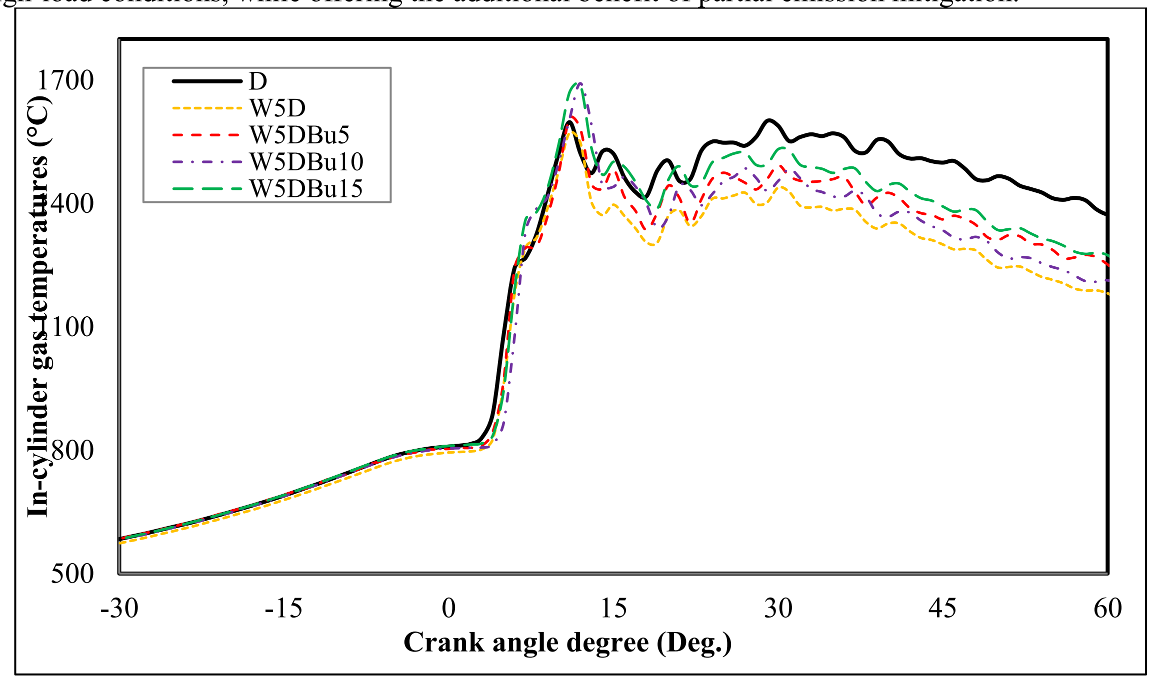


Figure 6: In-cylinder temperature for various blends of fuel operated at 35% load and speed of 3,000 rpm

Figure 7 presents the in-cylinder gas temperature profiles for various diesel-butanol-water blends (W5D, W5DBu5, W5DBu10, W5DBu15) and base diesel (D), operated under high load conditions (50%) at an engine speed of 3,000 rpm. The results exhibit a steep rise in gas temperature shortly after the top dead centre (TDC), corresponding to the ignition and combustion phases of the engine cycle. All fuel blends demonstrate a comparable combustion pattern during the pre-ignition phase (crank angles < 10°), with in-cylinder temperatures gradually increasing to approximately 820–840°C just before ignition. After ignition, the gas temperatures rise sharply, with the W5DBu15 blend achieving the highest peak temperature of roughly 1,860°C, followed closely by W5DBu10 at 1,830°C, W5DBu5 at 1,810°C, and W5D at 1,790°C. Base diesel records a slightly lower peak at around 1,780°C.

Figure

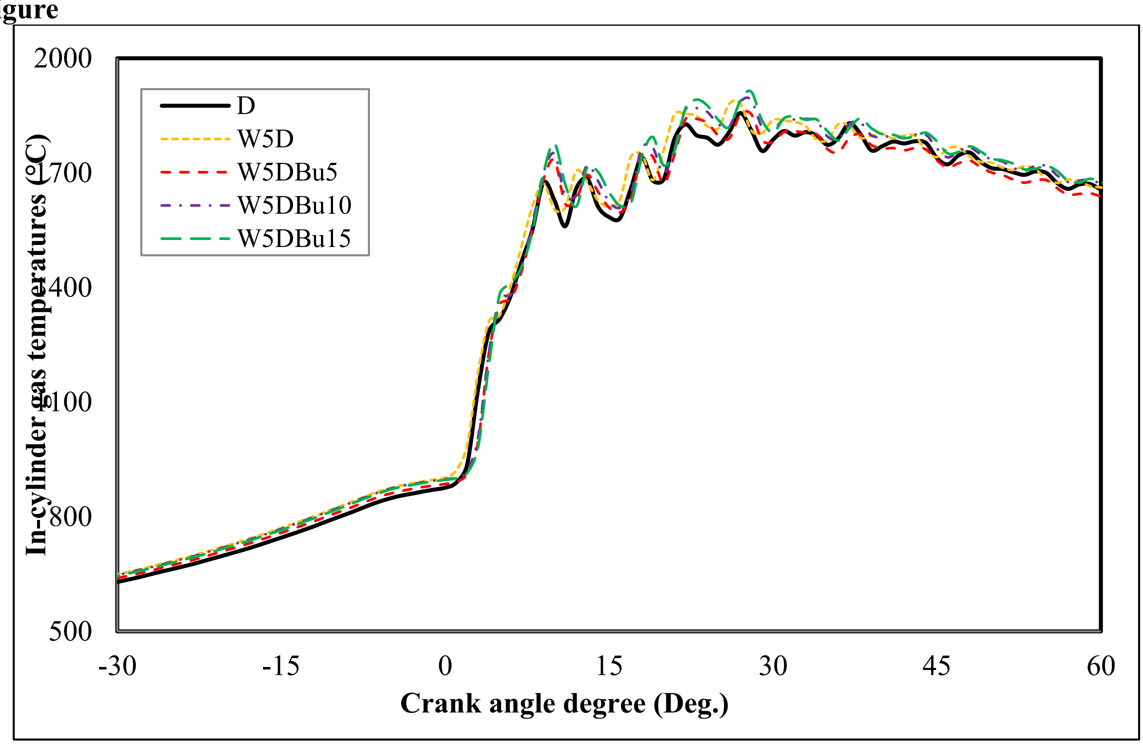


Figure 7: In-cylinder temperature for various blends of fuel operated at 50% load and speed of 3,000 rpm

These findings indicate that butanol-enriched blends, particularly W5DBu15, promote more intense combustion due to their higher oxygen content and enhanced premixing capabilities, resulting in a more complete and faster burning of the fuel-air mixture. The elevated temperatures are indicative of this improved combustion efficiency. Despite the high peak temperatures, all butanol blends maintain thermal profiles closely aligned with diesel during the expansion phase (after ~20° ATDC), ranging between 1,700°C and 1,750°C. This consistency suggests that while butanol enhances the peak combustion intensity, the process stabilises rapidly thereafter.

As more fuel is fully oxidised, the sharper heat release and higher combustion temperatures may reduce unburned hydrocarbon (HC) and carbon monoxide (CO) emissions. However, it is also important to note that higher in-cylinder temperatures may elevate NOx formation. Nonetheless, water in the emulsion can help mitigate this by absorbing heat through vaporisation, thereby reducing the average combustion temperature and limiting the formation of thermal NOx. In summary, diesel-butanol-water blends under high-load conditions demonstrate superior combustion behaviour, with W5DBu15 achieving the most pronounced thermal response, highlighting its potential for enhanced power output and combustion efficiency without compromising thermal stability during the expansion stroke.

Analysis of heat release rate

The heat release rate (HRR) represents the amount of thermal energy liberated during combustion. It is derived from in-cylinder pressure data by applying the first law of thermodynamics. This parameter is critical for characterising combustion behaviour, as it reflects the rate at which energy is transferred to the working fluid to produce the observed pressure rise within the cylinder. By analysing HRR profiles, the combustion performance of various fuel types in diesel engines can be comprehensively evaluated, including ignition delay, combustion intensity, and phase transitions [21,25]. In modern direct-injection diesel engines, the combustion process typically occurs in two distinct stages: premixed combustion and diffusion (or mixing-controlled) combustion. The premixed phase begins immediately after fuel injection and during the ignition delay period, where injected fuel mixes with high-pressure air, forming a locally fuel-rich mixture. Once ignition occurs, this pre-mixed charge burns rapidly, releasing a substantial amount of heat in a short duration and contributing to the initial sharp rise in pressure and temperature.

Following the premixed phase, the process transitions into the diffusion phase, where the remaining fuel burns more gradually as it mixes with available oxygen. The fuel-air mixing rate governs this phase and is typically associated with sustained heat release at a lower intensity. In conditions where oxygen availability becomes limited, incomplete combustion may occur, leading to higher emissions, particularly of unburned hydrocarbons and carbon monoxide. Furthermore, the extended residence time at elevated temperatures during this phase can contribute significantly to thermal NOx formation, especially under high-load conditions. Understanding the dynamics between these combustion phases is crucial for optimising fuel formulations, such as diesel-butanol-water blends, that aim to enhance combustion efficiency while reducing emissions.

Figure 8 illustrates the rate of heat release (ROHR) as a function of crank angle for base diesel (D), water-diesel (W5D), and diesel-butanol-water blends (W5DBu5, W5DBu10, W5DBu15) operated at 20% engine load and a constant speed of 3,000 rpm. This parameter reflects the rate at which chemical energy is converted into thermal energy during the combustion process, thereby directly indicating ignition delay, combustion phasing, and energy conversion efficiency. Before top dead centre (TDC), all fuel blends exhibit similar low heat release rates, approximately 80–100 kJ/s, indicating negligible pre-ignition activity. The primary combustion event occurs shortly after TDC, with a sharp increase in heat release rate observed across all fuel types. Among the blends, W5DBu15 produces the highest peak heat release rate of approximately 1,700 kJ/s at around 8° crank angle after TDC (CA ATDC), followed by W5DBu10 and W5DBu5, which peak at 1,580 kJ/s and 1,530 kJ/s, respectively. In comparison, base diesel (D) reaches a slightly lower peak of approximately 1,490 kJ/s, while W5D records a peak of about 1,510 kJ/s.

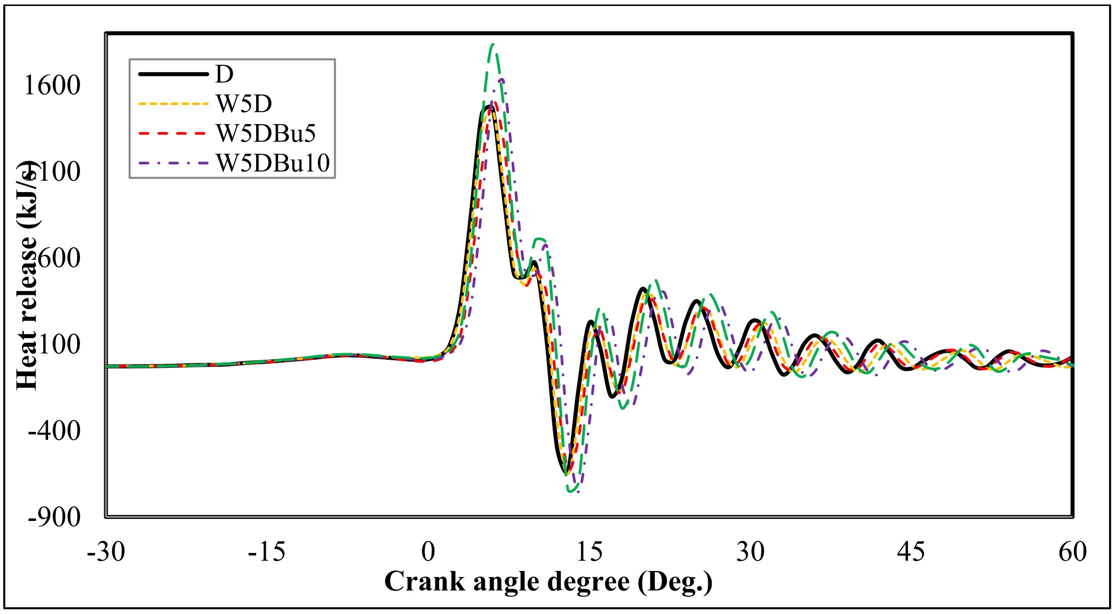


Figure 8: Rate of heat release for various blends of fuel operated at 20% load and speed of 3,000 rpm

This trend suggests that higher butanol content leads to more pronounced premixed combustion, likely due to improved fuel-air mixing and a longer ignition delay caused by butanol's lower cetane number. The oxygenated nature of butanol further enhances combustion intensity, as it promotes faster oxidation during the premixed phase. These effects result in a sharper and more concentrated energy release than base diesel. Following the peak, all blends experience a negative heat release dip reaching nearly 800 kJ/s, particularly between 12° and 18° CA ATDC, due to heat absorption associated with the vaporisation of water content and the transition to the mixing-controlled diffusion phase. Notably, the W5DBu15 blend shows slightly more pronounced oscillations in the post-combustion phase, possibly due to its more volatile combustion dynamics at low loads. Despite these fluctuations, the ROHR curves stabilise around 30°–60° CA, with all blends converging to nearly zero values, indicating the end of significant combustion activity. These findings confirm that including butanol and water leads to enhanced premixed combustion and higher initial heat release rates without altering the overall combustion duration. In summary, W5DBu15 exhibits superior premixed combustion characteristics under low-load conditions, as evidenced by the highest peak heat release rate. It demonstrates its potential to improve the thermal efficiency and energy conversion of diesel engines, particularly when early combustion energy is critical.

Figure 9 presents the rate of heat release (ROHR) profiles for diesel (D), water-diesel (W5D), and diesel-butanol-water blends (W5DBu5, W5DBu10, W5DBu15) at a medium engine load of 35% and constant speed of 3,000 rpm. The heat release rate is a critical indicator of combustion intensity, and its evolution with crank angle provides insight into ignition delay, premixed combustion characteristics, and energy conversion efficiency. Before combustion, all fuel blends demonstrate similar low heat release values, maintaining around 100 kJ/s before TDC. Shortly after TDC, a significant rise in heat release is observed across all blends, indicating the onset of the premixed combustion phase. The W5DBu15 blend records the highest peak heat release rate of approximately 2,150 kJ/s at around 8° crank angle after TDC (CA ATDC). W5DBu10 follows this with a peak of 1,920 kJ/s, W5DBu5 at 1,780 kJ/s, and W5D at 1,700 kJ/s, while base diesel (D) reaches the lowest peak at 1,660 kJ/s.

This increase in premixed heat release is directly correlated with the rising butanol concentration in the blend. Butanol's lower cetane number extends the ignition delay, allowing more fuel to premix with air before combustion [26]. This leads to a sharper and more intense heat release once ignition occurs. Additionally, butanol's inherent oxygen content enhances the oxidation process, further contributing to the higher energy release rates observed during the premixed phase. Post-combustion, all fuel blends exhibit a negative heat release dip, notably between 10° and 18° CA ATDC, reaching minimum values of approximately –600 to –650 kJ/s. This dip is attributed to the absorption of energy during the vaporisation of water content and the transition from combustion to a diffusion-controlled phase. Oscillations in the ROHR curve diminish progressively beyond 30° CA, indicating the decay of combustion activity and stabilisation of the expansion process. Overall, the ROHR pattern for all blends remains comparable to that of diesel, affirming that the introduction of butanol and water does not significantly disrupt the combustion phasing. However, the higher peak values, particularly in W5DBu15, confirm that increased butanol content enhances the premixed combustion intensity and improves air-fuel mixing, resulting in better thermal performance.

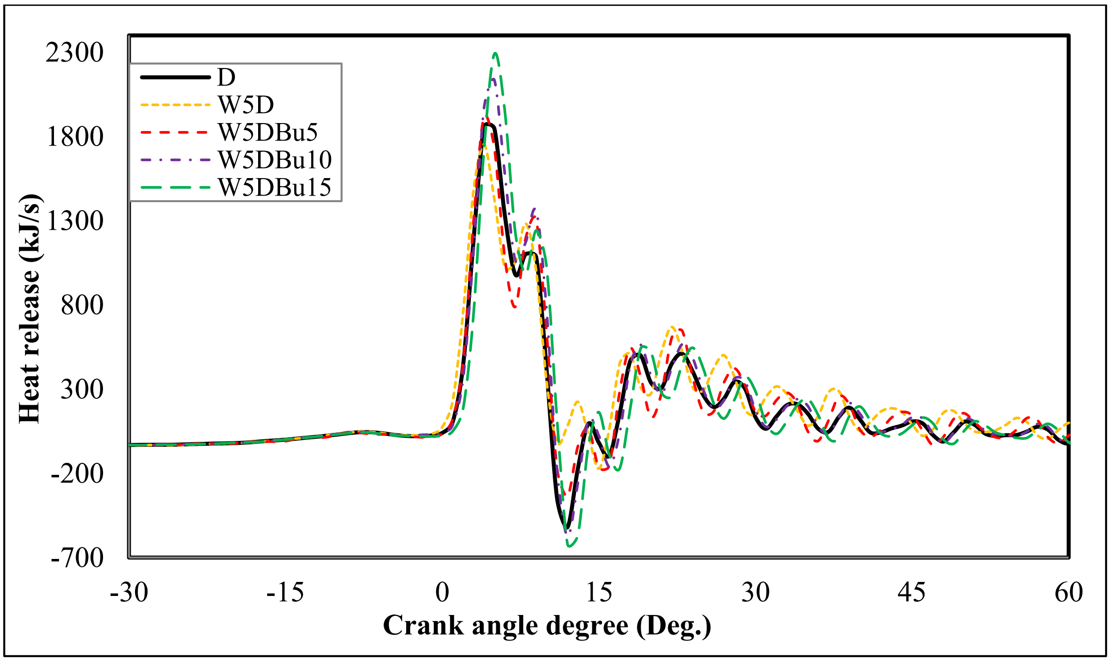


Figure 9: Rate of heat release for various blends of fuel operated at 35% load and speed of 3,000 rpm

The results of this study demonstrate that the incorporation of butanol and water into diesel fuel significantly alters the combustion characteristics, particularly under varying engine loads at a constant high speed of 3,000 rpm. It was observed that increasing the proportion of butanol in the emulsified blend led to higher peak in-cylinder pressures and enhanced heat release rates during the premixed combustion phase. For instance, at 35% load, the W5DBu15 blend reached a peak cylinder pressure approximately 82.5 bar higher than that of W5DBu10 and base diesel, indicating improved combustion efficiency due to better fuel-air premixing and enhanced ignition properties. These findings align with the increasing trend in in-cylinder temperatures and heat release rates as the butanol concentration increases.

A key novelty of this research lies in its comprehensive comparative analysis of pressure, temperature, and heat release behaviour across low, medium, and high load conditions, a parameter space often overlooked in previous studies. At 50% load, W5DBu15 exhibited peak in-cylinder gas temperatures close to 1,860°C and the highest heat release rate of 2,150 kJ/s, suggesting its capacity to deliver higher thermal energy without causing combustion instability. The presence of water in the emulsified blends contributed to micro-explosion phenomena that further improved atomization and combustion homogeneity while moderating post-combustion temperatures, potentially reducing NOx emissions.

Despite these advantages, the study also highlighted that higher heat release and temperature in the premixed phase must be carefully balanced to prevent excessive NOx formation. Therefore, the dual role of water as both a combustion enhancer through micro-explosions and a thermal moderator via latent heat absorption offers a promising pathway to cleaner and more efficient combustion. The results suggest that a W5DBu15 blend achieves an optimal trade-off between combustion performance and emission control under various engine loads, making it a viable candidate for alternative fuel applications in modern diesel engines. Future research should focus on optimising injection strategies (e.g., split injection or pilot injection timing) and exhaust after-treatment integration to further exploit the benefits of butanol-water blends. Additionally, long-term engine durability testing and complete emission profiling, including particulate matter (PM), NOx, and unburned hydrocarbons (UHC), are necessary to evaluate real-world applicability. Expanding the study to include transient engine operations and cold-start behaviour would also provide a deeper understanding of these fuels under dynamic driving conditions, ensuring their feasibility in commercial transportation and off-grid power systems.

4. Conclusion

The experimental analysis confirms that diesel-butanol-water blends have a significant influence on combustion behaviour, cylinder pressure, and heat release rate in high-speed diesel engines. Among all tested blends, W5DBu15 demonstrated the highest peak in-cylinder pressure at 35% load, exceeding base diesel performance due to improved combustion and higher in-cylinder temperatures. At 50% load and 3,000 rpm, all blends reached peak gas temperatures of approximately 2,000°C, slightly lower than those of pure diesel, indicating potential NOx reduction through water-induced cooling effects. Furthermore, heat release rate analysis showed that the premixed combustion phase increased proportionally with butanol concentration. W5DBu15 exhibited the highest heat release rate due to extended ignition delay and enhanced air-fuel mixing. Despite lower cetane numbers, the blended fuel maintains combustion patterns similar to those of base diesel without causing adverse impacts on engine operation. These findings suggest that diesel-butanol-water emulsions, particularly those with 15% butanol, can improve thermal efficiency and promote cleaner combustion, making them a promising alternative fuel option for diesel engines operating under medium to high loads.

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