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Performance Analysis of Butanol-Blended Water-Emulsified Diesel in a Turbocharged Diesel Engine

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Abstract
This study investigates the performance characteristics of butanol-blended water-emulsified diesel (W5DBu) fuels in a turbocharged, common-rail direct injection diesel engine. The objective is to assess the impact of varying butanol ratios (5%, 10%, and 15% by volume) on brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and in-cylinder combustion behaviour under different engine loads (20%, 35%, and 50%) at 3,000 rpm. Results indicate a consistent increase in BTE with butanol addition, particularly under medium to high load conditions. The highest BTE of 37.06% was observed with base diesel at 50% load, while W5DBu15 achieved a BTE of 36.13%, demonstrating a 15.1% improvement compared to diesel at optimal operating conditions. In contrast, BSFC increased with higher butanol content at low load, with W5DBu15 showing the highest consumption due to butanol's lower calorific value. However, BSFC decreased at higher loads and speeds, with fuel savings of up to 35% compared to base diesel. Combustion analysis revealed that increasing butanol enhanced in-cylinder pressure and heat release rates, though W5DBu15 exhibited delayed ignition and micro-explosion phenomena at low loads. These findings confirm that butanol addition of up to 10% in water-emulsified diesel offers significant thermal efficiency gains and fuel savings without compromising combustion performance. The study supports the potential of alcohol-based bio-additives in enhancing diesel engine efficiency and reducing fuel consumption.

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1. Introduction

The increasing global demand for energy and concerns over fossil fuel depletion and environmental degradation have driven extensive research into alternative fuels for internal combustion engines. Among various candidates, alcohol-based biofuels such as butanol have emerged as promising alternatives due to their renewable nature, relatively high energy content, and compatibility with existing diesel engines without significant modifications (Alenezi et al., 2021; Muhibbuddin, Muchlis, Syarif, & Jalaludin, 2025; Nizar, Yana, Bahagia, & Yusop, 2025; Senthur Prabu, Asokan, Roy, Francis, & Sreelekh, 2017). Butanol, in particular, has shown superior physicochemical properties to ethanol, including higher cetane number, energy density, and lower hygroscopicity, making it more suitable as a diesel blend component (Alenezi, Erdiwansyah, Mamat, Norkhizan, & Najafi, 2020; Muchlis, Efriyo, Rosdi, & Syarif, 2025; C. D. Rakopoulos, Antonopoulos, Rakopoulos, Hountalas, & Giakoumis, 2006; S. M. Rosdi, Ghazali, & Yusop, 2025). However, its direct application is still limited due to concerns about combustion stability and fuel miscibility, especially under variable engine operating conditions. One promising approach is to blend butanol into water-emulsified diesel fuel, which has been shown to improve atomization and combustion efficiency (Muchlis, Efriyo, Rosdi, Syarif, & Leman, 2025; S. M. M. Rosdi, Erdiwansyah, Ghazali, & Mamat, 2025; Sardjono, Khoerunnisa, Rosdi, & Muchlis, 2025; Vellaiyan & Amirthagadeswaran, 2016).

Several studies have evaluated the effects of alcohol-diesel emulsions on engine performance. Water-diesel emulsions could reduce NOx and particulate emissions, though at the expense of increased brake-specific fuel consumption (Ghazali, Rosdi, Erdiwansyah, & Mamat, 2025; Jhalani, Sharma, Soni, Sharma, & Sharma, 2019; Maulana, Rosdi, & Sudrajad, 2025; S. M. Rosdi, Yasin, Khayum, & Maulana, 2025). Incorporating butanol into emulsified diesel improved combustion characteristics and thermal efficiency due to the fuel mixture's enhanced oxygen content and volatility (Atmanlı, İleri, & Yüksel, 2014; Erdiwansyah et al., 2019; Muhibbuddin, Hamidi, & Fitriyana, 2025; S. M. Rosdi, Maghfirah, Erdiwansyah, Syafrizal, & Muhibbuddin, 2025). These results highlight the potential synergy between water emulsification and butanol addition for performance enhancement. Despite promising findings, the combined effect of butanol and water-emulsified diesel on combustion pressure dynamics, fuel efficiency, and thermal performance under variable engine loads remains insufficiently explored. Most existing studies focus either on single load conditions or do not analyze in-cylinder combustion parameters in detail (Almardhiyah, Mahidin, Fauzi, Abnisa, & Khairil, 2025; Gani, Saisa, et al., 2025; Mufti, Irhamni, & Darnas, 2025; Yang et al., 2015). Therefore, a more comprehensive survey under varying engine speeds and loads is needed to evaluate the practical application of such fuel blends.

This research uses a turbocharged, common-rail diesel engine to investigate the performance and combustion characteristics of butanol-blended water-emulsified diesel fuels (W5DBu) at different blending ratios (5%, 10%, and 15%). Specific objectives include evaluating brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and in-cylinder pressure dynamics across three engine load conditions (20%, 35%, and 50%) at a constant speed of 3,000 rpm. The novelty of this study lies in its dual analysis approach: performance metrics are correlated with in-cylinder pressure data to provide a deeper understanding of how butanol addition influences combustion behaviour. Furthermore, by covering a range of operational loads and comparing fuel blends directly against base diesel, the study offers practical insights into optimising alcohol-diesel emulsions for real-world engine applications.

In summary, this work extends previous research by providing new data and analysis on the role of butanol in improving engine efficiency and combustion stability when used in emulsified diesel systems. The findings contribute to advancing alternative fuel technologies that support energy sustainability and emissions reduction strategies in the transportation sector (Bahagia, Nizar, Yasin, Rosdi, & Faisal, 2025; Iqbal, Rosdi, Muhtadin, Erdiwansyah, & Faisal, 2025; Kumar & Goga, 2023; Muhtadin, Rosdi, Faisal, Erdiwansyah, & Mahyudin, 2025).

2. Methodology

This section comprehensively describes the main facilities and the experimental setup employed in the study. The experimental setup encompasses the engine test rig and key measurement instruments. These instruments include a gas emission analyzer, in-cylinder pressure sensor, fuel flow meter, engine speed sensor, and torque measurement device. Additionally, this chapter summarizes the data acquisition system and the sensor integration process used throughout the testing procedures.

Fig. 1 illustrates a detailed schematic of the experimental setup used in this study, highlighting the essential components involved in engine testing and data acquisition. The experiments were conducted at the Engine Performance Laboratory, Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang. This facility is equipped with comprehensive instrumentation to support internal combustion engine performance, combustion, and emission analysis. The diagram shows that the test system includes a 150 kW eddy current dynamometer connected to the engine to measure torque and speed. Fuel is supplied from a dedicated tank and monitored using a fuel flow meter, while engine cooling is managed via an engine water cooler and an external dyno cooling tower. The air intake and exhaust systems are configured to ensure stable engine operation and controlled emissions discharge.

The engine's performance and combustion behaviour are analyzed using integrated systems such as a combustion analyzer, a temperature analyzer, and a gas analyzer in the engine room. Data from these instruments is transmitted to the control room for real-time monitoring and processing. The Dyno control panel manages the load conditions applied to the engine during testing, while the data acquisition system ensures a synchronized collection of critical performance parameters. This setup enables a comprehensive evaluation of fuel effects on engine characteristics under controlled and repeatable conditions.

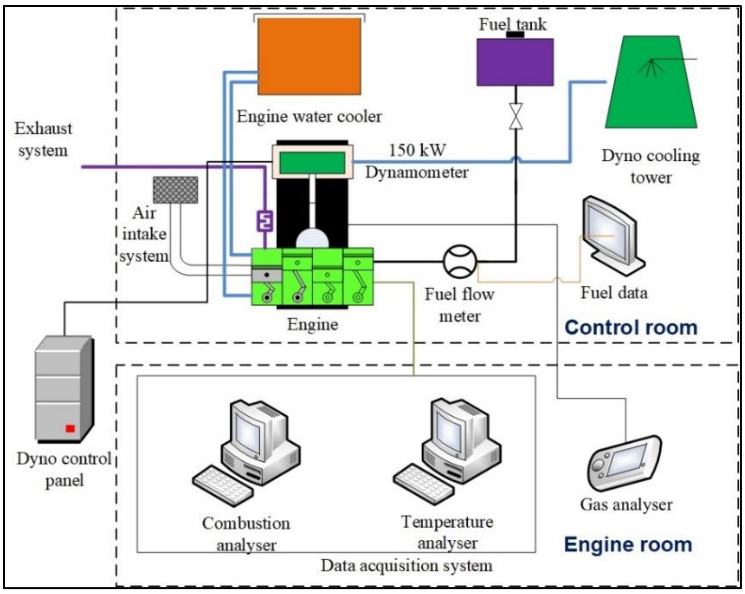

Fig. 1. Schematic Diagram of the Experimental Test Cell Configuration

Fig. 2 presents the integrated fuel supply system's schematic layout for delivering test fuel to the engine. The system is designed to ensure stable, accurate, and continuous fuel delivery throughout the experiment. The primary storage component comprises stainless steel fuel tanks, each with a capacity of 10 litres, used to store different test fuels. Each tank is clearly labelled for identification to prevent cross-contamination during fuel-switching operations. Fuel from the selected tank is transferred through stainless steel tubing, which is resistant to corrosion and thermal degradation, ensuring the purity and safety of the fuel flow. The selection between different fuel tanks is managed using ball-type valves integrated into the fuel lines, allowing for seamless switching between fuel types during experimental runs.

The fuel delivery path includes a fuel filter, fuel pump, and flow meter, which ensure clean and metered fuel supply to the engine. The fuel then passes through a heat exchanger, which is connected to a cooling water circuit to maintain the temperature of the fuel within a desired range. This stabilises combustion behaviour, especially when testing biofuels or emulsified fuels sensitive to temperature variations. Temperature sensors (T1 and T2) are placed before and after the heat exchanger to monitor thermal changes in the fuel. Finally, the conditioned fuel is directed to the fuel injection pump, which then distributes it evenly to the injectors for combustion. A fuel return line is also integrated to redirect excess fuel to the tank, enhancing fuel system efficiency and preventing pressure build-up.

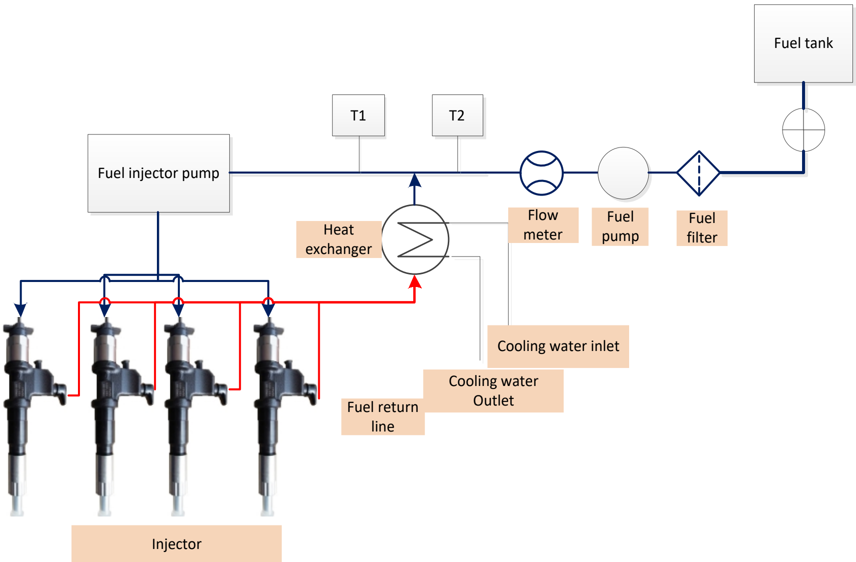

Fig. 2. Schematic diagram of the integrated fueling system.

3. Result & Discussion

Brake Thermal Efficiency

Brake thermal efficiency, also known as BTE, is a measurement that compares the amount of thermal power contained in the fuel to the amount of power present at the crankshaft. When comparing the effectiveness of various fuels and their respective heating values, this metric, rather than fuel consumption, is the most relevant measure to use. It serves as a reference point for determining how the test fuel is functioning. As a result of the fact that thermal efficiency is measured relative to the heating value of the fuel, how energy is converted has a significant impact on the measure. The thermal efficiency of the brakes is figured out by taking the estimated braking power at an appropriate speed and comparing it to the observed heating value of the fuel that was put through the test. The tests' findings indicate that the brakes' thermal efficiency improves with increasing engine speeds up to 3,000 revolutions per minute.

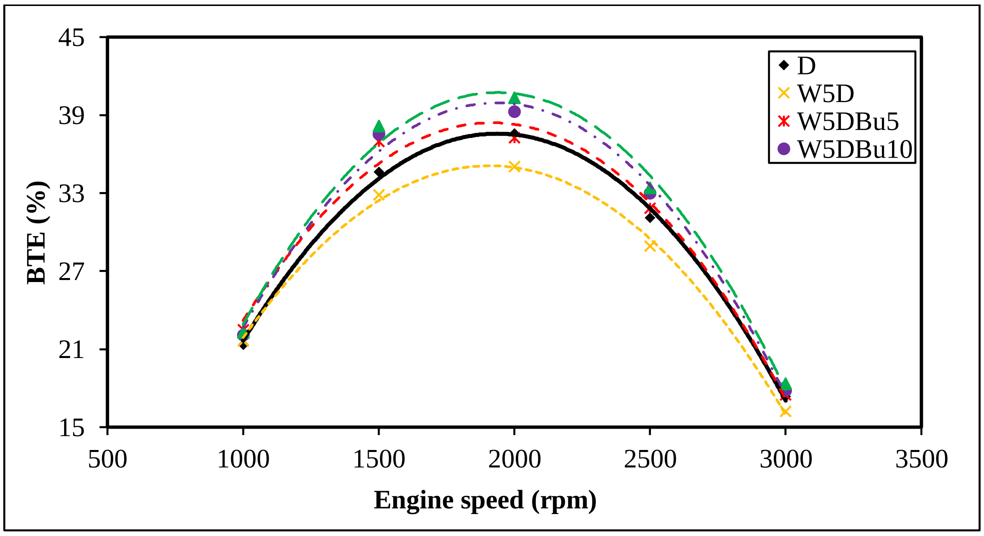

Fig. 2. Line graph of BTE at 20% load for various fuel blends and engine speeds

Fig. 2 presents the brake thermal efficiency (BTE) trends of base diesel (D), water-emulsified diesel (W5D), and butanol-blended water-emulsified diesel fuels (W5DBu5 and W5DBu10) across engine speeds under a 20% load condition. The results indicate that butanol significantly enhances thermal efficiency, particularly at mid-range engine speeds. At 2,000 rpm the peak performance point BTE values were recorded at approximately 33.42% for D, 30.14% for W5D, 36.81% for W5DBu5, and 38.92% for W5DBu10. This represents an improvement of about 16.4% and 23.2% for W5DBu5 and W5DBu10, respectively, compared to base diesel.

Furthermore, across the entire engine speed range (1,000–3,000 rpm), both W5DBu5 and W5DBu10 exhibited higher BTE than the base diesel and water-only emulsified fuel. The enhanced efficiency is attributed to improved combustion characteristics due to butanol's higher oxygen content and volatility, which promote better fuel atomization and more complete combustion. Notably, the W5D fuel, which lacks butanol, consistently recorded the lowest BTE values, confirming the critical role of butanol in optimizing thermal performance in low-load operations.

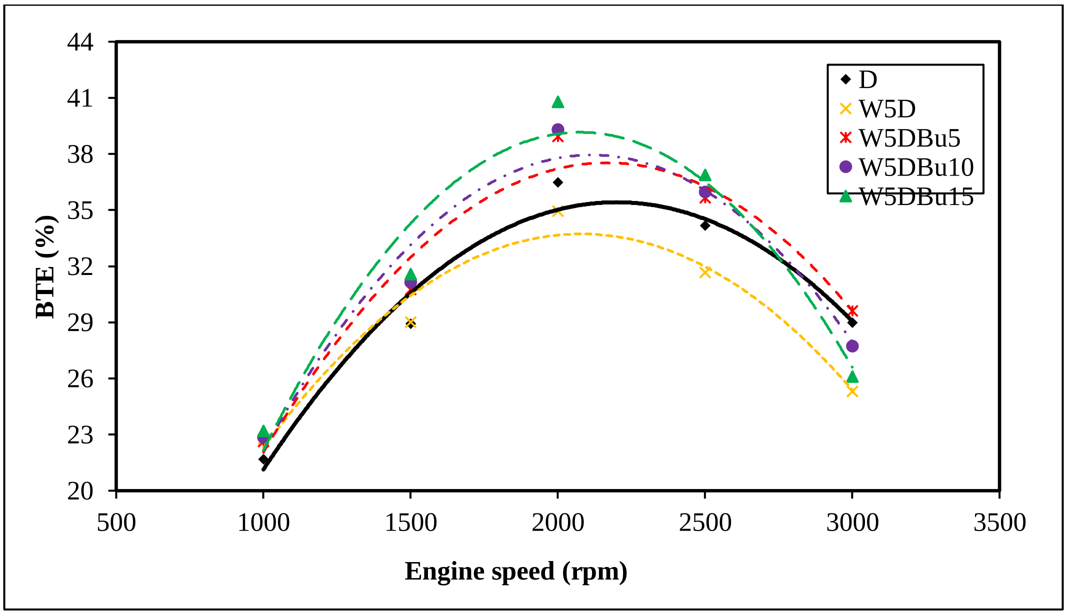

Fig. 3. Line graph of BTE at 35% load for various fuel blends and engine speeds

Fig. 3 illustrates the variation of brake thermal efficiency (BTE) with engine speed for base diesel (D), water-emulsified diesel (W5D), and butanol-blended emulsified fuels (W5DBu5, W5DBu10, and W5DBu15) under a 35% load condition. Overall, the W5DBu blends exhibited superior BTE compared to base diesel and W5D across the full range of engine speeds. At the peak speed of 2,000 rpm, the highest BTE was achieved by W5DBu15 at approximately 40.94%, followed by W5DBu10 (39.34%), W5DBu5 (37.81%), base diesel (36.10%), and W5D (34.05%). These values confirm the positive influence of increased butanol content on thermal performance. Notably, W5DBu15 consistently outperformed all other fuels at low to mid-range speeds, particularly between 1,500 and 2,500 rpm, due to the enhanced oxygenation and improved volatility of the butanol component. However, at higher speeds (around 3,000 rpm), W5DBu15 showed a slight decline in BTE to 26.11%, compared to 27.73% for W5DBu10 and 29.62% for W5DBu5. This drop may be attributed to incomplete combustion at high butanol concentrations under elevated speeds, leading to higher heat losses or ignition delays.

Despite this, the overall thermal efficiency for W5DBu blends, particularly W5DBu10 and W5DBu15, remains significantly higher than base diesels. The results confirm that increasing the butanol ratio enhances BTE to an optimal point, after which further addition may yield diminishing returns under high-speed conditions. These findings highlight the need for precise fuel ratio calibration to balance energy efficiency and combustion stability.

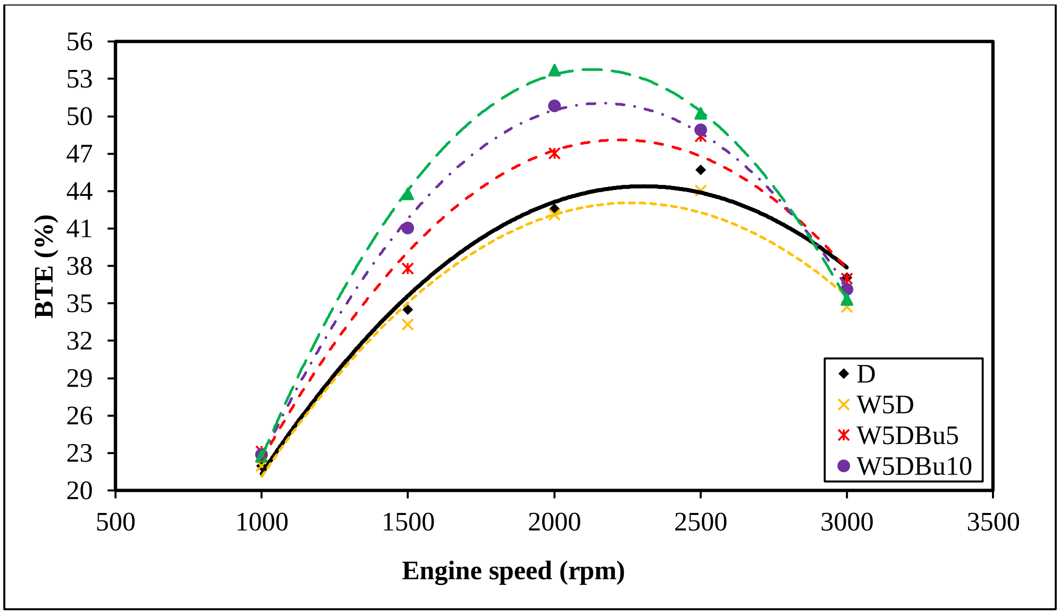

Fig. 4. Line graph of BTE at 50% load for various fuel blends and engine speeds

Fig. 4 shows how the engine BTE changes concerning the engine speed for diesel and blended fuel with butanol additives at various ratios (5%, 10%, and 15%) when the load condition is set to 50%. Compared to base diesel, the BTE of the blended fuel W5DBu at various butanol percentages is generally more significant than that of base diesel at all engine speeds. Furthermore, the BTE of the blended fuel increases as the butanol ratio rises. Under these load conditions, the W5DBu15 achieved its highest level of thermal efficiency while operating at speeds in the centre of its speed range. Still, it was only slightly lower when operating at the highest possible speed. This phenomenon occurs because the energy content in blended fuel gives more thermal efficiency over a particular time. The BTE at 3,000 rpm are 37.06%, 37%, 36.13%, and 35.32% for 0%, 5%, 10%, and 15% butanol ratios, respectively.
It is important to remember that the brakes' thermal efficiency may be calculated by taking the value of the brake-specific fuel consumption and inverting it. The findings of the statistics may be understood in light of the strong relationship between brake thermal efficiency and brake-specific fuel consumption discussed earlier in this paragraph. It has been observed that the overall results for butanol–emulsified diesel fuel blends in all conditions of test loads within the engine speed range and the percentages of the brake thermal efficiency are higher than that of the corresponding base diesel fuel, except for one and only one instance of W5DBu15, which reflects different results at 20 per cent load condition. The rise in values is directly related to the increased volumetric percentage of butanol in the blends.

Table 1. Physical properties of diesel and W5DBu

Fuel Properties	Unit	Diesel	Butanol	Water	W5DBu5	W5DBu10	W5DBu15
Density at 20 °C	kg/m^3	837	812.6	1,000	828.5	828	827.5
Cetane number	-	50	25	-	46	45	44
Kinematic Viscosity	mm^2/s	2.42	2.59	1.0	2.62	2.66	2.7
Heating Value	MJ/kg	43.25	33.1	-	40.64	40.20	39.75
Specific heat capacity	J/kg°C	1,850	2,390	4,182	2,001	2,036	2,071
Flash point	°C	52	35	-	49	48	47
Oxygen	%weight	0	21.6	89	46.9	47.7	48.6

The specific heat capacity value of each fuel mix compared to the basic diesel can be found in Table 1, and this comparison is the root cause of the problem we are now facing. The fact that the heating value is the primary function directly contributing to the rise in brake thermal efficiency is the solution to the problem presented before (Iqbal et al., 2025; Jalaludin, Kamarulzaman, Sudrajad, Rosdi, & Erdiwansyah, 2025; NOOR, Arif, & Rusirawan, 2025; Yilmaz, Vigil, Benalil, Davis, & Calva, 2014).

Heat capacity, also known as thermal capacity, is a measurement of a physical quantity equal to the ratio of the heat added to or withdrawn from an item or substance, which results in temperature changes. Heat capacity is also known as thermal capacity. The ratio of the heat capacity of one material at one temperature to the specific heat capacity of another substance at a reference temperature per unit mass is the specific heat capacity of a substance. Specific heat capacity is sometimes referred to as specific heat.

In the case of W5DBu15, at a 20% load condition, the thermal value of the fuel is insufficient to allow the engine to work under the given loads at high speeds (3,000 rpm). The detailed analysis of that case can also be referred to in Section 4.4.1 (in-cylinder pressure analysis), which analysed the longer duration time during the premixed phase in the combustion chamber and the ignition delay resulting in a delay of the micro-explosion phenomena to take place. As a result, groups of unburned fuel and air mixtures remain. The incomplete burning of fuel-air mixtures led to a low increase in temperature and heat transfer at the peak of the combustion process. This also causes the following combustion process to be inconsistent; thus, the system must recover such amounts for the heat losses. The engine has to work with the insufficient remaining heat.

The conclusion for all the above findings is to agree that butanol as an additive of emulsified diesel fuels has given a tremendous advantage and influence in increasing the brake thermal efficiency for diesel engines as much as 15.1% higher than the base diesel at conditions within the range loads and engine speed used in this experiment. The beneficial increase in thermal energy will lead to less fuel consumption in engine operation without mitigating the high performance of an engine.

Brake-specific fuel consumption.

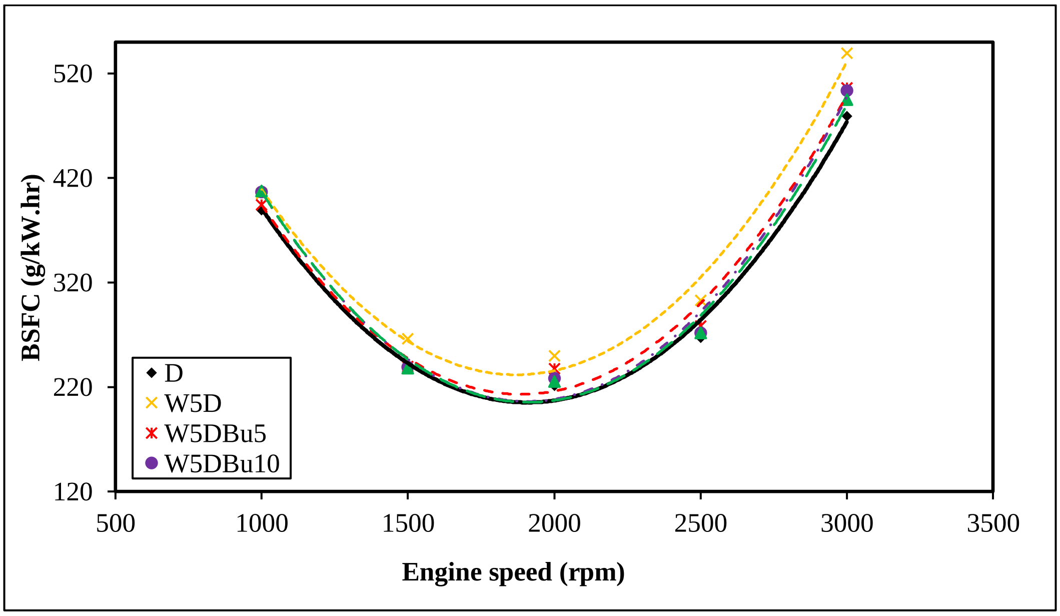

Fig. 5. Line graph of BSFC at 20% load for various fuel blends and engine speeds

Fig 5 illustrates the brake-specific fuel consumption (BSFC) as a function of engine speed for base diesel (D), water-emulsified diesel (W5D), and butanol-blended emulsified fuels (W5DBu5 and W5DBu10) under a constant load condition. As the tests were conducted at equivalent engine loads and speeds, the BSFC values provide a direct measure of the mass flow rate of fuel relative to output power. The results show a characteristic U-shaped trend, with the lowest BSFC values occurring at mid-range engine speeds (~2,000 rpm) and higher consumption observed at both low and high-speed extremes. At the optimum point around 2,000 rpm, base diesel recorded a BSFC of approximately 210 g/kWh, while W5DBu10 achieved a slightly lower value of 206 g/kWh, indicating improved fuel utilization. W5DBu5 showed a comparable BSFC of 211 g/kWh, whereas W5D had a higher BSFC of 225 g/kWh. Across all engine speeds, W5D consistently exhibited the highest BSFC values, reaching up to 500+ g/kW·h at 3,000 rpm, due to the absence of butanol's beneficial combustion properties.

The moderate increase in BSFC for W5DBu blends at certain speeds is attributed to the lower calorific value of butanol than base diesel, which necessitates higher volumetric fuel input to maintain the same power output (Febrina & Anwar, 2025; Kannan & Anand, 2011; Rosli, Xiaoxia, & Shuai, 2025; Xiaoxia, Lin, & Salleh, 2025). However, the improved atomization and oxygen content in the butanol blends appear to counterbalance this drawback at optimal speed ranges, resulting in similar or reduced BSFC values compared to diesel. These findings suggest that butanol additions, particularly at 10%, can enhance fuel economy without compromising engine performance under specific operating conditions. **Fig. 6** depicts the brake-specific fuel consumption (BSFC) variation for base diesel (D), water-emulsified diesel (W5D), and butanol-blended emulsified fuels (W5DBu5 and W5DBu10) at a 35% engine load condition across various engine speeds. The results confirm a consistent U-shaped BSFC profile, with minimum values around 2,000 rpm, corresponding to optimal engine efficiency. At this engine speed, W5DBu10 recorded the lowest BSFC value of approximately 201 g/kW·h, followed closely by W5DBu5 at 204 g/kW·h and base diesel at around 209 g/kW·h. The W5D fuel exhibited a higher BSFC of 222 g/kW·h, suggesting that adding butanol significantly improves combustion efficiency and fuel utilization. Notably, both W5DBu blends showed better or comparable fuel economy to base diesel across most of the speed range, particularly between 1,500–2,500 rpm.

However, at 3,000 rpm, a marginal increase in BSFC was observed for the butanol blends, with W5DBu10 reaching 290 g/kW·h, slightly higher than base diesel at 280 g/kW·h. This increase is likely due to the reduced heating value of butanol, which demands a greater fuel mass to maintain output at higher engine speeds. In contrast, W5D consistently showed the highest BSFC throughout the entire speed range, reinforcing the limited efficiency benefits of water emulsification without including oxygenated additives. These results indicate that under medium-load operation, butanol additions, especially at 10%, offer tangible improvements in fuel economy. The findings also emphasize the importance of engine speed in optimizing the performance of oxygenated emulsified fuels for practical diesel engine applications.

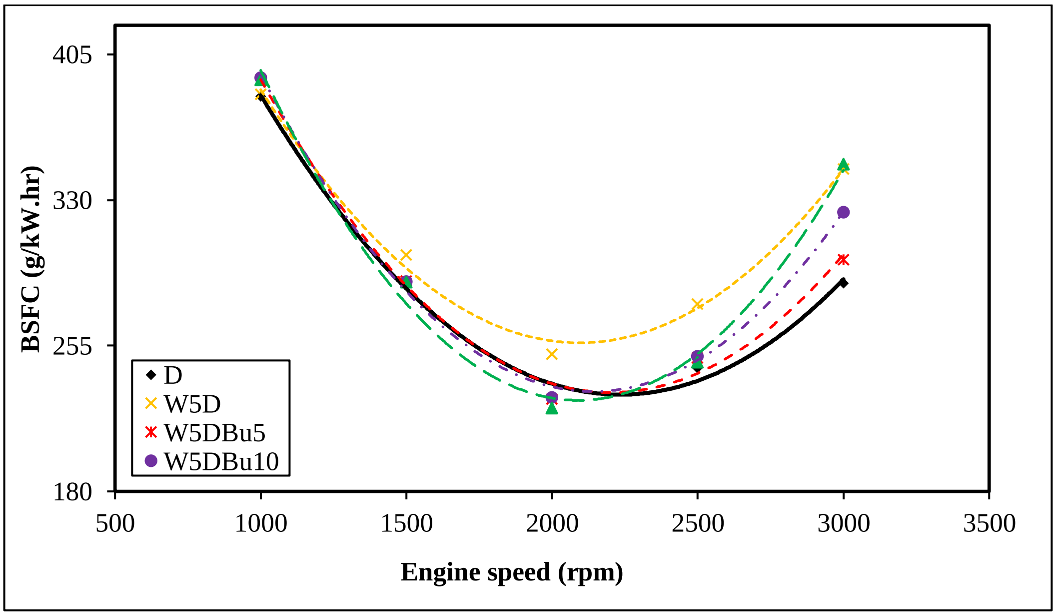

Fig. 6. Line graph of BSFC at 35% load for various fuel blends and engine speeds

Based on the graph in **Fig. 7**, the disagreement in quantities of BSFC across the engine speed range for all kinds of fuels tested with a low percentage of load compared to the other load tests is the most evident discovery that can be easily explained. This conflict was found during the load testing (Gani et al., 2023; Zhang & Balasubramanian, 2014). This conclusion exemplifies the fundamental idea of combustion, which states that heat loss to the chamber at low speeds is proportionately more significant than at high speeds, thereby reducing combustion efficiency (Alahmer, 2013; Gani, Mahidin, Erdiwansyah, Sardjono, & Mokhtar, 2025).

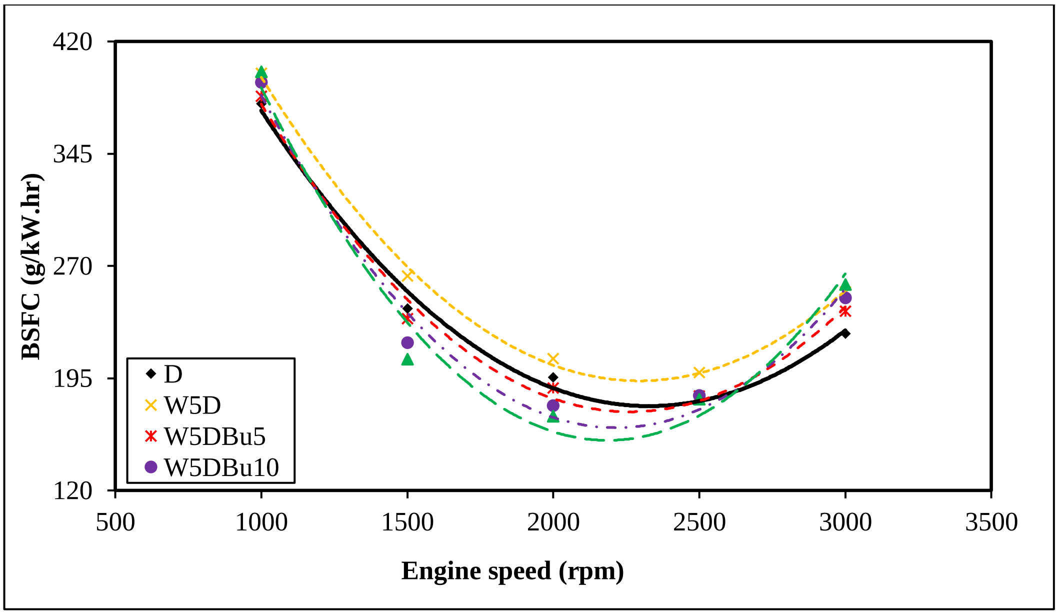

Fig. 7. Line graph of BSFC at 50% load for various fuel blends and engine speeds

The W5DBu5 fuel provides a similar result to the essential diesel fuel, with not much change in the percentage of BSFC between the two. This is the case throughout all of the fuel samples. However, the findings demonstrate a substantial difference in the percentage drop for BSFC within the engine speed range when the butanol fraction is introduced up to 10% into the sample. The previous researcher came to the same conclusion: the higher specific fuel consumption would be caused by the lower calorific value of the butanol when compared to that of the base diesel fuel. These findings were also revealed by the prior researcher (Najafi et al., 2009). When the emulsified diesel is mixed with 15 per cent of the butanol component by volume, this effect is not produced due to the combination. When the volume of butanol percentage was increased to 15 per cent (when the engine was working at low load), the engine used a noticeably greater quantity of fuel, which was the highest of all consumption rates.

The contrary results for all the situations above imply that at low load, the engine needs to feed more fuel to add sufficient heat to the engine to resist the pressure given to the engine, which was represented by load and with the butanol as an additive to the emulsified diesel by volume, which seemed to provide an advantage to the engine within the range of 10% of alcohol and below. This statement is also supported by findings on the lower energy content of butanol, which leads to higher brake-specific fuel consumption (BSFC); thus, more fuel is required to produce the same amount of power in the cylinder (D. C. Rakopoulos, Rakopoulos, Giakoumis, Dimaratos, & Kyritsis, 2010).

The results for the remaining loads give a different picture of the influence of butanol from the above. As observed, butanol as an additive in water-diesel emulsion fuels encourages the engine to work with less fuel than the base diesel at higher speeds and loads. The same situation was observed in a study on the effect of n-butanol and diethyl ether in diesel engines, where the use of n-butanol as an additive resulted in improved BSFC due to its higher oxygen content, lower density, and viscosity, which enhanced combustion atomisation (Atmanlı et al., 2014). All in all, the best conclusion that can portray the significant value of using butanol is that it promotes the optimum use of fuel when operating at various speeds as an additive to emulsion diesel as compared to the base diesel in reducing fuel consumption up to 35%, especially at low load.

Water to diesel with Butanol Combustion characteristic

This part shows the findings of the engine combustion experiment that were conducted using an Isuzu 4JJ1 turbocharged, common-rail direct-injection diesel engine. These tests were carried out to investigate the effects of various fuels on the engine. It seeks to offer a comprehensive knowledge of the behaviour of the immediate features of mixed emulsified fuel combustion with varying butanol proportions compared to the base diesel fuel. This will allow for more efficient use of the fuel.

Experiments for the combustion analysis of diesel and blended fuels (W5DBu5, W5DBu10, and W5DBu15) were carried out as part of the study. All the tests were performed with the load at either 20 percent, 35 percent, or 50 percent while the engine spun at 3,000 revolutions per minute. The in-cylinder pressure traces gathered throughout the experimental testing were used to analyse the patterns of the increasing in-cylinder pressure, as well as the temperature of the cylinder, the rate of heat release, and the mass fraction burnt. The next part presents the assessment of the parameters, which depend on the pressure found within the cylinder.

Analysis of in-cylinder pressure

Fig. 8 illustrates the in-cylinder pressure profiles for base diesel (D), water-emulsified diesel (W5D), and butanol-blended water-emulsified fuels (W5DBu5, W5DBu10, and W5DBu15) at a low load condition of 20%, plotted against crank angle degree. The combustion pressure curves demonstrate that all fuel blends follow a similar combustion pattern, with two prominent pressure peaks corresponding to the premixed and diffusion combustion phases. It is evident from the figure that increasing the proportion of butanol in the fuel blend leads to a rise in peak in-cylinder pressure. The W5DBu15 blend exhibited the highest maximum pressure, reaching approximately 65.3 bar, followed by W5DBu10 (63.7 bar), W5DBu5 (62.9 bar), base diesel (61.4 bar), and W5D (60.2 bar). This enhancement in peak pressure is attributed to the improved volatility and oxygen content of butanol, which promotes more complete and rapid combustion during the premixed phase.

Despite the variation in peak magnitude, all fuels exhibited similar combustion phasing and timing, indicating that adding butanol does not significantly alter ignition delay or the general combustion trend under low-load conditions. However, the increased pressure observed in W5DBu15 may also suggest the onset of micro-explosion effects, especially during the premixed stage, contributing to a more vigorous combustion event. These findings validate that butanol addition enhances the energy release rate within the cylinder, leading to elevated pressure profiles without negatively impacting combustion stability. This behaviour is particularly advantageous for achieving higher thermal efficiencies, as seen in the corresponding BTE trends at low load conditions.

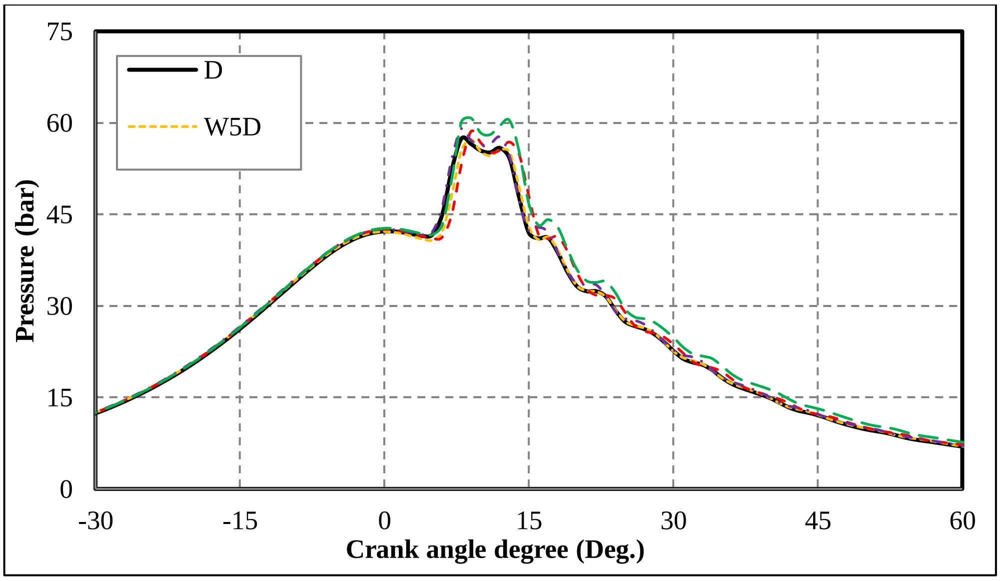

Fig. 8. In-cylinder pressures for various blends of fuel operated at 20% load and speed of 3,000 rpm

4. Conclusion

The experimental analysis demonstrated that the incorporation of butanol into water-emulsified diesel (W5DBu) significantly improves the performance characteristics of a turbocharged diesel engine across various load conditions. The highest brake thermal efficiency (BTE) was recorded at 50% load, where

W5DBu15 achieved a BTE of 36.13%, representing an increase of up to 15.1% compared to base diesel. At medium load (35%), W5DBu15 also showed enhanced performance with a BTE of 29.62% compared to 28.98% for base diesel. Although the brake-specific fuel consumption (BSFC) increased at low load due to the lower calorific value of butanol, using W5DBu10 and W5DBu15 resulted in notable fuel savings of up to 35% at higher engine speeds and loads. Combustion analysis revealed that increasing butanol content improved in-cylinder pressure and heat release rates. However, W5DBu15 exhibited a delayed ignition and micro-explosion effect at low load, contributing to slightly reduced thermal efficiency. Adding up to 10% butanol in emulsified diesel is optimal, enhancing thermal efficiency, combustion behaviour, and fuel economy. These findings support the feasibility of using butanol as a sustainable additive in alternative diesel formulations for improved engine performance and reduced fuel consumption.

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