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Research Paper

The Impact of Varying Mixing Rates in a Surfactant-Free Fuel Emulsion Mixer on the Efficiency and Emissions of a Diesel Engine

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Abstract

The research focuses on water diesel emulsion (WDE), a topic that has captivated researchers for an extended period. While previous studies predominantly employed surfactants to enhance mixing efficiency, their non-economic feasibility in transportation logistics has prompted a shift in recent investigations. This study presents experiments utilizing a cost-effective WDE comprising 15% water and a mixer devoid of surfactants to investigate the impact of mixer blade rotation on engine performance, fuel consumption, and NOx emissions. NOx emission tests were conducted under a constant engine speed of 2,000 rpm and a 75% load (3.23 kW). The optimal brake-specific fuel consumption (BSFC) for the 15% WDE fuel occurred at a blade rotation speed of 3,000 rpm, resulting in a 1% power reduction (from 4.41 kW to 4.38 kW), a 13.3% decrease in BSFC (from 694.98 gr/kW.h to 602.52 gr/kW.h), and a 30% reduction in NOx emissions (from 54 ppm to 38 ppm). This discovery holds promise for future advancements in green energy applications within the transportation sector.

Keywords: Mixing speed; Fuel emulsion mixer; Non-surfactant; Diesel engine; Emissions; Engine performance

1. Introduction

Fuel efficiency and emission mitigation have remained prominent areas of investigation in recent years [1]. The scientific community has diligently explored diverse methodologies to address these challenges, encompassing the integration of alternative fuels, such as plant-based oils, into conventional diesel fuel [2]–[6]. Concurrently, researchers have delved into comprehensive engine modifications, spanning internal adjustments within engine components (e.g., compression ratio settings, injection timing, injection pressure, fuel injectors, and modifications to the combustion chamber's configuration) and external enhancements to engine components (e.g., exhaust gas recirculation (EGR), catalytic converters) [7], modifications to the fuel delivery system [8], as well as a combination of engine component modifications and fuel modifications (coated pistons and emulsified fuel) [9]–[11]. In the current research landscape, particular emphasis has been placed on fuel delivery system modifications, with a noteworthy focus on the utilization of emulsion diesel fuel in diesel engines. This approach involves the creation of stable mixtures of water and diesel fuel, offering potential advantages in terms of combustion efficiency and emission reduction [12]. The exploration of emulsion diesel fuel as an innovative avenue aligns with the quest for sustainable and environmentally conscious solutions in the realm of internal combustion engines. Researchers aim to unravel the intricacies of emulsion diesel fuel utilization, its impact on combustion dynamics, and its potential as a viable strategy for enhancing the overall efficiency and environmental performance of diesel engines.

Diesel engines have assumed a pivotal role across diverse sectors, including industrial, transportation, agriculture, marine, and heavy equipment domains. Renowned for their high power output, commendable fuel efficiency, and robust durability, diesel engines have become indispensable for various heavy-duty applications [13]. However, the indispensable nature of diesel engines has spurred concerted efforts to mitigate reliance on conventional diesel fuel. This pursuit encompasses strategies aimed at further enhancing fuel efficiency and curtailing emissions, with a particular emphasis on addressing the longstanding challenge of nitrogen oxide (NOx) emissions [12], [14]–[16]. Stringent regulatory frameworks increasingly necessitate comprehensive approaches to alleviate the environmental impact of diesel engines, prompting a focused exploration into innovative solutions for achieving sustainability and emission reduction in this critical sector [17]–[19].

One effective strategy to mitigate NOx emissions in diesel engines involves the utilization of water-diesel fuel emulsion (WDE) [20]. WDE is formulated as a blend of diesel fuel and water in specific proportions, with research into emulsion fuels dating back to the 1970s, as evidenced by studies conducted by Law et al. in 1977 [21], Cook et al. in 1978 [22], and Lasheras et al. in 1979 [23]. Subsequently, there has been a notable resurgence in the exploration of WDE since 2012 [24]. This particular fuel has demonstrated its capacity to curtail diesel fuel consumption without imposing significant compromises on engine performance, simultaneously achieving reductions in NOx emissions, Particulate Matter (PM), and smoke emissions without necessitating extensive engine modifications [25]. Notably, until the present research initiative, the proportion of water admixed with diesel fuel had been investigated and found to be viable at levels reaching up to 30% [26]. This research aims to contribute to the evolving understanding of the optimal water-to-diesel ratio in emulsion fuels, seeking to elucidate the intricate interplay between composition and combustion characteristics. The investigation aspires to provide insights into the viability of higher water content in the emulsion, addressing its implications on combustion efficiency, emissions, and overall engine performance.

The production of Water Diesel Emulsion (WDE) involves the crucial decision of whether to employ surfactants or adopt a surfactant-free approach. The inherent challenge arises from the difficulty in dissolving diesel fuel and water without the aid of surfactants, which, although effective, present a cost constraint due to their high price. In response to this, researchers have embarked on innovative methodologies aimed at circumventing the use of surfactants. An overarching obstacle in the development and implementation of surfactant-free emulsion fuels lies in the compromised stability of the emulsion, leading to a propensity for rapid separation. Addressing this challenge necessitates inventive strategies, and one promising avenue is the implementation of a real-time mixing process. This involves the direct amalgamation of fuel components immediately before injection into the engine. Despite the advancements in this domain, the concentration of water in surfactant-free WDE in single-cylinder diesel engines has, as of the present, only reached a modest 5%. Researchers have explored various equipment and methods for WDE mixing without surfactants. Prior studies have employed microchannel emulsifiers [27], steam generators [28], and the combination of ultrasonic and mixers known as RTES [29]. These techniques represent diverse approaches to achieving stable and well-dispersed emulsions without relying on surfactants, showcasing the ongoing efforts to overcome the challenges associated with the cost and stability of surfactant-free emulsion fuels in the quest for sustainable and efficient fuel alternatives for diesel engines.

The implementation of an ultrasonic RTES system incurs significant expenses, prompting the exploration of alternative methodologies in this study. The difference between this research and others was that this study applied emulsion fuel without surfactants with a high-water content (15%) and mixed it using a mixer directly connected in real-time to the diesel engine. Specifically, this research investigates the mixing of water diesel emulsion (WDE) without resorting to ultrasonic equipment, opting instead for a conventional mixer directly preceding the injection into a diesel engine. Employing a mixer presents a straightforward and cost-effective approach. The mixer blade underwent rotations at varying speeds, specifically 3,000 rpm, 5,000 rpm, and 7,000 rpm, for the thorough mixing of a 15% WDE composition devoid of surfactant. Parameters such as engine performance, fuel consumption, and NOx emissions during diesel engine testing serve as the critical metrics for evaluating the efficacy of this methodological approach.

2. Materials and Method

2.1. *Micro-explosion Phenomenon*

A notable benefit associated with emulsion fuel utilization is the occurrence of the micro-explosion phenomenon within the combustion process. Illustrated in **Figure 1**, this phenomenon entails the explosive reaction of water droplets during the combustion phase within the combustion chamber [30]. The detonation of water droplets serves to disperse the diesel fuel into minute droplets, subsequently subjecting these diminutive fuel particles to a secondary explosive event referred to as a micro-explosion. This dual-stage process significantly enhances combustion efficiency while simultaneously mitigating hydrocarbon emissions (HC).

2.2. *Micro-explosion Phenomenon*

A mixer is used to make a mixture of two or more different liquids into a homogeneous mixture or to increase the homogeneity of the mixture. A mixer consists of a driving system and a mixer tube with a mixer blade in it. A mixer-drive system consists of an electric motor equipped with an inverter and a rotation sensor. The inverter is used to adjust the rotational speed of the electric motor, so the mixing speed of the mixer can be adjusted as needed. The mixer tank is made from aluminum with a volume of 450 ml and has an aluminum four-blade propeller. This propeller is connected to an electric motor via a stainless steel shaft. The mixer is equipped with two inlet channels (DF and water), one outlet channel (WDE), and one valve on the outlet channel.

The mixing power is a crucial factor in mixer applications on diesel engines because the required power of the mixer will affect the total efficiency of the machine. Therefore, it is necessary to calculate the required power for the mixer. The electric power consumption of the mixer can be calculated from the electric current and the electric voltage flowing to the electric motor. The calculation was carried out for each variation of the mixer rotation, namely from 3,000 rpm to 7,000 rpm. The used electric motor was an electric motor 3-phase, so Eq. 1 was used to calculate the electric power [31].

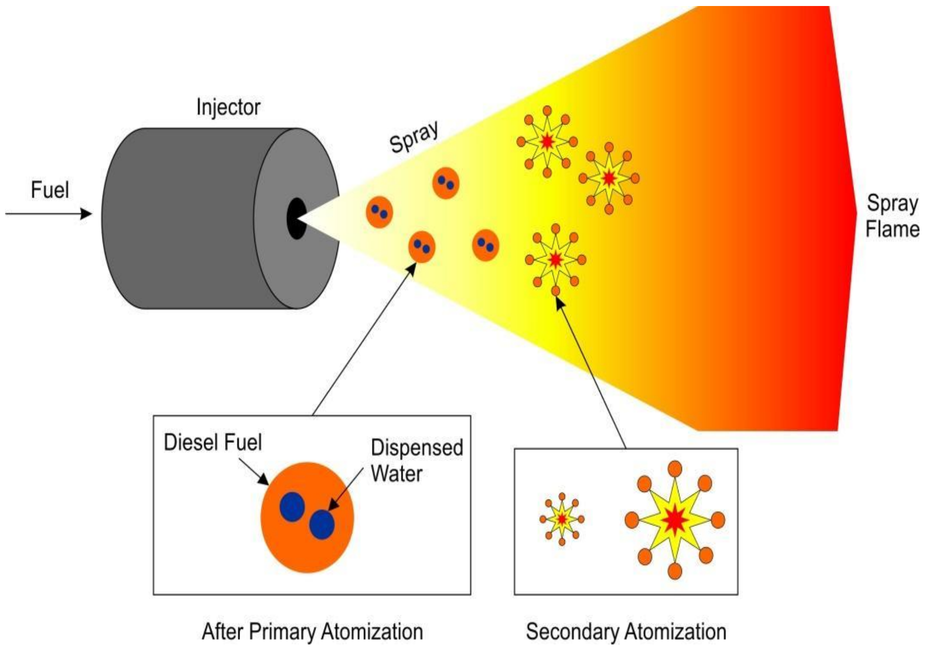

Figure 1. Micro-explosion phenomenon [30]

The power consumption data is used to calculate and determine the operational conditions of the mixer that will be used in a diesel engine. The efficiency level of the mixer operations and diesel engine can be mapped accurately, so the operating conditions will be more effective and efficient [1].

$$P_e = I \; x \; V \; x \; Cos\varphi \; x \; \sqrt{3} \qquad (1)$$

2.3. *Non-Surfactant Water-Diesel Fuel Emulsion Preparation*

This study used two types of fuel, which were Pertamina Indonesia biodiesel (DF) diesel fuel and 15% water (WDE15) emulsion fuel. The research on emulsion fuel without surfactants with low water content has been conducted by several researchers. Therefore, in this study, a higher water content was used. Emulsion fuel, which consisted of 85% diesel fuel and 15% water (distilled water), was blended without using surfactants. The properties of diesel fuel and distilled water are shown in **Table 1**, while the schematic of the emulsion fuel mixing process can be seen in **Figure 2**. Diesel fuel and water were stored in two different containers. The volume of the two materials was measured according to the desired ratio before flowing into the mixer tube. This was done to ensure the ratio of diesel fuel to water is exactly 85:15. Each liquid then flowed into the mixer tube simultaneously through the valve opening and was mixed in the mixer. Stirring was carried out with three variations of the mixer rotation: 3,000 rpm, 5,000 rpm, and 7,000 rpm, which were named WDE15-3, WDE15-5, and WDE15-7, respectively.

The emulsion fuel stability was visually observed and taken using a camera image. In this observation, both the variations of the mixer rotation and stirring time were carried out for 1 minute and 3 minutes. The observation process was carried out for 10 minutes to see the process of separating water and diesel fuel from emulsion fuel in real-time conditions. The results of this observation were used to determine the length of the fuel line from the mixer to the engine injector pump.

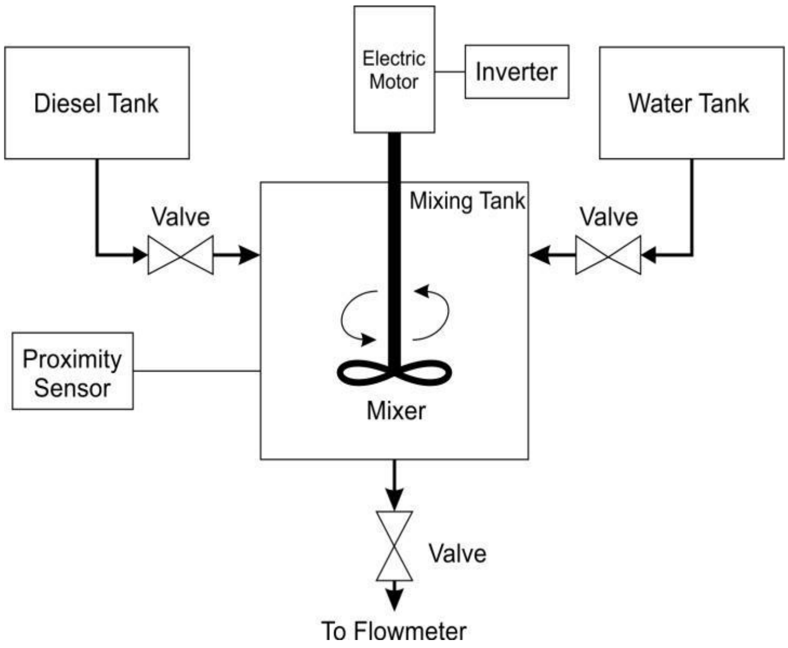

Figure 2. Mixing process schematic

Table 1. Diesel fuel and water properties

Properties	Unit	Diesel fuel	Water
Calorific value	MJ/kg	45.28	-
Density at 40 °C	kg/L	0.850	1.0
Viscosity at 40 °C	mm^2/s	5.2	0.658
Cetane number	-	48	-

The properties of the emulsion fuel itself couldn't be determined or displayed here. The fuel emulsion itself would easily separate from each other since there's no surfactant as a binder, so it's hard to determine its properties in the laboratory. Table 1 shows the properties of both diesel fuel and water, according to the laboratory.

2.4. Test Bed Set-up and Testing

The engine test bed is equipped with various measurement tools and sensors that are integrated into one small system through analog and digital data acquisition systems. The schematic of the engine test bed is shown in Figure 3. The engine test bed that was used in this study had four main parts, which were a dynamometer, diesel engine, exhaust gas analyzer, and mixer system. The system mixer is described in Section 2.2.

A dynamometer is a tool for measuring the mechanical power (speed and torque) of the engine. This study used an eddy current dynamometer that was modified from an AC generator with a capacity of 10 kW.The dynamometer was equipped with a lamp-loading system (10 kW) and a voltage regulator. The flow of electricity from lamps created a magnetic field in the dynamometer and would hold the engine speed, so the torque could be read through the load cell. The diesel engine used in this study was a single-cylinder diesel engine. The diesel engine specification describes as follows: maximum power of 5.5 kW at 2,600 rpm, maximum torque of 24 Nm at 1,800 rpm, volume of 353 cc, bore x stroke 75 mm x 80 mm, water hopper cooling system, and direct injection. The fuel line was removed from the tank and connected to the burette for measurement of fuel consumption. The engine speed and dynamometer were read using a autonics proximity sensor (range of measurement 2.5-99,999 rpm, distance of measurement 50-500 mm) that was attached to the engine shaft. A Testo 350 gas analyzer was used to measure the emissions of NOx and CO exhaust gases. This gas analyzer has a measurement range for CO (0–10,000 ppm) and NO (0–4,000 ppm). For emission sampling, a gas analyzer probe was attached to the exhaust gas line of the diesel engine. The sampling pump sucked the exhaust gases into the gas analyzer, which were then analyzed by sensors in the instrument. This sensor worked according to the type of gas to be analyzed. The results of the sensor readings appeared on the gas analyzer display for further use as research data. Figure 3 represents the test bed schematic.

These experiments would test the engine's performance and emissions. Before the testing, the diesel engine was preheated for about 10 minutes to reach a working temperature of 90 °C. Performance testing was used to determine the maximum engine performance, including torque, shaft power, and fuel consumption. The experiment was carried out at full load conditions, and the data was taken at an engine speed of 1,600 rpm to 2,600 rpm with 200 rpm intervals.

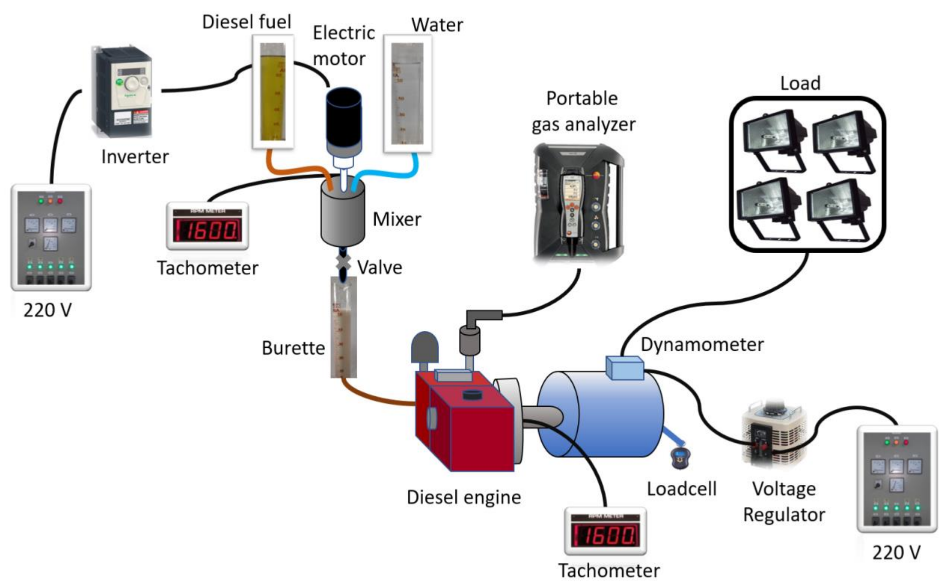

Figure 3. Engine test bed schematic

Emission testing aims to determine exhaust gas emissions (CO and NOx emissions) under constant loading conditions. The test was carried out at a loading factor of 75% and a constant rotation of 2,000 rpm. The engine rotation speed was measured in accordance with the testing standard SNI 0119:2012 (Indonesian national standards). During performance and fuel consumption testing, data were collected at a minimum of 5 engine rotation speed points. The test results indicated that the most fuel-efficient consumption occurred at an engine rotation speed of 2,000 rpm. Therefore, the 2,000 rpm rotation speed was selected as the emission gas testing point, as emissions typically tend to be lowest at this point alongside the most fuel-efficient consumption. The experiments were carried out on all variations of the fuel. The data collection was conducted after the stable number of each sensor and each parameter. The experiment would be repeated two more times for each emission. All data was recorded on the provided form for further data processing.

3. Results and Discussion

The measurement of the electric power consumption of the mixer, the observation of emulsion fuel stability, the performance testing, and the emissions testing using diesel fuel (DF) and emulsion fuel (WDE15-3, WDE15-5, and WDE15-7) have been done. The results are displayed in the form of tables, graphs, and figures and are analyzed together with some reputable literature.

3.1. Power Consumption on The Mixer

Based on the measurement of electric current and voltage at various rotations of the electric motor driving the mixer, the electric power consumption data is shown in **Table 2**. The power value was obtained from the calculations using Eq. (1).

The data showed that the higher the mixer rotation, the higher the required current and power. This is expected because getting a higher rotation requires more energy. The main focus of measuring the consumption of electric power is to map the amount of electrical power that is required for each variation of the mixer rotation. The results of the mapping were used to determine the operating conditions of the mixer when integrated with a diesel engine, so the overall efficiency of the diesel engine could be calculated and the aspect and ideal specification of the mixer could be determined.

3.2. Non-surfactant Water-diesel Fuel Emulsion Stability

The observation of emulsion fuel stability was only done visually. The observation was started right after stirring for up to 10 minutes. The results showed that the visual appearance was not much different between variations of emulsion fuels. **Figure 4**. shows the observations of the emulsion fuel after stirring, when the clumps started to form, and when 85%–95% of the emulsion fuel was separated.

Initially, the emulsion fuel exhibited a homogeneous and milky-white appearance. However, after 1.5 minutes, the emergence of white blobs marked the onset of a distinct phase characterized as flocculation [32]. During this stage, the emulsion fuel undergoes separation as the repulsive force between water droplets weakens. Notably, the water droplets within the diesel fuel do not achieve complete dissolution in the emulsion, leading to the formation of dispersed water droplets that coalesce to generate prominent white lumps. Subsequently, these water droplets move towards one another, culminating in the coalescence stage, where larger droplets are formed. The final phase, referred to as sedimentation, involves the visual separation of the diesel fuel layer from the water in the

Table 2. The power consumption of the mixer on variations in blade rotation.

Blade speed (*rpm*)	I (A)	V (Volt)	P_e (Watt)
3,000	0.47	220	152
4,000	0.65	220	210
5,000	0.81	220	262
6,000	1.13	220	365
7,000	1.34	220	433

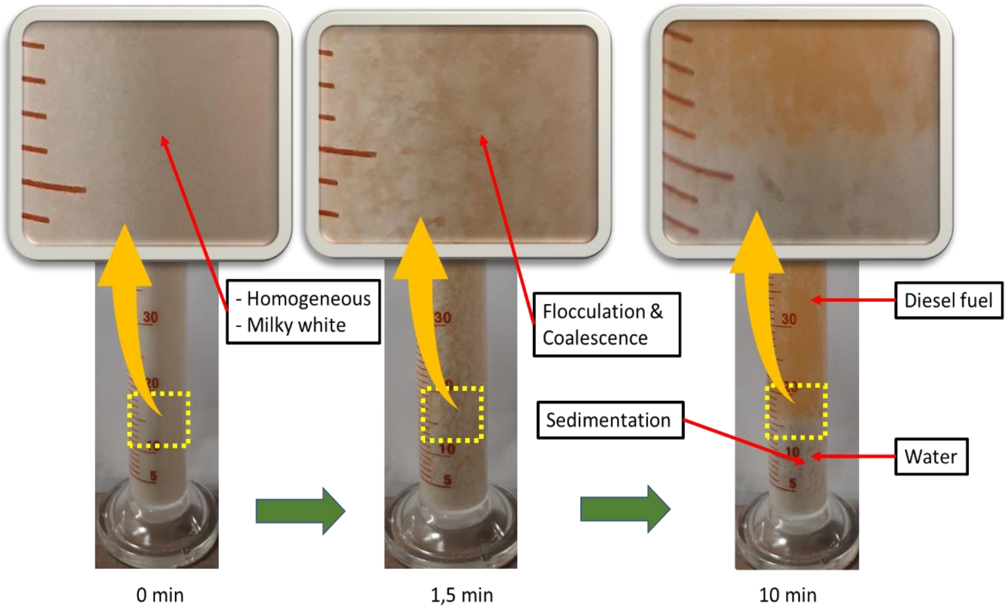

Figure 4. Visual observation of the emulsion fuel stability

emulsion system, attributable to the density disparity between the dispersed and dispersant phases [33]. The precarious formation of the system renders it susceptible to the influence of external forces, particularly gravitational and centrifugal forces [34]. These forces induce the separation of the dispersed phase from the dispersing phase based on density. In this context, water, possessing a higher density than diesel fuel, descends while diesel fuel remains above. Consequently, all water droplets coalesce on the underside, leading to the complete segregation of the emulsion.

The rapid separation of emulsion fuel observed in this study posed challenges in analyzing and presenting the emulsion fuel properties. Similar findings were reported in a study conducted by Ithnin et al. [35]. The swift separation of emulsion fuel hindered the comprehensive analysis and documentation of its properties in both studies. Consequently, the inherent limitations stemming from the rapid emulsion separation precluded the elucidation of key fuel characteristics. To address this challenge, the research employed a strategic approach to minimizing the fuel line distance from the mixer to the fuel pump. This design aimed to mitigate emulsion changes during transit, ensuring that the emulsion fuel remained relatively homogeneous upon reaching the fuel pump.

The duration of emulsion stability was identified as a critical factor, with the quantity of water playing a pivotal role in determining emulsion longevity. Research conducted by Suryadi et al. [36] corroborates this observation, demonstrating that lower water content contributes to prolonged emulsion stability. While Suryadi et al. focused on emulsion as a binder, their findings offer valuable insights into the general behavior of emulsion stability, providing a foundation for understanding the impact of water content on the emulsion's resilience. Despite the experimental context centered on emulsion as a binder, the study's outcomes resonate with broader implications for emulsion stability in fuel applications.

3.3. *Engine Performance*

A comparison of the performance between variations of diesel fuel and emulsion fuel, as well as the phenomena that occurred during the research, will be discussed in this section. Some of the parameters that will be discussed are torque, shaft power, and break-specific fuel consumption (BSFC).

3.3.1. *Engine Torque*

The torque graph of both diesel fuel and emulsion fuel had the same trend, where the torque value decreased with increasing engine speed, as shown in **Figure 5**.

The engine equipped with emulsion fuel exhibited diminished torque across all engine speeds in contrast to its diesel fuel counterpart.

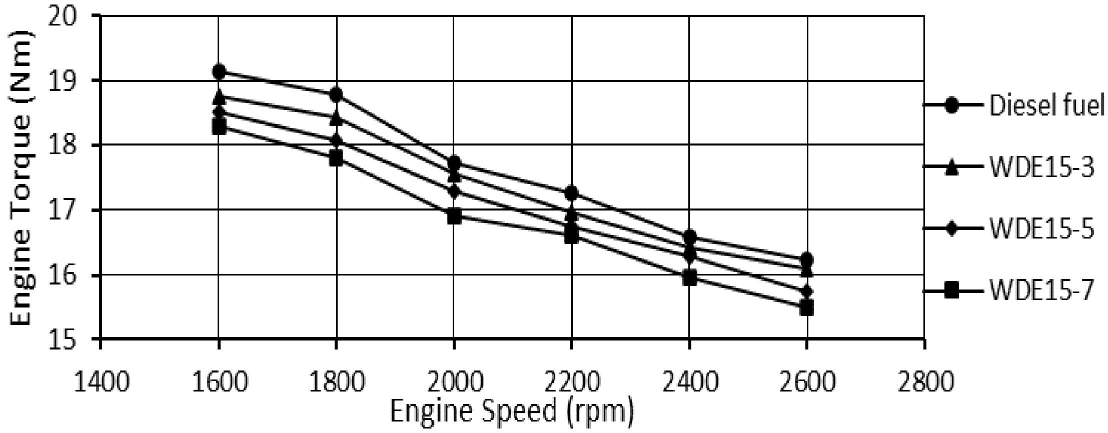

Figure 5. Engine torque of various fuels in different engine speeds

Specifically, the average reduction in torque for each emulsion fuel variant was quantified as 1.37% for WDE15-3, 2.88% for WDE15-5, and 4.40% for WDE15-7. This discernible decrease in torque levels can be primarily attributed to the lower heating value inherent in emulsion fuel when compared to diesel fuel. The reduced heating value of emulsion fuel results in a slight deficit in the energy released during the combustion process. Consequently, this deficiency in available energy manifests as a tangible reduction in torque across the varied engine speeds tested.

The observed torque reduction underscores the critical influence of fuel heating value on engine performance, elucidating the nuanced interplay between fuel composition and combustion dynamics. The intricacies of emulsion fuel combustion, characterized by a lower energy release, contribute to the discerned torque disparities when compared to the reference diesel fuel. This nuanced understanding of torque variations between emulsion and diesel fuels contributes to a broader comprehension of the intricacies associated with alternative fuel sources and their implications for internal combustion engine performance.

In a parallel investigation, Hasannuddin et al. [32] conducted a study focusing on the torque characteristics of emulsion fuel utilization, comparing it to traditional diesel fuel. The findings revealed consistently lower torque values across various engine speed conditions when emulsion fuel was employed. Specifically, the average reduction in torque for each emulsion fuel variant was observed as 1.37% (WDE15-3), 2.88% (WDE15-5), and 4.40% (WDE15-7). This decrease in torque can be attributed to the lower heating value of emulsion fuel compared to diesel fuel, as documented in previous research [37]. The study utilized a single-cylinder diesel engine, adopting a methodology consistent with the present investigation, thereby enhancing the comparability of results.

The reduction in torque values underscores the impact of the emulsion fuel's lower heating value on engine performance. The study's findings align with the broader understanding that the incorporation of emulsion fuels, particularly those with a 10% water content, leads to a discernible decline in torque. This insight contributes to a nuanced understanding of the relationship between emulsion fuel composition and its consequences on engine dynamics. Consequently, the investigation by Hasannuddin et al. augments the body of knowledge regarding the torque implications of emulsion fuel adoption, offering valuable insights for the optimization of emulsion fuel formulations in the pursuit of enhanced engine efficiency.

Another investigation into emulsion fuel was undertaken by Sakhrieh et al. [38], wherein emulsion fuel comprising 25% water and 2% surfactant was utilized. The experimental setup involved a 4-cylinder diesel engine with a capacity of 1,450 cc. Employing the load change test method, the research incorporated rotational variations spanning 1,000 rpm to 3,000 rpm at 500 rpm intervals. The emphasis of the investigation was on assessing the impact of water content on engine performance, particularly torque output.

The outcomes of the study revealed a notable correlation between water content and torque. Beyond a water content threshold of 5%, a discernible reduction in torque was observed. This finding underscores the sensitivity of engine performance to higher water concentrations in emulsion fuel, providing valuable insights into the optimal balance between water inclusion and torque efficiency. Additionally, the utilization of a systematic load change test method, coupled with a comprehensive range of rotational variations, allowed for a nuanced examination of the intricate interplay between emulsion composition and engine behavior. These findings contribute to the ongoing discourse on emulsion fuel formulations, offering nuanced insights that can inform the development of emulsion fuels with optimized performance characteristics.

3.3.2. Engine Power

Shaft power, a critical parameter in the performance analysis of internal combustion engines, is intricately linked to the interplay of torque and engine speed. The dynamic relationship between these variables dictates the resultant shaft power, making it imperative to comprehend their influence on the overall system. The impact of alterations in torque and engine speed manifests in the consequential modulation of shaft power. An elevation in engine speed, as visually depicted in **Figure 6**, is observed to yield a proportional augmentation in shaft power. It is noteworthy that this observed phenomenon is consistent across diverse fuel variations, underscoring the universality of the relationship between engine speed and shaft power. This empirical evidence establishes a foundational understanding of the intricate dynamics governing the power output of internal combustion engines across various fuel compositions.

The engine utilizing emulsion fuel consistently exhibited diminished shaft power across all engine speeds in comparison to conventional diesel fuel. The recorded average reductions were as follows: WDE15-3: 1.37%, WDE15-5: 2.88%, and WDE15-7: 4.40%. This phenomenon mirrors the previously observed diminishing torque, attributed to a decline in the calorific value of the emulsion fuel. In a study by Fahd et al. [39], a 4-cylinder diesel engine with a displacement of 2,494 cc was employed, utilizing a 10% water emulsion fuel. Engine speed varied from 800 rpm to 3,600 rpm in increments of 400 rpm. Findings from this research indicated that the shaft power for emulsion fuel was consistently lower than that of pure diesel fuel, attributed to the reduction in the calorific value of fuel combustion resulting from the addition of water to diesel fuel. This same trend was corroborated in a study conducted by Karim et al. [40] on a Ford diesel engine. Employing a changing load testing method with variations from 1,000 rpm to 4,000 rpm at intervals of 500 rpm and emulsion fuel comprising up to 20% water, a substantial decrease in shaft power of 19.8% was observed.

The rotational speed of the mixer blades exhibited a discernible impact on both the generated torque and shaft power. Examination of the research data revealed an inverse relationship between blade rotation speed and the produced torque and shaft power. This phenomenon can be attributed to factors such as water droplet size, micro-explosion occurrences, and ignition timing. Specifically, the size of water droplets proved to

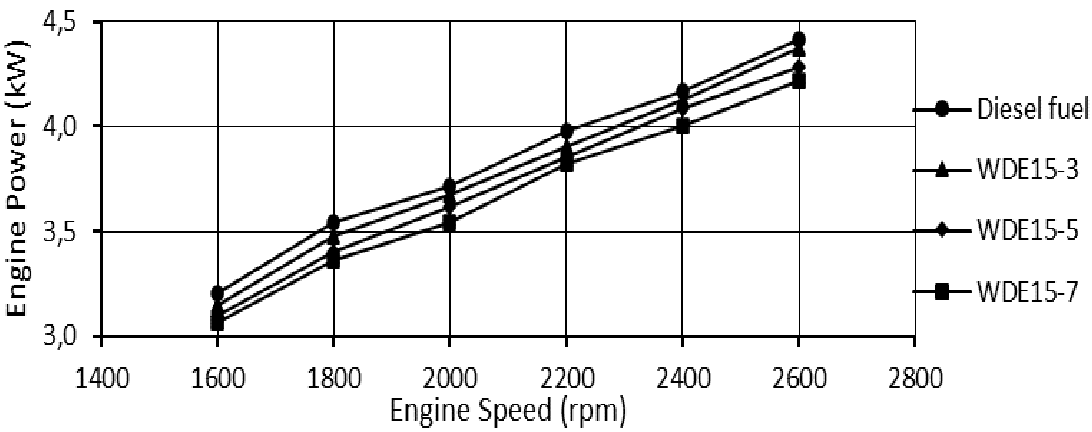

Figure 6. Engine power of various fuels in different engine speed

be contingent on the rotational speed of the mixer blades, with higher blade rotation resulting in smaller water droplet sizes [41]. As asserted by Tsukahara et al. [42], a reduction in water droplet size leads to diminished secondary atomization and a lower likelihood of micro-explosion events. Consequently, this reduction in micro-explosion occurrences contributes to a decrease in the heat release rate, ignition timing, and pressure within the combustion chamber, culminating in diminished torque and shaft power output.

3.3.3. Brake-Specific Fuel Consumption

The empirical findings derived from the research investigation distinctly illustrate a discernible pattern in fuel consumption dynamics across varying engine speeds. Specifically, the analysis revealed a noteworthy reduction in fuel consumption from an engine speed of 1,600 rpm to 2,000 rpm, followed by a subsequent increase in fuel consumption until the engine speed reached 2,600 rpm, as graphically depicted in **Figure 7**. Notably, this observed trend was consistent across all tested fuel variations. Consequently, a synthesis of these observations leads to the discerning conclusion that the optimum conditions for achieving the most economical fuel consumption manifest at an engine speed of 2,000 rpm. This key insight contributes valuable knowledge to the optimization of fuel efficiency within the specified operational parameters.

Koc and Abdullah [43] conducted research using a single-cylinder diesel engine with a capacity of 659 cc. The research used emulsion fuel with a ratio of 20% water. The test method used a changing load testing method with variations in engine speed of 1,200 rpm to 3,300 rpm with intervals of 300 rpm. The results showed the same trend as this study. Fuel consumption decreased until a certain engine speed, then increased again at a higher engine speed. This can happen because, at low engine speed, the heat loss from combustion to the cylinder is proportionally larger, so the combustion efficiency was worse and fuel consumption was higher for the produced power. At higher engine speeds, the frictional force increased with increasing engine speed, but the increase in power generated was relatively constant, if not smaller, so fuel consumption was higher. Another phenomenon that occurred was that emulsion fuel consumption increased when compared to the consumption of pure diesel fuel. According to Koc and Abdullah [43], this increase occurred because the energy value of the emulsion fuel was lower than that of pure diesel fuel.

Furthermore, the fuel consumption of emulsion fuel increased when compared to the consumption of diesel fuel. The average increases were: 6.43% (WDE15-3), 8.56% (WDE15-5), and 10.14% (WDE15-7). This phenomenon occurred because emulsion fuel had a smaller heating calorific value when compared to diesel fuel. Therefore, emulsion fuel will produce less energy. This will lead to a decrease in the generated output power and an increase in fuel flow rate, so the BSFC will increase.

Lin and Chen [44] conducted research on 15% water emulsion fuel in diesel engines. Emulsion fuel consumption had a higher value when compared to pure diesel fuel consumption. According to Lin, this happened due to a decrease in the calorific value of the emulsion fuel and an increase in the fuel flow rate, so the BSFC was increased. The absorption of combustion heat by the water contained in the emulsion fuel could also reduce the power output of the engine. Nadeem et al. [45] stated that the presence of evenly dispersed water in the emulsion fuel can be attributed to the finer fuel spray yield because the rapid evaporation of water will cause more combustion, so the BSFC of the emulsion fuel will increase.

The mixing speed (blade rotation) of the mixer on emulsion fuel also affects fuel consumption, as shown in **Figure 8**. This happens with the size of the water droplets and micro-explosion phenomena. The size of water droplets is greatly affected by the mixing speed; the higher the mixing speed, the smaller the water droplets. Meanwhile, the size of the water droplets will affect the performance. From this explanation, it can be concluded that water droplets on WDE15-7 had a smaller size than on WDE15-3. Research conducted by Tsukahara et al. stated that emulsion fuel with larger water droplets will have less fuel consumption. This phenomenon is because the size of the water droplets is larger, which would produce a stronger secondary atomization or micro-explosion and increase the heat release rate, so the power output will be greater.

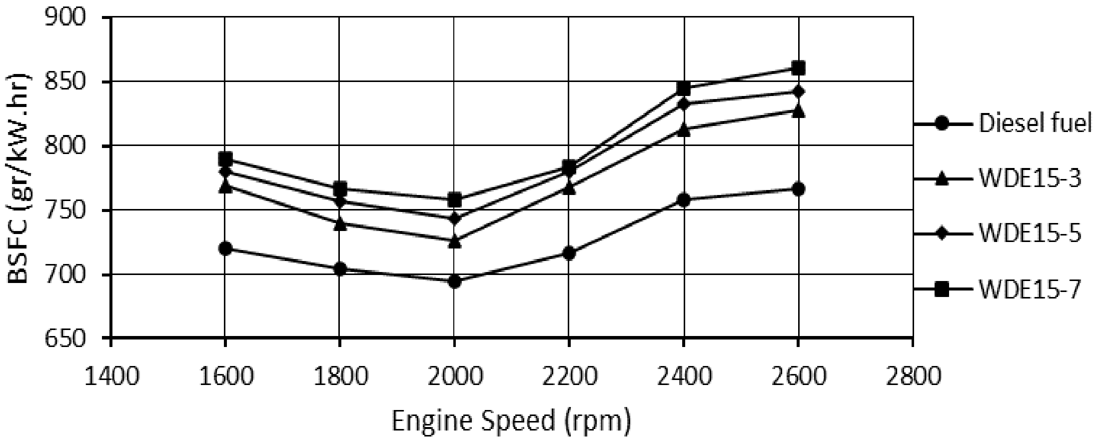

Figure 7. BSFC of various fuels in different engine speeds.

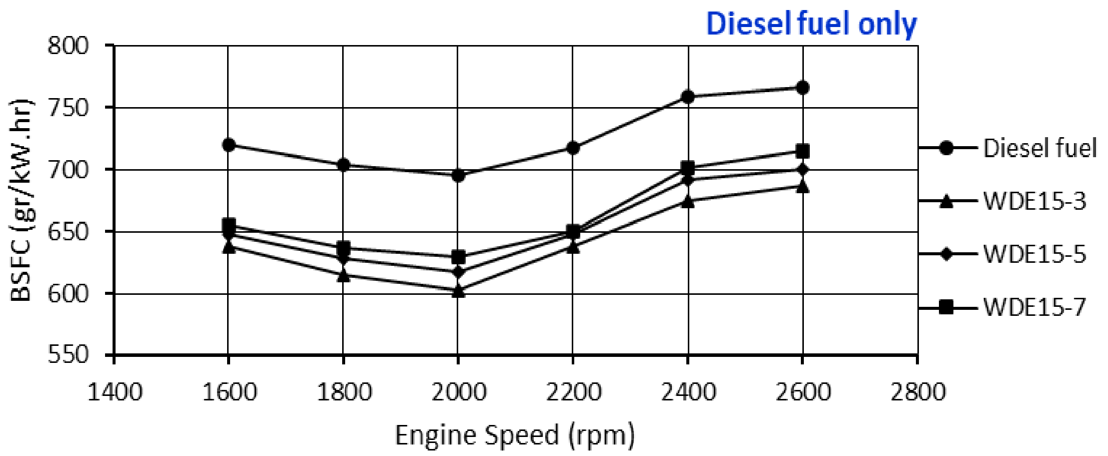

Figure 8. BSFC of various fuels in different engine speeds (diesel fuel only)

When considering only pure diesel fuel, the emulsion fuel consumption in this study is overall less when compared to diesel fuel only, as shown in **Figure 8**. The average decreases were: WDE15-3 (11.64%), WDE15-5 (9.88%), and WDE15-7 (8.57%). This decrease occurred because the water contained in the emulsion fuel was not counted as fuel consumption, so the large mass flow rate of the fuel in the calculation process was smaller.

According to Tsukahara, et al. [42], the cause of the reduction in fuel consumption of emulsion fuel is as follows: the effect of the micro-explosion phenomenon, the increase in the amount of air in the spray due to the increase in spray momentum, the addition of an excess fuel due to the delay in the ignition, the increase in the excess air ratio due to the water, the reduction of cooling losses due to lower combustion temperatures, suppression of thermal decomposition as a result of a decrease in combustion temperature, and the increase in the number of combustion gases due to the water in the emulsion.

3.4. Engine Emissions

3.4.1. Engine Emissions

The use of emulsion fuel showed an unfavorable effect on the resulting CO emissions. CO emissions increased with the use of all emulsion fuels, as shown in **Figure 9**. The highest increase occurred in the WDE15-7 fuel variation of 13.5%. Increased levels of CO emissions indicate that there was a decrease in combustion quality. The addition of water to the emulsion fuel reduced the calorific value of the fuel and increased the ignition delay, resulting in a decrease in combustion quality and an increase in CO emissions in exhaust gases [46]. In addition, the water in the emulsion fuel will increase the OH radicals. This OH radical causes an increase in the oxidation of carbon (C) to carbon monoxide (CO), so CO emissions will increase.

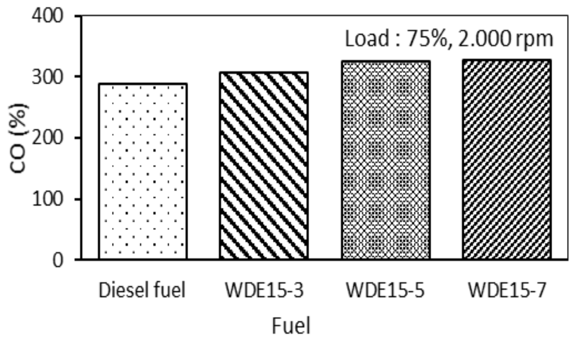

Figure 9. CO emissions of various fuels in constant engine load

The increasing CO emissions also occurred with variations in mixing speed. The research data showed that CO emissions increased slightly with increasing mixing speeds. The average increase in CO emissions for each emulsion fuel variation was 5.9% (WDE15-3), 12.8% (WDE15-5), and 13.5% (WDE15-7). The highest increase occurred in the use of WDE15-7 emulsion fuel.

The previous analysis stated that a higher mixing speed results in smaller water droplets. Small water droplets will produce more micro-explosions in the combustion chamber, which will cause the temperature in the chamber to be higher.

This higher combustion temperature will accelerate the oxidation reaction of CO to CO_2, so CO emissions will decrease [47]. Based on this statement, the use of WDE15-7 fuel should produce lower CO emissions because of the higher combustion chamber temperature. However, in reality, the produced CO emissions had a higher value when compared to WDE15-3 and WDE15-5 fuels. However, the OH radicals that are carried by water have a major role in the formation of CO emissions. If the distribution of OH radicals in the use of WDE15-7 fuel is more even, it will affect the increase in the oxidation of carbon (C) to carbon monoxide (CO), so carbon monoxide will be formed faster and cause more CO emissions. Because the speed of CO oxidation to CO_2 was not comparable with the oxidation of C to CO, there were still a lot of CO emissions that had not been oxidized, so WDE15-7 fuel CO emissions were still higher than other emulsion fuels.

3.4.2. NOx Emission

The results showed that emulsion fuel can reduce NOx emissions, as shown in **Figure 10**. The highest emission reduction occurred in the WDE15-7 fuel variation of 48%. This phenomenon is the same as the research that was conducted by Arbab et al. [48]. According to Ithnin, this phenomenon occurred due to the effect of decreasing the combustion temperature in the combustion chamber caused by the water content in the emulsion fuel. The high latent heat of the evaporation of water in the emulsion fuel will absorb heat during the combustion process, resulting in a decrease in combustion temperature. The endothermic reaction of the transition phase from water to steam that occurred in the combustion chamber caused a decrease in temperature in the combustion chamber [49]. Farfaletti et al. [50] stated that the decrease in temperature in the combustion chamber is a heat sink effect of the water content in the emulsion fuel, thereby reducing the formation of NOx emissions.

Alahmer et al. [51] stated that the decrease in temperature in the combustion chamber directly affects the formation of NOx, which decreases the rate of chemical reactions during the combustion process. Eq. (1) until Eq. (4) show the reaction of the Zeldovich mechanism:

$$N_2 + O + \overset{k}{\rightarrow} NO + N \tag{2}$$

$$N + O_2 + \overset{k}{\rightarrow} NO + O \tag{3}$$

$$N + OH + \overset{k}{\rightarrow} NO + H \tag{4}$$

where k is the rate of the chemical reaction for the formation of NOx, which is a function of temperature. The rate equation for a chemical reaction is formulated as Eq. (5).

$$k = Ae^{-E/_{RT}} \tag{5}$$

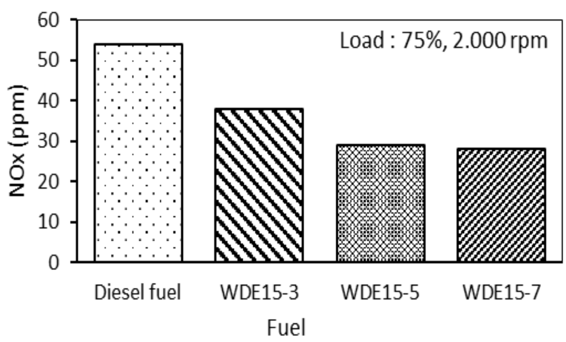

Figure 10. NOx emissions of various fuels in constant engine load

From the equation above, it can be seen that the reaction rate is affected by the reaction temperature (T), in this case, the combustion chamber temperature. If the reaction temperature decreases, the reaction rate will slow down. This will reduce the formation of NOx gas emissions.

The NOx emission reduction also occurred with variations in mixing speed. The data showed that NOx emissions decreased with increasing mixing speeds. This happened because high mixing speeds would result in smaller water droplets. The small droplet size causes the distribution of water droplets in the combustion chamber to be more even, so the secondary explosion phenomenon will result in better air-fuel mixing, and the resulting exhaust gas emissions will be better. A good air-fuel mixture means that hydrocarbons (fuels) and oxygen (O_2) react well to form carbon dioxide (CO_2). Meanwhile, the reaction between nitrogen (N_2) and oxygen (O_2) will be less, so the NOx formed will be reduced. The micro-explosion phenomenon will be more difficult to occur in smaller water droplets. This will cause the ignition timing to be reversed. The delay in ignition timing will cause the combustion process and NOx formation reactions to be shorter, so that the NOx emissions formed will be reduced.

In general, an interesting phenomenon to discuss is that the higher mixing speed will result in lower shaft power and NOx emissions. Based on the results of the analysis and discussion of shaft power and NOx emissions above, the higher the mixing speed, the smaller the water droplets. The small water droplets will result in a more even distribution of water droplets. Moreover, the phenomenon of micro-explosion is more difficult to occur, so the secondary atomization is weaker. This causes a delay in the ignition timing, so the heat release rate becomes smaller and the combustion process becomes shorter. A small heat release will produce less shaft power, while a short combustion process will produce smaller NOx emissions.

4. Conclusion

There's a direct correlation between adding water to a fuel mixture and a decrease in performance, an increase in brake-specific fuel consumption, a reduction of NOx emissions, and an increase in CO emissions. The mixing speed also contributes to a 1.37–4.40% decrease in power. 6.43–10.14% increase in BSFC, 5.9%–13.5% increase in CO, and up to a 20–48% reduction in NOx. The stability level of WDE at 15% at 3,000 rpm was indicated by the separation of water from diesel fuel after 1.5 minutes. The best BSFC diesel fuel and WDE 15% were obtained at 2,000 rpm engine speed. The best 15% WDE BSFC was obtained at 3,000 rpm blade rotation, with a 13.3% decrease in BSFC and a 1% reduction in power compared to diesel fuel. NOx WDE emissions decreased by 15% for blade rotations of 3,000 rpm, 5,000 rpm, and 7,000 rpm. The use of 15% WDE fuel at 3,000 rpm blade rotation could reduce NOx emissions by 30% in testing the engine for 2,000 rpm and 75% load. In the near future, mixer size and blade design need to be developed, so the required power becomes smaller. Furthermore, water is corrosive to metals. Several engine components are made of metal, including the fuel filter, fuel line, fuel pump, injector, piston, inlet valve, exhaust valve, and cylinder liner. These components may be corroded by water, so it is necessary to research these components. There is still little research that discusses the durability or endurance test. This test can determine the effect of emulsion fuel on engine components as well as changes in performance after operating for a long duration, so this kind of research is needed to be conducted.

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Author's Declaration

Authors' contributions and responsibilities

The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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Availability of data and materials

All data are available from the authors.

Competing interests

The authors declare no competing interest.

Additional information

No additional information from the authors.

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