

ANALYSIS OF EMISSION CHARACTERISTICS OF A B35 WITH HYDROGEN PEROXIDE EMULSION WITHOUT SURFACTANTS

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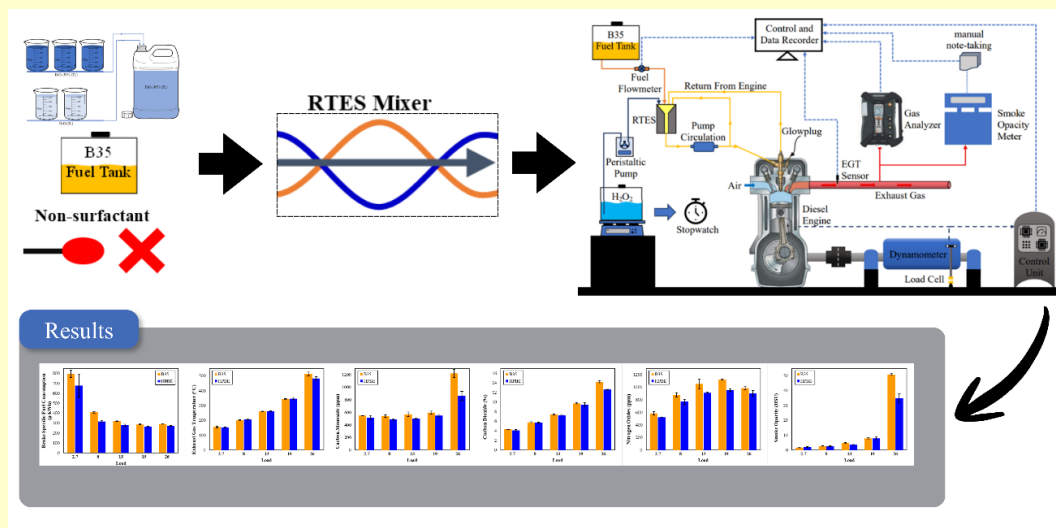
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Research Paper

Abstract

The use of hydrogen peroxide or H_2O_2 as a fuel additive is known to improve the combustion quality of conventional fuels, including Indonesia's biodiesel B35. Because H_2O_2 and B35 do not mix naturally, the H_2O_2 must be emulsified into B35 to ensure stable fuel delivery and consistent combustion. Conventional emulsification methods typically rely on chemical surfactants, which require a separate preparation step. This study therefore aimed to evaluate the effects of an H_2O_2 -B35 emulsion (HPBE) produced without surfactants on diesel engine performance and emissions. The emulsion was prepared using B35 as the base fuel and 10% (v/v) of 30% aqueous H_2O_2 as the dispersed phase. Emulsification was carried out using an inline mixer known as the Real-Time Non-Surfactant Emulsion Fuel Supply System (RTES). Engine tests were performed on a Kubota Z482 operating at a constant speed of 2800 rpm under loads of 2.7, 8, 13, 19, and 26 Nm, applied using a Cussons eddy current dynamometer. The parameters measured include Brake Specific Fuel Consumption (BSFC), exhaust gas temperature (EGT) as well as Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxide (NO_x) emissions, and smoke opacity. The results showed that, compared to B35, HPBE improved all measured parameters across all loads. BSFC decreased, with the maximum reduction of 22.9% occurring at 8 Nm. At full load, HPBE produced the maximum reductions in smoke opacity (31.3%), CO (29.5%), and CO_2 (11.2%). Meanwhile, the maximum NO_x reduction of 14.3% was observed at 75% load.



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Keywords: Biodiesel B35, Hydrogen Peroxide, In-line Mixing, Non-surfactant.

Introduction

Energy independence and environmental impact mitigation have become top priorities in Indonesia's national development policy. The Indonesian government has mandated the use of biodiesel B35, a blend of 35% palm oil biodiesel and 65% diesel, as a key strategy to reduce greenhouse gas emissions [1]–[5]. This implementation is increasingly crucial given that vehicle emissions data is now used as a baseline variable in modeling motor vehicle tax coefficients in Indonesia, which require compliance with stricter emission standards [6]. However, the use of B35 in conventional diesel engines often faces challenges such as higher viscosity and lower volatility, which affect atomization and combustion [7]–[11].

To address this issue, the use of oxygenator additives such as hydrogen peroxide or H_2O_2 has been extensively researched. According to research by Chebattina et al. [12], the use of H_2O_2 as a fuel additive has

the potential to significantly increase thermal efficiency and reduce emissions. Sanjeevannavar et al. demonstrated that adding H_2O_2 can increase Brake Thermal Efficiency or BTE and reduce Brake Specific Fuel Consumption or BSFC by providing additional oxygen, which accelerates the combustion reaction rate [13]. Furthermore, Subramani et al. explained that the presence of water in H_2O_2 triggers micro-explosions during the secondary atomization process, which breaks down fuel droplets into finer particles, thereby improving the efficiency of air-fuel mixing [14]. In addition to the micro-explosion mechanism, Mandal et al. stress that lower fuel density and viscosity have the potential to improve flow characteristics, spray quality, and atomization during injection, preventing the formation of large, difficult-to-ignite droplets [7].

Furthermore, ignition characteristics are also a determining factor in engine stability. Similarly, Vellaiyan explains that a higher cetane number has the potential to shorten the ignition period and ensure a more stable combustion process, minimizing the risk of combustion instability that often occurs with alternative fuels [15]. Regarding emissions, Moujдин et al., explained that the presence of hydroxyl radical groups (OH) from the decomposition of H_2O_2 and the secondary atomization phenomenon due to micro-explosions play a vital role in accelerating carbon oxidation and preventing the formation of fuel-rich zones, thereby effectively reducing smoke opacity and Carbon Monoxide or CO while the formation of Nitrogen Oxide or NO_x is influenced by the competition of thermal mechanisms [16]. While Chebattina et al., noted the risk of increasing NO_x due to oxygen enrichment, Vellaiyan emphasized that the cooling effect (heat sink) of the water content in the emulsion is able to absorb latent heat and suppress the peak combustion temperature, which has the potential to reduce the rate of thermal NO_x formation [12]. Furthermore, for Carbon Dioxide or CO_2 emissions, Vellaiyan, highlighted that the substitution of a portion of the hydrocarbon fuel fraction with non-carbon compounds effectively reduces the total carbon mass input into the cylinder (carbon dilution), which directly correlates with a decrease in the carbon footprint produced per unit of power [15].

On the other hand, the Exhaust Gas Temperature or EGT shows complex thermodynamic interactions. On the one hand, Vellaiyan stated that the water content in the emulsion acts as a heat sink through the absorption of latent heat of vaporization, which plays a role in reducing the peak combustion temperature [15]. However, Mohan & Dinesha reported an increasing trend in EGT when using H_2O_2 due to the exothermic reaction of peroxide decomposition and the over burning phenomenon. This indicates that the thermal characteristics of H_2O_2 emulsions depend on the dominance competition between the physical cooling effect and the intensity of chemical kinetics during the combustion cycle [17].

In this study, a blend consisting of B35 and 10% (v/v) of 30% aqueous H_2O_2 was selected for analysis. Previous studies on oxygenated additives have demonstrated the optimal feasibility of utilizing a 10% H_2O_2 concentration. According to research by Chebattina et al. [12], an addition of 10% H_2O_2 yielded the most favorable balance of improved engine performance and reduced emissions compared to 5% or 15% ratios. Furthermore, Moujдин et al. [16] concluded that concentrations between 5% and 10% are the most effective fractions for significantly mitigating smoke opacity and overall exhaust emissions. Higher concentrations, such as 15%, are not recommended as they induce an excessive cooling effect that ultimately sacrifices the engine's mechanical performance.

Despite offering many advantages, the use of H_2O_2 as an additive faces a major technical challenge, namely the instability of the mixture between the water and oil phases. According to Moujдин et al., conventional methods typically use chemical surfactants to maintain long-term emulsion stability, but this increases the cost and complexity of fuel formulation [16]. Furthermore, Oh et al. found that a separate water injection strategy to lower combustion chamber temperatures to reduce NO_x requires significant engine modifications [18]. As an alternative solution, Real-Time Non-Surfactant Emulsion Fuel Supply System (RTES) technology was developed to produce emulsions in situ using high shear mixing and ultrasonics just before injection [19], [20]. This approach eliminates the need for long-term stability and expensive surfactants, making the method more economical and practical [21]. However, its effectiveness on B35 blended fuel has not been thoroughly explored.

The application of RTES becomes an opportunity when dealing with B35. Compared to pure diesel, B35 exhibits significantly higher kinematic viscosity and density, which inherently deteriorates fuel atomization and accelerates phase separation. While conventional chemical surfactants struggle to stabilize highly viscous biodiesel-water mixtures without requiring large volumetric additions of stabilizers, RTES introduces high-shear mechanical forces capable of breaking down the viscous B35 matrix into fine emulsion droplets instantly. Furthermore, literature on the effectiveness of non-surfactant emulsion systems specifically applied to B35 fuel remains limited. This gap requires further empirical investigation to validate whether RTES can provide optimal emission mitigation while addressing the weaknesses of conventional methods.

Therefore, this study aims to analyze the effect of adding 10% (v/v) H_2O_2 -30% to B35 on engine emission characteristics without using surfactants. Emulsification using RTES and experiments were conducted by comparing B35 with HPBE at various engine load conditions and constant speed at 2800

rpm. The parameters measured include Brake Specific Fuel Consumption (BSFC), exhaust gas temperature (EGT) as well as Carbon Monoxide (CO), Carbon Dioxide (CO₂), Nitrogen Oxide (NO_x) emissions, and smoke opacity.

Research Methods

This study uses an experimental method to analyze the effect of adding 10% (v/v) H₂O₂-30% to B35 on engine emission characteristics without using surfactants.

1. Fuel

The base fuel used in this study was B35 supplied by Pertamina. Aqueous H₂O₂ with a concentration of 30% is used as an oxygenating additive. To obtain a 30% H₂O₂ solution, a 50% H₂O₂ stock solution was diluted with distilled water in a 3:2 volume ratio, as illustrated in Fig. 1. Physicochemical properties including density, viscosity, and calorific value are listed in Table 1. For experimental testing, B35 was emulsified using RTES with 10% (v/v) H₂O₂. The resulting emulsion mixture was named Hydrogen Peroxide Biodiesel Emulsion (HPBE). As shown in Table 1, B35's density at 15°C was measured at 854 kg/m³, which is higher than petroleum diesel (826 kg/m³). The measured kinematic viscosity at 40 °C was also higher at 3.6 mm²/s compared to 2.77 mm²/s for diesel. B35 shows a cetane number of 52.7, which is higher than that of diesel (51). Meanwhile, the aqueous H₂O₂ solution exhibits a high-density of 1143 kg/m³, a kinematic viscosity of 2.35 mm²/s, and a very high theoretical cetane number (150).

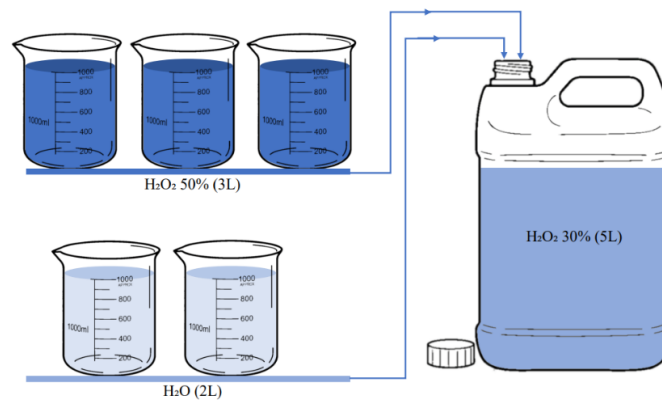


Figure 1. The process of making H₂O₂ 30% (5L)

Table 1. Properties of the emulsion components

Property	Unit	Diesel	B35	H ₂ O ₂ Aqueous Solution 30%	Mode of obtained
Density @15°C	kg/m ³	826	854	1143	Measured
Kinematic Viscosity @40°C	mm ² /s	2.77	3.6	2.35	Measured
Cetane Number	-	51 [22]	52.7 [7]	150 [12]	Referenced
Flash Point	°C	55 [23]	82.5 [24]	-	Referenced

2. Experimental Setup

Fig. 2. illustrates the experimental study using a Kubota Z482 diesel engine (Table 2.). This engine was coupled to a Cussons' eddy current dynamometer. The parameters measured include BSFC, EGT as well as CO, CO₂, NO_x emissions, and smoke opacity. The experiment started with the warming up using B35 to a temperature of 60°C at 2800 rpm. The engine was then tested at loads of 2.7, 8, 13, 19, and 26 Nm. At each load, the engine was conditioned for 2 minutes to ensure that steady-state operation was achieved before measurements were taken. The BSFC is obtained from the total mass flow divided by the brake power, referred to in Eq. (1).

$$BSFC = \frac{\dot{m}_{B35} + \dot{m}_{H_2O_2}}{Brake\ Power} \quad (1)$$

The mass flow of B35 ($\dot{m}_{B35}$) was measured directly using a fuel flowmeter, while the mass flow of H₂O₂ ($\dot{m}_{H_2O_2}$) was determined by recording the reduction in H₂O₂-solution's mass using a digital balance over a 5-minute period. B35 were used as baseline for HPBE's exhaust gas emissions. The emissions were measured using a Testo 350 gas analyzer to determine the concentrations of NO_x, CO, and CO₂. The sampling probe is positioned close to the engine outlet to maintain a high gas temperature for more accurate readings. Meanwhile,

smoke opacity was measured using an AVL 493 opacimeter, and EGT is measured using a heat sensor located in the exhaust system. Table 3 shows the range and uncertainty of each measurement device used in this study.

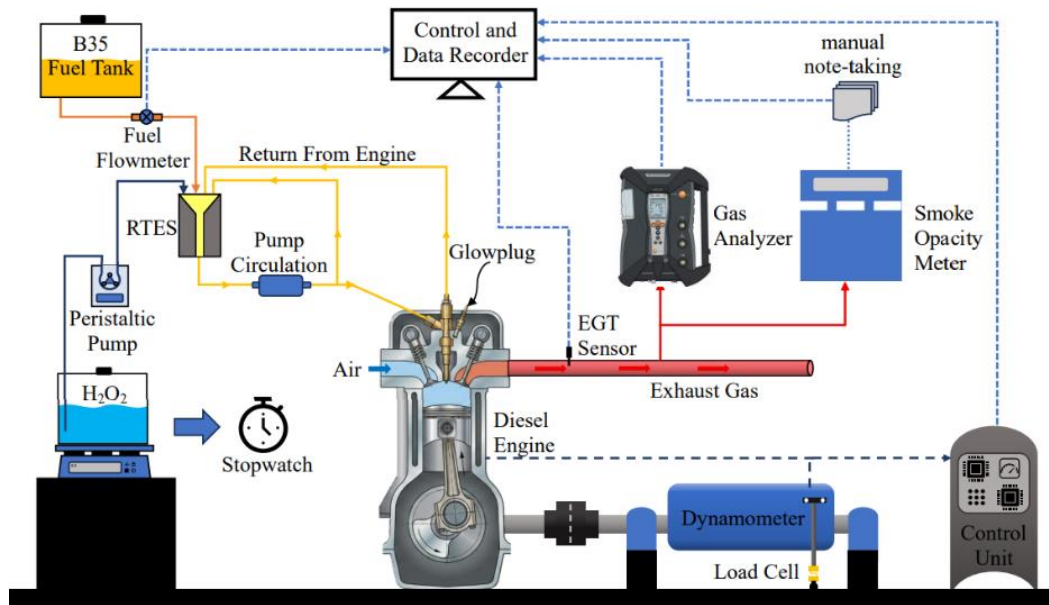


Figure 2. Schematic representation of the test setup

Table 2. Engine specifications

Parameter	Specification
Model	Kubota Z482
Type	Indirect Diesel Injection
No Cylinder	2
Bore x Stroke	67 x 68 mm
Displacement	479 CC
Max. Power	9.9 kW (13.3 HP) / 3600 rpm
Max. Torque	29.7 Nm / 2600 rpm
Cooling System	Radiator
Lubricating Oil Type	SAE 30
Weight	53.1 Kg

Table 3. Specifications and uncertainty of measurement instruments

Parameter	Range	Uncertainty
Dynamometer	-50-150 Nm	± 0.04%
	0-4000 rpm	± 0.06%
Fuel Flowmeter	0-60 l/hr	± 1.98%
Temperature	0-600 °C	± 0.3%
CO ₂ (IR)	0-40 vol% %	± 1%
CO	0-3000 ppm	± 1%
NO _x	0-3000 ppm	± 1%
Opacity	0-100% HSU	± 0.1%

3. Analysis of Uncertainty

To ensure the reliability and accuracy of the experimental data, an uncertainty analysis was conducted using the Root Sum Square (RSS) method. The percentage of uncertainty for each individual measurement instrument was obtained from the manufacturer's calibration specifications, as detailed in Table 3. The overall experimental uncertainty (U_{total}) is calculated by determining the root mean square of the individual uncertainties of the measuring instruments used during the engine testing, expressed by the Eq. (2)

$$U_{total} = \sqrt{\sum_{i=1}^n \sigma_i^2} \quad (2)$$

The overall experimental uncertainty was determined to be $\pm 2.65\%$. Since this value is well below the generally acceptable threshold of $\pm 5\%$ for internal combustion engine experiments [25], it validates the high accuracy, repeatability, and reliability of the experimental results presented in this study.

Results and Discussion

1. Brake Specific Fuel Consumption (BSFC)

The BSFC evaluation in Fig. 3. shows a significant performance improvement with HPBE compared to B35 across the entire load range. The BSFC decreases with increasing engine load, but HPBE consistently indicate lower fuel consumption for the same power output. The highest BSFC reduction was recorded at 8 Nm, where the BSFC decreased 22.9% from 410 g/kWh in B35 to 316 g/kWh in HPBE. This efficiency increase is most likely the result of micro-explosions and the high cetane number of H_2O_2 contributes to a reduction in ignition delay and enhances the combustion process. Sanjeevannavar et al. reported BSFC reductions of up to 25% with the use of additives that promote micro-explosions, as this mechanism increases the fuel-air contact surface area, resulting in more complete combustion [25]. Similar observations were reported by Vellaiyan, who found that emulsion containing additional oxygen improve thermal efficiency and reduce specific fuel consumption compared to neat diesel fuel [15].

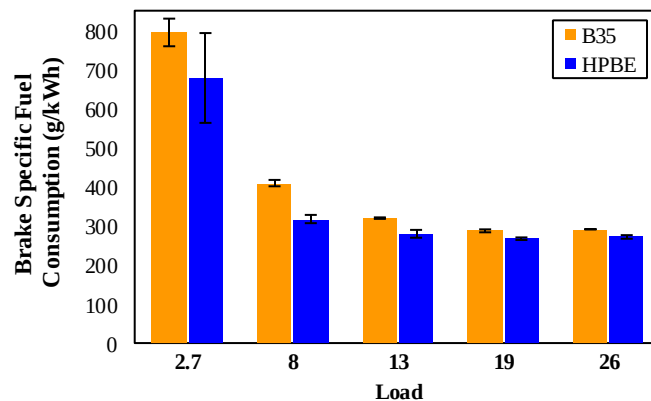


Figure 3. Brake specific fuel consumption

2. Exhaust Gas Temperature

The Exhaust Gas Temperature (EGT) profile exhibits a dynamic, nonlinear characteristic with changes in engine load, as illustrated in Fig. 4. At a load of 2.7 Nm, the EGT of HPBE is lower than that of B35. This decrease is likely due to the water content in the emulsion. Although the presence of extra oxygen potentially increases combustion temperature, the water content in H_2O_2 acts as a heat sink. This is consistent with the findings of Vellaiyan, who reported that the presence of water in emulsion fuel acts as a heat sink, absorbing latent heat and lowering combustion temperatures under certain conditions, [15].

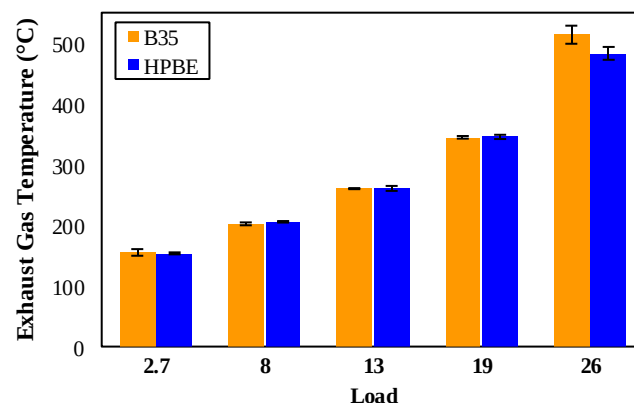


Figure 4. Exhaust gas temperature

On the other hand, in the medium load range of 8-19 Nm, the EGT trend reverses, with HPBE registering higher temperatures than B35. This increase is likely due to a shift in the dominant mechanism toward chemical kinetics. The thermal decomposition of H_2O_2 releases heat and provides additional oxygen, making the combustion process more efficient and robust. Furthermore, the presence of water prolongs the

flame delay period, shifting the primary heat release back to the expansion stroke. As a result, the combustion gases still have high enthalpy when the exhaust valve opens. The characteristic increase in EGT due to the addition of H_2O_2 is consistent with the results of a study by Mohan & Dinesha, which confirmed that increasing peroxide concentration correlates with an increase in exhaust gas temperature due to intensive oxidation reactions and afterburning [17].

However, at a load of 26 Nm, the EGT again shows a decreasing trend below B35. This is likely due to the cooling effect of the large volume of water, which again takes over the dominance of the chemical heating effect. At this operating point, the fuel mass flow rate reaches its maximum, which proportionally increases the mass of water injected into the cylinder drastically, effectively dampening the peaking combustion temperature. This temperature-lowering behavior at high loads due to water-based injection was also reported by Moujдин et al., who stated that H_2O_2 mixtures in diesel showed nearly 20–41% lower exhaust gas temperatures of loaded generators because H_2O_2 contains water particles, which interact with the coolant and absorb more heat, thereby lowering or controlling the exhaust gas emission temperature [16].

3. Carbon Monoxide (CO)

Fig. 5. shows a reduction in CO emissions across the entire load range when using HPBE, with a maximum reduction of 29.5% observed at 26 Nm compared to B35. This reduction is consistent with the observed BSFC trend, indicating that the amount of available carbon also reduces, resulting in a CO reduction in HPBE. Furthermore, the presence of H_2O_2 likely enhances the in-cylinder oxygen availability, promoting the conversion of CO to CO_2 through further oxidation reactions. Mohan & Dinesha also reported a CO reduction of up to 53.7% with the use of H_2O_2 , which facilitated more conversion of CO to CO_2 [17].

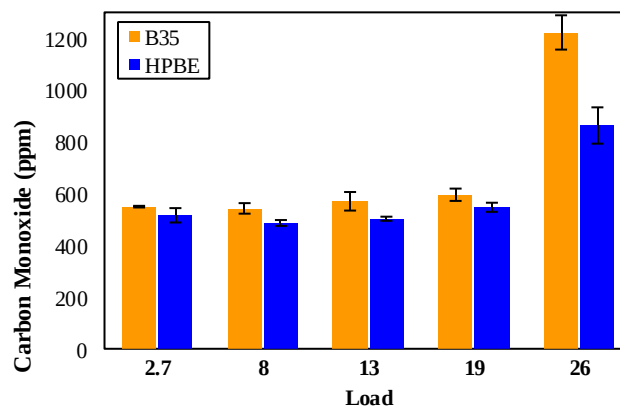


Figure 5. Carbon monoxide

4. Carbon Dioxide (CO₂)

Fig. 6. shows a consistent reduction in CO_2 emissions when using HPBE, with the most significant reduction reaching 11.2% at 26 Nm compared to B35. This reduction is likely a direct result of the reduction in BSFC, indicating that less fuel is used with HPBE and the addition of H_2O_2 reduces the amount of carbon in the fuel resulting in CO_2 production from HPBE being insufficient to match B35. Zhang et al., also reported a simultaneous reduction in carbon monoxide (CO) and carbon dioxide (CO_2) emissions due to increased combustion efficiency and the absence of carbon [26].

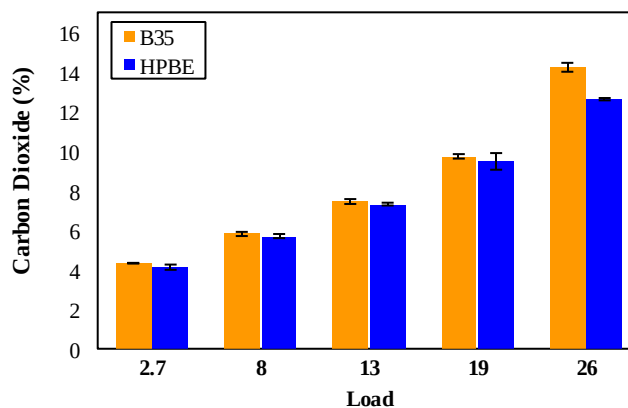


Figure 6. Carbon dioxide

5. Nitrogen Oxides (NO_x)

The NO_x emission profile analysis in Fig. 7. shows a decrease across the engine load range, indicating the effectiveness of HPBE in reducing NO_x. The largest decrease was recorded at a load of 19 Nm, reaching 14.3% compared to B35. This decrease is likely due to the shorter combustion duration caused by the additional oxygen supply from H₂O₂ which accelerates the combustion reaction rate which can then reduce the EGT such as at 2.7 Nm and 26 Nm. Although there is an increase in EGT at 8 Nm, 13 Nm, and 19 Nm, this shorter duration has the potential to shorten the thermal window for NO_x formation. This is in line with the report of Moujдин et al. where the addition of H₂O₂ in a diesel blend increases the cetane number, which precedes the reduction in ignition delay which lowers the peak temperature [16]. Elkelawy et al. also reported a decrease in NO_x after the addition of H₂O₂ [27].

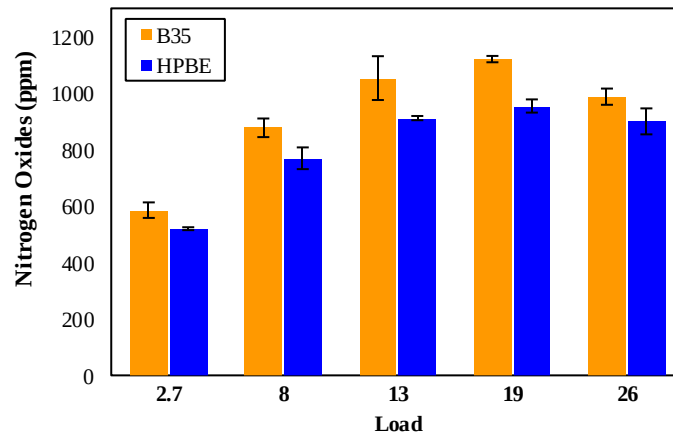


Figure 7. Nitrogen oxides

6. Smoke Opacity

Fig. 8. presents a comparison of smoke opacity between B35 and HPBE at various load levels. In general, the use of HPBE resulted in lower smoke opacity than B35, with the largest reduction reaching 31.3%, from 50.87% HSU in B35 to 34.78% HSU at a 26 Nm. This decrease in smoke opacity is likely due to the addition of oxygen and the presence of hydroxyl radicals (OH) from H₂O₂ which create micro-explosions thereby improving combustion performance. This is consistent with the report of Moujдин et al., who noted a decrease of up to 25% caused by excess oxygen content and an increase in the molar mass of OH radicals in the combustion chamber [16]. Vellaian also reported that micro-explosions break down fuel droplets into very fine sizes, thereby improving the efficiency of air-fuel mixing and effectively reducing smoke opacity [15].

At a load of 26 Nm, a significant increase was observed for both fuel types compared to previous loads. This increase is likely a characteristic phenomenon in diesel engines, where increased load demands a higher fuel flow rate, resulting in the formation of fuel-rich zones, thus triggering the formation of soot particles. Vellaian also reported that as engine load increases, fuel flow rate also increases, resulting in increased smoke opacity at higher engine load conditions [15].

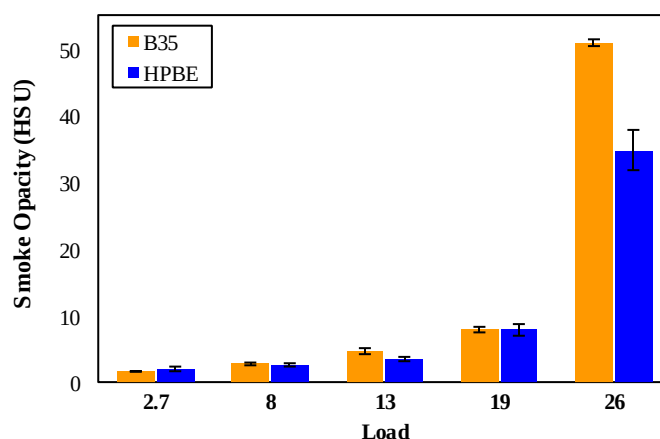


Figure 8. Smoke opacity

Conclusion

Based on the results of experiments conducted on a Kubota Z482 diesel engine using RTES, it can be concluded that the application of RTES is proven to be effective in facilitating stable combustion of HPBE emulsion without the need for chemical surfactants. The presence of H_2O_2 improves combustion quality through a micro-explosion mechanism and the provision of additional oxygen, which directly addresses the weakness of high viscosity in B35 fuel. Quantitative results show significant improvements in all measured parameters compared to pure B35. The use of HPBE reduces BSFC across the entire load range, with a maximum reduction of 22.9% at 8 Nm. Regarding emissions, the most optimal reduction occurs at 26 Nm, where HPBE is able to reduce smoke opacity by 31.3%, CO by 29.5%, and CO_2 by 11.2%. In addition, NO_x emissions are successfully suppressed with a maximum reduction reaching 14.3% at a load of 19 Nm. Exhaust gas temperature (EGT) shows dynamic behavior, but the cooling effect (heat sink) of water is again dominant at maximum load, which helps control combustion temperature. A strong correlation can be observed between the reduction in BSFC and the overall improvement in emission characteristics. A lower BSFC signifies that less fuel mass is consumed to produce the specific brake power, effectively reducing the total carbon input into the combustion chamber and minimizes the formation of unburnt carbon residues, directly correlating with the significant reductions achieved in CO, CO_2 , and smoke opacity.

The main contribution of this study is the confirmation that RTES can be a practical and economical solution to improve the efficiency of B35. While the long-term application of H_2O_2 has the potential to accelerate injector nozzle corrosion and cause lubricating oil dilution during long operating hours, based on the results of this study, the implementation of RTES significantly mitigates these risks by eliminating water pooling and phase separation in the main fuel production line, as the emulsion is generated entirely on-demand just before injection. This system has the potential to eliminate the complexity and additional cost of surfactant use while effectively reducing harmful emissions from diesel engines. For future research, it is recommended to conduct long-term durability tests to evaluate the impact of corrosion or wear on injector components due to the use of H_2O_2 without surfactants. In addition, further investigations into variations in H_2O_2 concentration and its effects at various engine speeds are needed to obtain the most optimal formulation.

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Declaration of Competing Interest

The authors declare no competing interests.

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