Article

Emulsifier-Free Water-in-Biodiesel Emulsion Fuel via Steam Emulsification: Its Physical Properties, Combustion Performance, and Exhaust Emission

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Abstract: The focus of this work is to investigate the effect of emulsifier-free emulsion fuel via steam emulsification (SD) to the diesel engine through physical properties, combustion performance, and exhaust analysis, and compare with conventional emulsion fuel with water percentages of 5% and 10% (E5 and E10) and biodiesel blend (B5). The SD was prepared using a custom 200 mL glass mixing column. The B5 fuel quantitatively was filled in the column, and then the steam was injected from the bottom of the mixing column through the porous frit glass with the pores ranging from 40 to 100 µm. The average water droplet size of SD is 0.375 µm with the average water percentage of 6.18%. The brake specific fuel consumption (BSFC) and brake thermal efficiency (BTE) of SD improved 4.19% and 3.92%, respectively, as compared to B5. The in-cylinder pressure (ICP) was lower than B5, however, yielding close to the B5 at 4 kW engine load. As for the exhaust emission test, NOx and PM for SD were reduced significantly with a percentage reduction of 25.22% and 10.68%, respectively, as compared to neat B5. The steam emulsification method offers a huge potential to be explored further as the concept offers the alternative method of making emulsion fuel without the use of conventional mechanical mixers.

Keywords: steam condensation; diesel engine; exhaust gas emission; water-in-biodiesel emulsion fuel; combustion characteristic

1. Introduction

Research interest in water-in-diesel/biodiesel emulsion fuel has grown exponentially worldwide. This is due to its significant impact on the exhaust emission, especially on the simultaneous reduction of nitrogen oxides (NOx) and particulate matter (PM). Recent studies focused on improving the quality of the emulsion fuel by the addition of nano-sized particles, which include metallic, nonmetallic, organic, oxygenated, and their combination. The results reported that the nanoadditive is able to improve the thermal physical properties, enhance the heat transfer rate, and stabilize the fuel mixtures [1]. Hasanuddin et al. [2] tested various nanometal additives blended into water-in-diesel emulsion fuel (WD) consisting of aluminum oxide (Al2O3), copper(II) oxide (CuO), magnesium oxide (MgO), manganese(IV) oxide (MnO), and zinc oxide (ZnO). The authors reported that WD blended with Al2O3 yielded the highest reduction of brake specific fuel consumption, up to 5.5%, as compared to neat WD. Sajith et al. [3] carried out an extensive investigation on a diesel engine fuelled with and without cerium oxide additives (CeO2), to study the performance and emission characteristics. They found that the
viscosity and volatility hold direct relations with the doping level of 20–80 ppm. The emission levels of HC and NO\textsubscript{x} are appreciably reduced with the inclusion of CeO\textsubscript{2}. Another study tested nanofluid emulsion, which consists of 50 and 100 ppm of TiO\textsubscript{2} nanoparticles blended in the orange peel oil biodiesel that are denoted as OOME-T50 and OOME-T100, respectively. The engine test results were compared with the neat biodiesel. The result reported that brake thermal efficiency (BTE) increased by 1.4% and 3.0% for OOME-T50 and OOME-T100, respectively, as compared to the biodiesel. In addition, a significant reduction of about 9.7%, 24.2%, 18.4%, and 16.0% in smoke, CO, NO\textsubscript{x}, and HC was observed for OOME-T100 nanoemulsion fuel [4]. Nevertheless, the drawbacks of inclusion of nanoadditives in WD are high cost and engines prone to technical issues after long-term usage, such as injector chocking and piston ring sticking [5].

Apart from that, the water-in-diesel/biodiesel emulsion has a major weakness that hinders the commercialization of the fuel, which is a stability issue. The stability of WD is strongly dependent on the surfactant that functions as a stabilizing agent by reducing the interfacial tension between water and oil [6]. However, once exceeding the stability period, the immiscible liquids will separate and will harm the engine system. Most of the studies conducted are towards finding the best stabilizing agent that is able to preserve its stability for a very long time [7]. Preetika et al. [8] conducted a detailed analysis of the stability of water-in-diesel emulsion fuel stabilized by a commercially available surfactant, Span\textsuperscript{®}80 and Tween\textsuperscript{®}80. The authors found that 10% of the surfactant was able to enhance time stability with no macroscopic separation, although the droplet size increases from 159 to 330 nm in 50 days.

Apart from fuel quality enhancement through nanoadditives and surfactant studies, there are a few studies heading toward a different research direction, which is producing WD without the presence of surfactant and/or additives, the so-called emulsifier-free WD or nonsurfactant emulsion fuel (NWD) [6,9,10]. This fuel is considered as unstable emulsion fuel when the fuel will reach to sedimentation within less than 60 s. The NWD was made by continuously mixing water and diesel through an in-line mixing system and directly supplied into the engine, thus eliminating the need for high-stability emulsion. Ithnin et al. [6] tested the NWD in a single-cylinder diesel engine through an in-line mixing system that consists of a combination of high-shear mixer and ultrasonicator. The result revealed that the NWD does give substantial improvement to the engine, with a 3.89% reduction in BSFC and 3.59% increase in BTE as compared to diesel fuel. PM and NO\textsubscript{x} decreased with a significant reduction of 16.33% and 31.66%, respectively. Another method of producing NWD was reported by Aizam et al. [9], by using a concept of rapid mixing through an internal mixing injector. However, this concept is applied to the burner system.

The drawback of producing NWD through a continuous rapid mixing method is the setup employed many components, among others, a pump, high-shear mixer, and ultrasonic transducer thus requiring additional maintenance cost to the engine. Sugeng et al. [11] have tested a new concept of making NWD by employing thermal energy carried by steam and found out that the emulsion possibly can be made without the use of a mechanical stirrer and/or ultrasonic transducer, yielding potential savings in costs. However, the constraint of the concept is that it is difficult to control the same condition of the fuel every time the fuel supplied to the engine, especially the water content. Apart from that, no detailed studies have been conducted to evaluate the physical properties and combustion characteristic of NWD via steam emulsification. From that motivation, this study aims to further investigate the effect of emulsifier-free emulsion fuel via steam emulsification (SD) to the diesel engine through the physical properties, combustion performance, and exhaust analysis, and compare it with conventional WD and biodiesel–diesel blend. The biodiesel blend used in the study is B5, where 5% palm oil methyl ester is blended with the neat diesel fuel (B5). A new prototype of steam emulsification has been developed with control parameters, such as flow rate and temperature for ensuring the consistent condition of SD supplied to the engine; it is installed close to the engine fuel feed system. In the present experimental work, the surfactant-added emulsions with 5% and 10% water content, denoted as E5 and E10, respectively, and are tested for comparison with SD. A single-cylinder,
direct injection diesel engine is tested under four different load conditions (1, 2, 3, and 4 kW) and with a constant engine speed of 2000 rpm. As for the engine combustion performance analysis, the brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder pressure (ICP) and rate of heat release (ROHR) are analyzed in detail. The exhaust emission analysis, on the other hand, covers the PM, NOX, CO, and CO2.

2. Experimental Setup and Procedure

2.1. Fuel Preparation

In the present study, SD was compared with surfactant-added emulsion fuel and biodiesel–diesel blend fuel. The surfactant-added WD was prepared using the conventional method by adding 5% and 10% water percentage to B5 and fuels denoted as E5 and E10, respectively. The Span®80 with a HLB (hydrophilic–lipophilic balance) of 4.3 was added at a concentration of 2% to stabilize the emulsions. The emulsion fuel was prepared by using a mechanical homogenizer at a propeller speed of 2500 rpm for 5 min. As for the biodiesel–diesel blend fuel, 5% of palm oil methyl ester blended with the neat diesel fuel (B5) was used.

SD was prepared using a custom 200 mL glass column with the schematics of the mixing column as illustrated in Figure 1. The experimental setup for the steam emulsification system is shown in Figure 2. As shown in Figure 1, the biodiesel was filled halfway up the column through the biodiesel inlet (2) to allow the fuel to exit through the side nozzle, and then the engine was run for 10 min. The steam was supplied at the bottom nozzle of the column through the steam inlet (4). The steam inlet (4) nozzle was attached with porous frit glass orifices with a P2 (P100) European standard mesh size (ISO 4793), as shown in Figure 3 P2 has pores ranging from 40 to 100 µm. A 400 W steam generator was used for the production of steam. Thermocouples were installed at the column’s body and the fuel feed system to monitor the emulsion temperature in the column and at the point of injection, respectively. After the 10 min warm-up, the steam was supplied to the column and bubbles of steam rose from the steam nozzle creating a turbulent mixing. Some steam leaves the bulk liquid uncondensed as vapor through the steam outlet channel (1), as shown in Figure 1. Accumulated water condensate at the bottom of the device was discharged from the mixer manually through the water discharge channel (5). As the temperature in the column stabilized at 80 °C, the measurements began. The fuel eventually cooled down during transport and reached the injector pump of the engine at 70 °C before the fuel was injected into the combustion chamber through the emulsion outlet channel (3).

Figure 1. Schematic diagram of the steam emulsification mixing device.
2.2. Fuel Properties Test

The fuel properties test of SD includes water droplet size and distribution, water percentage, calorific value, and viscosity. The water droplet size and distribution measurements were conducted.

Figure 2. Apparatus setup for steam-generated emulsion fuel.

Figure 3. Porous frit P2 in the mixing column.
2.2. Fuel Properties Test

The fuel properties test of SD includes water droplet size and distribution, water percentage, calorific value, and viscosity. The water droplet size and distribution measurements were conducted using a laser diffraction particle size analyzer SALD-2300. Calorific value and viscosity were measured using a CAL2k ECO Bomb Calorimeter and rotary viscometer. As for the water percentage measurement of SD, the distillation method was utilized. SD samples were taken during the engine tests at each incremental load of 1 kW. Conforming to the ASTM D95 standards, the samples were then distilled at 130 °C, just enough to remove the water from the emulsion. The water percentage is determined by calculating the weight of the fuel before and after the distillation process.

2.3. Engine Test Setup

The type of engine used in the test is a Yanmar TF90-M, 0.493 L single-cylinder, four-stroke, water-cooled, direct injection diesel engine. Other basic specifications of the engine are shown in Table 1. The dynamometer used in the experiment is a 10 kW eddy current KLAM RETARDER T10 with maximum torque up to 25 Nm at 3700 rpm. The accuracy for torque and speed sensor is ±0.25% and ±1 rpm, respectively. The BSFC of B5 and emulsion fuels were measured by using a 50 mL burette. The fuel consumption was then measured by measuring the time elapsed for the fuel to reach the 5 mL mark. The tests were repeated at least three times. As for the combustion characteristic analysis, a Kistler in-cylinder pressure sensor with Dewesoft Data acquisition system was utilized. The data logger is capable of recording a pressure measurement for every 0.1 degree of crank rotation increment. For each test, a continuous 50 cycle combustion pressure was recorded and reported after averaging them. The injection timing of the engine for the test was set constant to 18° (BTDC) for all engine loads (1–4 kW). As for the emission measurements, an ECOM J2KN gas analyzer was used for the measurement of NO\textsubscript{x}, HC, CO, and CO\textsubscript{2}. As for the measurement of the PM, a custom minidilution tunnel with a dilution ratio of 10 was used. The filter was used for trapping the PM was a Teflon filter (MILLIPORE FHLP04700) with a diameter and orifice of 47 mm and 0.45 µm, respectively. The PM concentration was determined by weighing the PM filter before and after the experiment. A schematic diagram of the minidilution tunnel is shown in Figure 4.

| Table 1. Specifications of the diesel engine. |
|------------------------------------------------|
| **No. of Cylinders** | 1 |
| **Brand** | Yanmar TF90-M |
| **Cylinder bore × stroke, mm** | 85 × 87 |
| **Displacement, L** | 0.493 |
| **Cooling system** | Water-cooled |
| **Maximum rated power output, kW** | 7.0 |
| **Maximum torque, kgf.m/rpm** | 3.4/1600 |
| **Rated engine speed, rpm** | 2400 |
| **Fuel injection pump, kg/cm\textsuperscript{2}** | Borsch type |
| **Injection pressure** | 200 |
| **Injection timing.** | 18 BTDC |
| **Compression ratio** | 18 |
3. Result and Discussion

3.1. SD Formation Observation

The sequence formation of SD via steam emulsification from 7 to 40 s duration is shown in Figure 5. As shown in the figure, by using the porous frit membrane for steam distribution, an interesting mechanism was observed. As the steam enters the mixing column homogenously by the help of the porous frit membrane, the steam turned directly into cloudy water droplets due to the high-temperature difference between steam and biodiesel at 20 s duration time. During the contact, some steam will condense and change its phase to liquid water droplets suspended in the dispersion. The phase change is called the warm condensation effect, a condensation process where the vapor temperature is higher than the sink. Later in the steady-state phase, as the temperature of the bulk emulsion approaches the steam temperature, a fraction of the steam bubbles reached the surface and created boiling effects, which agitated the emulsion bulk at 25 s duration time. At 40 s mixing time, a whitish milky color emulsion was formed in the mixing column indicating that emulsion had started to form homogenously. The agitation created by the steam ensures that the emulsion stays homogenous before it enters the engine fuel feed system. From the observation experiment, it is clearly shown that the emulsion fuel possibly can be formed without using any surfactant and mechanical mixers through steam emulsification.
Figure 5. Sequence formation of SD via steam emulsification.

3.2. Fuel Properties

The water content of SD that was measured by the distillation method is listed in Table 2. As shown in the table, the water content in SD was obtained with an average of 6.18% using the distillation method. The sample of SD was taken from every load condition (1 kW to 4 kW). The value of the water content of SD showed slight differences between each load; this is due to the difficulty in controlling precisely the rate of condensation of steam injected into biodiesel. The density, viscosity, and calorific value for all types of fuel are tabulated in Table 3. The viscosity of E10 was the highest compared to other fuels due to its highest water content. The viscosity of SD was measured at 70 °C since the fuel reached the engine fuel feed system was at that particular temperature caused by the high temperature of the steam. The viscosity of SD was the lowest as compared to other fuel, which was 2.2 mm²/s at 70 °C. However, as the temperature decreased to 40 °C, the viscosity equaled to that of E5, which was 4.6 mm²/s. This was due to the almost similar water content for both emulsions. As for the calorific value, all types of WD were lower than that of B5. However, when comparing calorific value between the emulsions, E5 was the highest, followed by SD and E10. It was clearly shown that the calorific value of the WD was reduced when the amount of water in the WD was increased. This was due to the presence of water that lowers the heating value of WD.

| Load (kW) | 1  | 2  | 3  | 4  | Average |
|-----------|----|----|----|----|---------|
| Water Percentage (%) | 5.99 | 6.34 | 6.27 | 6.13 | 6.18 |

Table 2. Water percentage of SD.

| Properties | B5 | E10 | E5 | SD |
|------------|----|-----|----|----|
| Density (g/cm³) | 0.86 | 0.88 | 0.87 | 0.87 |
| Calorific Value (MJ/kg) | 45.28 | 40.78 | 43.02 | 42.54 |
| Viscosity (mm²/s) @40 °C | 4.3 | 4.7 | 4.6 | 4.6 |

Table 3. Properties of fuels.

3.3. Droplet Size Distribution

The presence of the submicron droplets was confirmed by the droplet size distribution measurement using the Shimadzu SALD 2300, as shown in Figure 6. The measurements were
started 45 min after the preparation process. As shown in the figure, the distribution curves show a lognormal distribution with a mean droplet size of 0.375 μm for SD. The lognormal distribution in fine particles follows the Smoluchowsky model, where fine particles meet and coalesce [12]. As shown in the figure, a series of average droplet size is plotted at an interval of 15 min. The mean droplet size was increased, from 0.375 μm to 0.476 μm. The SD is considered as unstable emulsion fuel. Due to the absence of the surfactant, the dispersed water droplets tend to gather with each other. The droplets initially are separated by a thin film. Due to the attraction of the van der Waals forces, the thin film thickness rapidly decreased over a short period of time. Once the droplet film reached a critical value, it broke and lead to newly formed droplets to move to each other, forming a larger droplet [6]. However, the system employed the concept of continuously mixing biodiesel fuel with steam through an in-line mixing column before the produced fuel is directly supplied into the engine. Thus, the concept does not require high stability of emulsion for fuelling the engine.

![Droplet size distributions of SD.](image)

**Figure 6.** Droplet size distributions of SD.

### 3.4. Engine Performance

For the engine performance test, all types of fuels were tested at an engine speed of 2000 rpm with four different loads ranging from 1 to 4 kW applied on separate runs. Brake specific fuel consumption (BSFC), brake thermal efficiency (BTE), in-cylinder pressure (ICP), and rate of heat release (ROHR) for each fuel were analyzed and evaluated.

#### 3.4.1. Brake Specific Fuel Consumption

The brake specific fuel consumption (BSFC) of the engine, fuelled with B5, SD, E5, and E10 under varying load from 1 to 4 kW with a constant speed of 2000 rpm, is illustrated in Figure 7. As shown in the graph, the fuel consumption of all types of fuel shows a similar trend where the BSFC reduced as the load increased, indicating that the engine combats more efficiently at a higher load. When comparing the emulsions with B5, all WD consumed lower fuel usage with the average reduction of 8.14%, 4.19%, and 2.08% for E10, SD, and E5, respectively. The BSFC of WD was considered by taking only biodiesel as total fuel for all types of emulsion fuel, including E5, E10, and SD. By means, the amount of water
inside WD was not considered as fuel consumption. Although the energy content for all the WD is significantly lower compared to the B5, the WD consumed the fuel much less than the B5. This is due to the help of microexplosion phenomena that improve combustion efficiency [13]. Microexplosion is secondary atomization of the primary spray as a result of the rapid evaporation process of water that is initially contained in the oil drop, resulting in more surface area of the fine droplets that can be exposed to the air, leading to an improvement in the fuel and air mixing process [7]. E10 consumed the least amount of fuel, followed by SD and E5. This is because of the higher water content in the fuel as compared to the other WD. According to Jeong and Lee [14], the higher water content in the emulsion will create a longer and more intense microexplosion. Nevertheless, SD was still able to combust better compared to E5 and B5 due to higher water content. Other than that, the viscosity of SD is much lower compared to the other emulsions due to the higher temperature caused by the steam, resulting in improved spray atomization and broader spray angle. Consequently, this enhances the air–fuel mixing, thus improving the combustion.

![Figure 7. Brake specific fuel consumption versus load.](image)

3.4.2. Brake Thermal Efficiency

The brake thermal efficiency (BTE) of the engine fuelled with B5 and all types of WD with different loads ranging from 1 to 4 kW is shown in Figure 8. As shown in the graph, the brake thermal efficiency of all types of fuel increases as the load increases. Again, this is due to the improvement of engine combustion at high loads, which is in agreement with the finding from the BSFC result. The BTE of all types of WD is higher than that of B5 in all load conditions. Similar to BSFC, the calculation of BTE only considers the biodiesel as the total fuel. The BTE of E10 is reported to be the highest compared to B5 with 5.67% improvement, followed by SD (3.92%), and E5 (1.77%), though all the emulsions have lower calorific value than B5. A similar trend as in BSFC result, BTE of SD stands between E10 and E5, which is mainly due to the amount of water content in the emulsion that affects the onset and strength of the microexplosion. Other than that, the low viscosity of SD as compared to E5 and E10 also contribute to the improvement of the combustion efficiency through better fuel atomization and wider spray angle. In addition, the improvements of BTE for all WD also come from the ignition delay of the fuels. The detailed discussion on the combustion analysis is discussed in the subsection on combustion characteristics. The longer ignition delay during the combustion, the more fuel that can be physically prepared for the chemical reaction, leading to an increase in the rate of heat release.
3.4.3. In-Cylinder Pressure

Figures 9–12 show the in-cylinder pressure (ICP) for B5 and all types of WD with different loads ranging from 1 to 4 kW under constant speed. As shown in Figures 9–12, it is clear that at a low load condition, the peak pressure of all types of fuel rises a little late after TDC. Nonetheless, at a high load condition, the peak pressure starts to rise earlier. This is because, at a low load condition, less fuel is injected into the combustion chamber, thus producing a lower residual gas temperature and wall temperature, leading to a lower charge temperature at injection timing. As a result, the ignition delay increased and retards the start of combustion (SOC). At high engine load, the gas temperature inside the cylinder is higher due to the higher amount of fuel injected into the engine, promoting to shorten the ignition delay period and advancing the SOC [15]. Compared to B5, the peak of in-cylinder pressure of all types of WD is lower and rises later in all load conditions. The lower ICP for all WD is due to the lower energy content of the emulsions due to the small amount of fuel that is replaced with water. When comparing between the emulsions, E5 has the highest ICP, followed by SD and E10 at load condition of 1–3 kW. At 1 kW, the trace of ICP for SD is close to E10 while at 2 kW and 3 kW, the peak in-cylinder pressure of SD is slightly lower than that of E5. These may be due to unstable and inconsistent water percentage inside SD that formed through the steam condensation method. However, at 4 kW, SD combusts with the highest ICP, yielding closest to B5. This is due to the lower viscosity of SD that enhanced the fuel atomization at high temperature and load condition, thus improving the air–fuel mixing process, which results in higher peak cylinder pressure. In addition to that, the occurrence of microexplosion of the emulsion is advanced at a higher engine load condition. If the temperature is relatively high, the heat flux is larger, leading to the transference of a higher rate of heat transfer, and, hence, leading to a quicker onset of microexplosion [16].
Figure 9. In-cylinder pressure (ICP) traces for B5, E10, E5, and SD at 1 kW.

Figure 10. In-cylinder pressure traces for B5, E10, E5, and SD at 2 kW.
3.4.4. Rate of Heat Release

Figures 13–16 show the rate of heat release ROHR with traces for B5 and WD (E5, E10, and SD) at varied engine load conditions from 1 to 4 kW and constant speed of 2000 rpm. Rate of heat release is calculated through the following equation, which is based on the pressure data of the engine cylinder and the ratio of specific heat, $\gamma$, is set constant.

$$Q = \frac{\mu \rho \gamma}{\gamma + 1} + \frac{1}{\gamma} \frac{\mu \rho}{\gamma + 1}$$

Figure 11. In-cylinder pressure traces for B5, E10, E5, and SD at 3 kW.

Figure 12. In-cylinder pressure traces for B5, E10, E5, and SD at 4 kW.
calculated through the following equation, which is based on the pressure data of the engine cylinder and the ratio of specific heat, $\gamma$, is set constant.

\[ Q = \frac{\gamma}{\gamma + 1} P \frac{dV}{d\theta} + \frac{1}{\gamma - 1} V \frac{dP}{d\theta} \]

Figure 13. Comparison of the ROHR at 1 kW for various fuels.

Figure 14. Comparison of the ROHR at 2 kW for various fuels.
As shown in the figures, all fuels show the trend of its respective ROHR peak rises steadily as the load increases, confirming that the engine combusts more efficiently as the load is increased. Comparing the emulsions with B5, it is clearly shown that the SOC of all emulsions was delayed. The increase in ignition delay is due to the presence of the water in the emulsion, where the water forms latent heat during the vaporization process. Subsequently, it slows the rate of the temperature increment of the droplet. As a result, the physical delay increases. Simultaneously, the presence of water vapor reduces
the fuel concentration, resulting in an increase in the chemical delay. Both the chemical and physical delay increase in the overall ignition delay [17]. However, as the load increases, the ignition delay for all WD is shortened and almost similar to biodiesel, especially at 4 kW. Once again, this is due to the onset and strength of the microexplosion that is perceptible at a high load condition. Both SD and E10 produced higher ROHR as compared to B5, especially at 3 and 4 kW load. The microexplosion most likely caused this. The same effect did not show as clearly in the lower loads. This might be that at lower loads the effect of water quenching is more perceptible than the effect of the microexplosion.

3.5. Exhaust Emission

3.5.1. Nitrogen Oxides

Nitrogen oxides (NO\textsubscript{x}) emissions are among the major issues of diesel engines. Figure 17 shows the concentration of NO\textsubscript{x} of diesel engine fuelled with B5, E10, E5, and SD under different load conditions with constant speed. As shown in the graph, the concentration of NO\textsubscript{x} in all types of WD is greatly reduced compared to that of B5. E10 records the lowest concentration of NO\textsubscript{x} compared to B5, with an average reduction of 28.16% in every load condition, followed by SD (25.22%) and E5 (21.67%). It is clearly shown that NO\textsubscript{x} formation is reduced when the amount of water is increased. This is due to the high latent heat from the evaporation of water in the emulsion when it absorbs the heat during the combustion [18]. According to Farfaletti et al. [19], the combustion temperature is reduced due to the heat sink effect where the water content in the inner phase absorbs the calorific heat value of the emulsion, thus reducing the burning gas temperature inside the combustion. As a result, the generation of NO\textsubscript{x} was restricted. However, when comparing the fuels in each load, at 4 kW the NO\textsubscript{x} reduction for all the emulsions was lower compared to other loads. There was only 5.51%, 6.16%, and 7.09% NO\textsubscript{x} reduction for E5, SD, and E10, respectively, as compared to B5. This phenomenon is another proof showing that microexplosion helps the fuel to combust better at high load, causing the higher combustion temperature. Nevertheless, with the presence of water, WD still emits lower NO\textsubscript{x} as compared to B5.

![Figure 17. Concentration of NO\textsubscript{x} for B5, E10, E5, and SD under different load conditions.](image-url)
3.5.2. Carbon Monoxide

Figure 18 shows the concentration of CO for B5, E10, E5, and SD with different loads ranging from 1 to 4 kW under the constant speed of 2000 rpm. As shown in the graph, all fuels consistently show a similar trend, where the CO formation is significantly reduced as the load increased, evidence indicating the engine combusts more efficiently at a higher load condition. This is because, in the low load condition, the combustion is usually in the quenching and lean flame zones, resulting in the formation of more CO. All WD produced higher CO in all load conditions as compared to B5. The highest formation of CO is recorded at 1 kW where E10 emits the highest value, with 52.66% of increment followed by SD (41.84%) and E5 (37.7%). The main reason for the increment of CO in WD is due to the presence of water, which lowers the calorific value of the fuels. As a result, the combustion temperature decreased, resulting in shortened oxygenating time for the CO gas. In addition, the oxidation process of CO would freeze when the combustion temperature is lower than 1400 K, thus, retarding the conversion process of CO to carbon dioxide (CO₂) [20]. Furthermore, the longer ignition delay of the emulsions also contributed to higher CO. However, as the load increases, the increment of CO of emulsions as compared to B5 are reduced; at 4 kW, the E5, SD, and E10 produce 19.12%, 23.12%, and 34.77% higher CO, respectively, as compared to B5. At the higher engine load condition, the temperature is high enough to enhance the benefit of microexplosions, which affect its onset and the strength of the explosion, thus showing significant improvement in CO formation. As compared with the emulsions, SD emits a fair amount of CO, standing between E5 and E10. Other than the effect from the amount of water content in the SD, the lower viscosity of SD plays a significant role in reducing the formation of CO, which helps to improve the fuel atomization and evaporation during the combustion.

![Figure 18. Concentration of CO for B5, E10, E5, and SD under different load conditions.](image)

3.5.3. Particulate Matter

Figure 19 shows the concentration of particulate matter (PM) emissions for B5 and all types of WD at different engine loads ranging from 1 to 4 kW under the constant speed of 2000 rpm. A similar trend is shown in the graph where PM formation for all fuels is reduced as the load is increased, indicating better combustion at higher load. When comparing the emulsions with B5, it is clearly shown that the PM for all types of emulsions is lower. The PM concentration in E10 is recorded to be the highest formation of CO is recorded at 1 kW where E10 emits the highest value, with 52.66% of increment followed by SD (41.84%) and E5 (37.7%). The main reason for the increment of CO in WD is due to the presence of water, which lowers the calorific value of the fuels. As a result, the combustion temperature decreased, resulting in shortened oxygenating time for the CO gas. In addition, the oxidation process of CO would freeze when the combustion temperature is lower than 1400 K, thus, retarding the conversion process of CO to carbon dioxide (CO₂) [20]. Furthermore, the longer ignition delay of the emulsions also contributed to higher CO. However, as the load increases, the increment of CO of emulsions as compared to B5 are reduced; at 4 kW, the E5, SD, and E10 produce 19.12%, 23.12%, and 34.77% higher CO, respectively, as compared to B5. At the higher engine load condition, the temperature is high enough to enhance the benefit of microexplosions, which affect its onset and the strength of the explosion, thus showing significant improvement in CO formation. As compared with the emulsions, SD emits a fair amount of CO, standing between E5 and E10. Other than the effect from the amount of water content in the SD, the lower viscosity of SD plays a significant role in reducing the formation of CO, which helps to improve the fuel atomization and evaporation during the combustion.

![Figure 19. Concentration of particulate matter (PM) emissions for B5 and all types of WD under different load conditions.](image)
The reduction of PM in WD can be explained by the occurrence of microexplosions. The secondary atomization promotes the combination of fuel and air, which improves combustion efficiency and suppresses the formation of soot. The reduction of PM can also be attributed to the increase in the amount of hydroxyl (OH) radicals in the presence of water, which leads to the oxidation of soot precursor [21]. The increased concentration of OH radical weakens the formation of soot in the gas phase and restricts the soot growth rates [22]. However, SD still produced considerably lower PM as compared to B5 and E5. This is due to the lower viscosity of the fuel that helps to improve the spray atomization and evaporation. Other than that, the small water droplet size and distribution in SD promotes and enhances the onset and the strength of microexplosions.

![Figure 19. Concentration of PM for B5, E10, E5, and SD under different load conditions.](image)

### 3.5.4. Carbon Dioxide

The main product of the exhaust emission of a diesel engine is carbon dioxide (CO₂). The formation of CO₂ indicates complete combustion within the diesel engine. In general, incomplete combustion reduces the formation of CO₂ but increases CO concentration [23]. Figure 20 shows the concentration of CO₂ for B5, E10, E5, and SD under different load conditions. At low loads, the concentration of CO₂ for all types of WD is slightly lower than that of B5. Nevertheless, at a higher engine load condition, the formation of CO₂ in WD is slightly higher than that of B5. This indicates that, at higher load, the emulsions combust more efficiently compared to the low load condition. This is supported by the results shown in Figure 18, where the CO formation is reduced significantly as the engine operates at a higher load condition.
The concept of producing the emulsifier-free water-in-biodiesel emulsion fuel (SD) through the steam emulsification method was proven to work, as demonstrated by this research and elimination of the conventional mixing method. SD was successfully produced by injecting steam through the porous frit glass into the mixing column, which initially was filled with biodiesel. The steam emulsification process took 40 s before the homogenous SD started to form and directly supplied the engine fuel feed system. The average water droplet size of SD is around 0.375 μm with an average water percentage of 6.18%. From the engine performance results, it can be concluded that SD maintained the emulsion fuel benefits towards the environment and energy usage, where BSFC and BTE improved 4.19% and 3.92%, respectively, as compared to neat B5. The ICP was lower than B5, however, yielding close to the B5 at 4 kW engine load. The ROHR was slightly higher than B5 and the SOC shifted closest to B5 at higher engine load. As for the exhaust emission test, NOx and PM for SD were reduced significantly, with a percentage reduction of 25.22% and 10.68%, respectively, as compared to neat B5. However, the CO emission rises at a low load condition, and is significantly reduced closest to B5 as the load is increased.

Although in this study the emulsion can be produced via the steam emulsification method and comparable with conventional emulsion, the system requires high energy to produce the steam. In the present study, the energy to produce the steam was not considered as part of the load. However, if this energy is considered as the load, the SD would consume more fuel compared to the conventional emulsion. The research on SD is relatively new in the study of emulsion fuel, yet offers a potential to be explored further as the concept offers the alternative method of making emulsifier-free emulsion fuel without the use of the conventional mixers. Therefore, as for future research, the method of producing the steam taken from the engine heat waste can be explored further as it can significantly reduce the energy usage for the heating system.

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