

Analysis of emission and combustion behaviors of water-emulsified diesel with various water contents and droplet diameters

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Abstract

This study investigates the combustion and emission characteristics of water-in-diesel emulsified fuels, focusing on varying water content and droplet sizes. Emulsified fuels were prepared with water contents ranging from 2 to 24 vol% and droplet diameters of $<3\ \mu\text{m}$, $26.5\ \mu\text{m}$, and $39.8\ \mu\text{m}$, produced using both strong stirring and membrane emulsification methods. These fuels were tested in a single cylinder, air-cooled direct injection diesel engine at a constant speed of 2300 rpm. The results showed that increasing water content generally decreased engine output power due to reduced diesel fraction and latent heat effects. However, thermal efficiency improved up to 14 vol% for small droplets and 20 vol% for larger droplets, driven by an extended ignition delay and higher peak heat release during premixed combustion. Beyond these water content thresholds, thermal efficiency declined due to increased ratio of phase-specific combustion durations after and before CA50 i.e., burn ratio, leading to energy losses from prolonged diffusion-controlled combustion. Emission measurements indicated that higher water content reduced NOx and soot emissions but increased CO levels. This study concludes that emulsified fuels with larger water droplets and 20 vol% water content offer the best balance between thermal efficiency and emission reduction.

Keywords : Water-emulsified fuel, Thermal efficiency, Ignition delay, Burn ratio, Combustion phase

1. Introduction

Diesel engines are well-known for their fuel efficiency and economical performance, largely due to their high thermal efficiency, which is achieved through a high compression ratio. However, the combustion process in diesel engines generates emissions like soot and nitrogen oxides (NOx). These emissions pose a significant challenge, especially with the growing stringency of emission regulations. While technologies that modify the engine have been introduced to address this issue, the focus has shifted towards modifying the fuel itself. One promising approach is fuel emulsification, which shows potential in simultaneously reducing NOx and soot emissions while enhancing thermal efficiency (Armas et al., 2004; Takeda et al., 2008; Dan, 2016; Tentora and Fuchihata, 2019; Yahaya Khan et al., 2014; Abu-Zaid, 2004; Alahmer et al., 2010).

Extensive research has been conducted on emulsified fuels, particularly exploring the impact of varying water content. Abu-Zaid (2004) investigated the influence of water content in emulsified fuels on the performance of a single-cylinder, direct-injection engine. Water content in the emulsified fuels ranged from 5 vol% to 20 vol% with 5 vol% increments. Higher water content resulted in increased brake thermal efficiency. A significant average thermal efficiency increase of approximately 3.5% was achieved with 20 vol% emulsified fuel compared to diesel across the

engine speed range investigated. Increasing the water content also led to a reduction in brake-specific fuel consumption and exhaust gas temperature. Similarly, Alahmer et al. (2010) examined the performance and emissions of a water-cooled, four-cylinder diesel engine fueled with emulsified diesel containing water content ranging from 5 vol% to 30 vol%. The engine speed was varied from 1000 rpm to 3000 rpm. It was reported that usage of emulsified fuels resulted in reduced NO_x emissions and maintained or improved thermal efficiency under certain conditions compared to diesel. The highest average thermal efficiency increase was observed at a 5% water content due to increased brake power. NO_x emissions decreased with increasing water content at all engine speeds, and exhaust gas temperature decreased as well. However, emulsified fuel combustion emitted higher CO₂ compared to pure diesel across all engine speeds.

Fahd et al. (2013) conducted an experimental study on the emissions and performance of a 4-cylinder turbocharged diesel engine fueled with 10% water-emulsified diesel under different load conditions. They observed improved NO emissions throughout all load conditions, but higher CO emissions over diesel at low load conditions due to lower combustion temperature. The thermal efficiency of emulsified fuel was lower than that of diesel due to its lower calorific value.

While these reports provide insights into engine emissions and performance with emulsified fuel at varying water content, there have been inconsistencies in the results, particularly concerning thermal efficiency improvements (Khatri and Goyal, 2020). Different studies (Abu-Zaid, 2004; Alahmer et al., 2010; Fahd et al., 2013; Kannan and Udayakumar, 2009) report varying optimal water contents for efficiency enhancements. Factors such as engine load condition, engine speed, and base fuel type may contribute to these inconsistencies. One crucial factor is the water droplet size in emulsified fuel, which has been actively studied in spray flame and hot plate experiments, demonstrating its influence on micro explosion occurrence and intensity (Takeda et al., 2008; Suzuki et al., 2011; Fu et al., 2002). However, the influence of water droplet size on emulsified fuels in diesel engine studies remains limited. The occurrence of micro explosions in diesel engines is yet to be definitively proven, with differing views (Nakagawa and Tateishi, 1978; Zhang et al., 1989), but the water droplet size can affect the degree of water dispersion in emulsified fuels. Therefore, there is a need to investigate the influence of different water droplet sizes in emulsified fuels with various water contents to elucidate their effects on diesel engines. Furthermore, the optimal properties of emulsified fuel (water content and droplet size) that improve both engine emissions and performance have not been reported.

Hence, this research aims to clarify the optimal water content and droplet diameter in emulsified fuel that improve engine emissions and performance. Additionally, considering the limited studies on the combustion characteristics of water-emulsified fuels (Khatri and Goyal, 2020), this study focuses on analyzing heat release rate behaviors to clarify the combustion characteristics of emulsified fuels.

2. Experimental method

2.1 Surfactant selection

To achieve stability of an emulsion, which is thermodynamically unstable, the addition of a surfactant becomes crucial in the emulsification process. Surfactants play a vital role in reducing the interfacial tension between water and oil. The hydrophilic-lipophilic balance (HLB) value of surfactants holds significant importance in achieving a stable emulsion. The HLB value needs to be adjusted based on the intended application of the emulsion, as a higher HLB value indicates a greater hydrophilic tendency. To produce a water-in-oil (W/O) emulsion, an HLB value of approximately 3 to 6 is recommended (Griffin, 1949). This study employs a combination of two surfactants, Emasol O-10(F) and Emanon 4110 to achieve an HLB value of 6. The properties of the surfactants are tabulated in Table 1. The selection of surfactants and their respective volumes are determined based on the works of Mizutani and Taki (1981) and Mizutani et al. (2000), which investigated the effect of surfactant volume on the emulsion fuel's separation time and emulsification rate.

Table 1 Properties of surfactants.

Product name	Type	Composition	HLB Value
Emasol O-10(F)	Nonionic	Sorbitan monooleate	4.3
Emanon 4110	Nonionic	Polyethylene glycol monooleate	11.6

2.2 Emulsified fuel preparation

In this study, emulsification of a commercially available diesel with purified water in varying volumes was conducted to produce water-in-oil (W/O) emulsified fuels with different water contents and droplet diameters. A total volume of 2 vol% surfactants indicated in Table 1 was added to the diesel and stirred for a certain period. Subsequently, the desired volume of water was added and stirred for approximately 3 minutes as the final preparation step before emulsification. Two emulsification methods were employed:

1. The strong stirring method (STR) utilizing a magnetic stirrer, which involved vigorous stirring (2500 rpm) of the premix for over 6 hours, resulting in the creation of very fine water droplets.

2. The permeate membrane emulsification method, as illustrated in Fig. 1. A tube pump (EYELA RP-1000) was employed to force the mixture to flow through a porous glass membrane known as Shirasu Porous Glass (SPG). This method ensured the formation of emulsified fuels with uniform water droplets within the desired diameter range (SPG Technology Co., Ltd, 2013). SPG membranes with pore diameters of 30 μm and 50 μm , referred to as SPG30 and SPG50, respectively, were employed in this research. The dispersed water droplet diameters of the emulsified fuels are varied using the STR method and permeate membrane emulsification method using SPG30 and SPG50. The water contents are varied from 2 vol% to 24 vol% with the increment of 2 vol%, as shown in Table 2 below. It must be mentioned in this context that the emulsified fuels produced using STR methods, SPG30 membrane and SPG50 membrane will be indicated as STR, SPG30 and SPG50, accordingly.

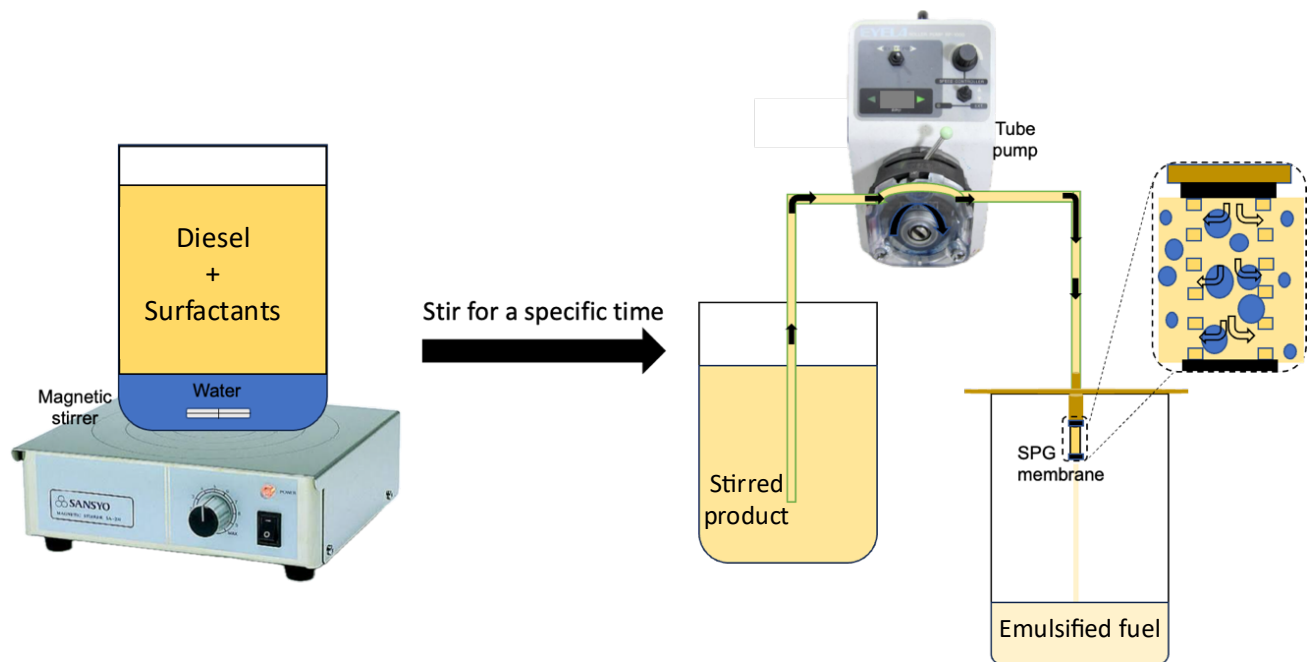


Fig. 1 Emulsified fuel production using permeate membrane emulsification method.

Table 2 Experimental conditions for emulsified fuel.

Fuel	STR	SPG30	SPG50
Diesel [vol%]	96, 94, 92, 90, 88, 86, 84, 82, 80, 78, 76, 74		
Emanon 4110 [vol%]	0.46		
Emasol O-10(F) [vol%]	1.54		
Water [vol%]	2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22, 24		

2.3 Engine and experiment details

The experiments were carried out using a YANMAR L70V-MEJ2, which is a single-cylinder, air-cooled direct-injection diesel engine. The engine was operated at a constant speed of 2300 rpm, and prior to the start of the experiment, engine heating-up procedures were performed until the engine oil reached a temperature of approximately 353 K. The specifications of the test engine can be found in Table 3. To ensure consistent fuel spray conditions throughout the experiments, the governor lever of the engine was fixed at an opening position of 7/8. For power measurement, a hydraulic dynamometer (Tokyo Plant PTB-30R-B) was connected to the engine crankshaft. The fuel consumption rate was examined using a ball-shaped burette connected to the fuel supply system. Two gas analyzers (HODAKA HT-1300Z and testo 330-LL) were employed to measure NO_x and CO emissions while the soot emission was measured using a smoke tester (BACHARACH True Spot). Figure 2 shows the experimental setup for this study.

Table 3 Specifications of test engine.

Model	YANMAR L70V6-MEJ2
Fuel injection system	Jerk pump driven direct injection
Displacement [cc]	320
Compression ratio	21.1
Operating speed [rpm]	2300

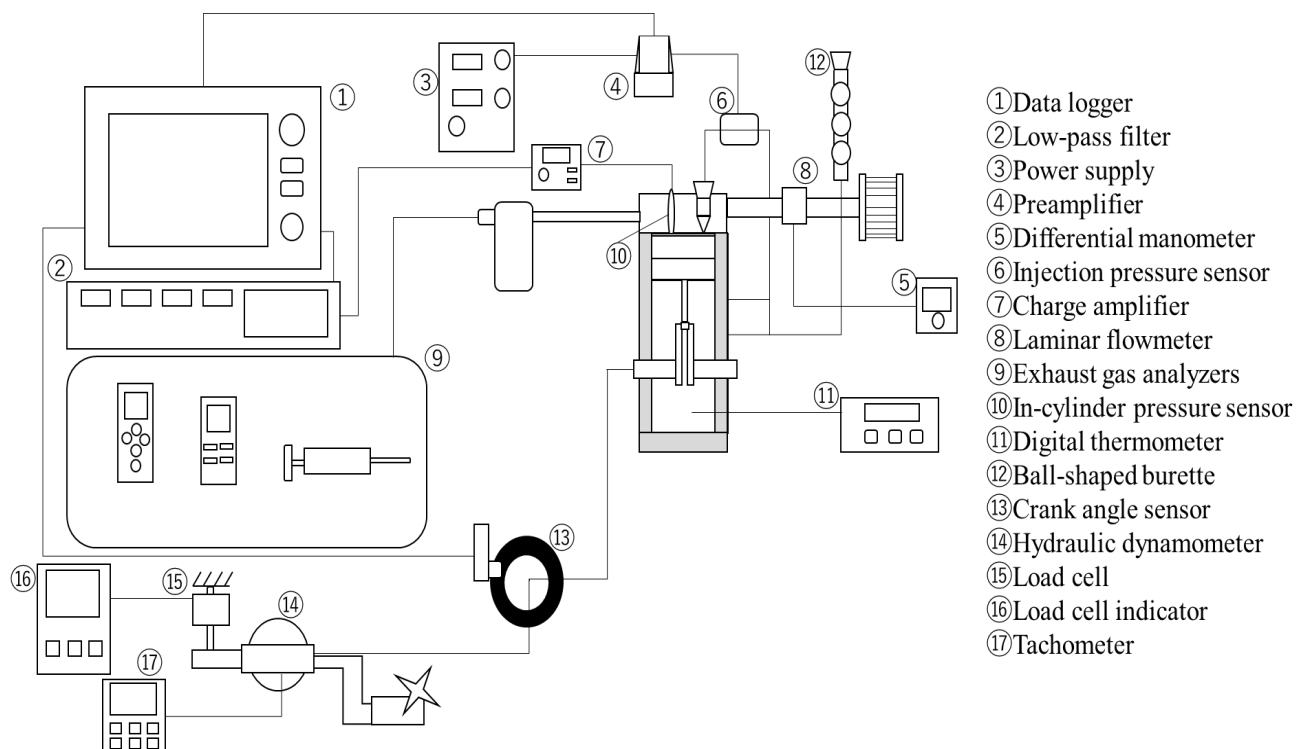


Fig. 2 Experimental setup.

2.4 Heat release rate

In this study, the combustion behaviors are analyzed by mainly examining the heat release rate, specifically focusing on the apparent rate of heat release (aRoHR). The aRoHR is determined based on the principles of the first

law of thermodynamics and could be expressed as Eq. (1).

$$\frac{dQ}{d\theta} = \frac{\kappa}{\kappa-1} p \left(\frac{dV}{d\theta} \right) + \frac{1}{\kappa-1} V \left(\frac{dP}{d\theta} \right) \quad (1)$$

where p stands for in-cylinder pressure, and V is defined as the volume of the combustion chamber. The temperature and composition-dependent specific heat ratio, κ , is calculated for each crank angle timing using the NIST-JANAF polynomials (Chase, 1998) while considering the global gas temperature and average gas composition.

2.5 Ignition delay and burn ratio calculations

2.5.1 Ignition delay

Figure 3 indicates the method used to measure the ignition delay. The ignition delay is measured by calculating the crank angle differences, $\Delta\theta$ from the start of injection (SOI) to the rising point of the heat release rate. Here, SOI is defined as the crank angle timing for the first pressure peak in the fuel injector, which should be constant for all conditions. $\Delta\theta$ is converted to ignition delay time using the engine speed.

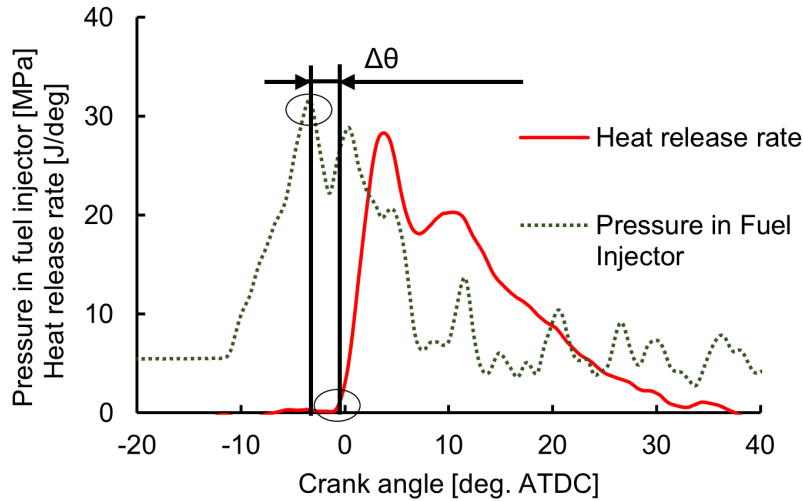


Fig. 3 Ignition delay measurement method.

2.5.2 Burn ratio

Willems et al. (2021) introduced the burn ratio (Rb) to characterize this feature as the heat release rate can exhibit either single stage or dual stages during reactivity stratification. Rb is defined as the ratio of the phase-specific combustion durations after and before CA50 and calculated by using the following equation. It was concluded that Rb correlates well with the gross indicated thermal efficiency (GIE) as well as combustion loss (Willems et al., 2021).

$$Rb = \frac{CA90 - CA50}{CA50 - CA10} \quad (2)$$

where CA90, CA50 and CA10 are crank angles at 90%, 50% and 10% of total heat release, respectively.

3. Results and discussions

3.1 Fuel formation results

Figure 4 shows the images of water droplets in diesel. The images were taken using a digital camera (Nikon, Nikon 1 J3) connected to a microscope (Kenko, KML-1500V). The microscope used was an optical microscope with a maximum magnification ratio of 1500. Regarding STR fuels, the water droplets are so fine that they cannot be seen clearly using a microscope. As the smallest pixel of water droplet diameter that was measured is 3 pixels (equivalent to $3.3\ \mu\text{m}$), $3\ \mu\text{m}$ is chosen as the representative SMD for STR fuels. The water droplet diameter distribution and SMD for the emulsified fuels are as indicated in Fig. 5.

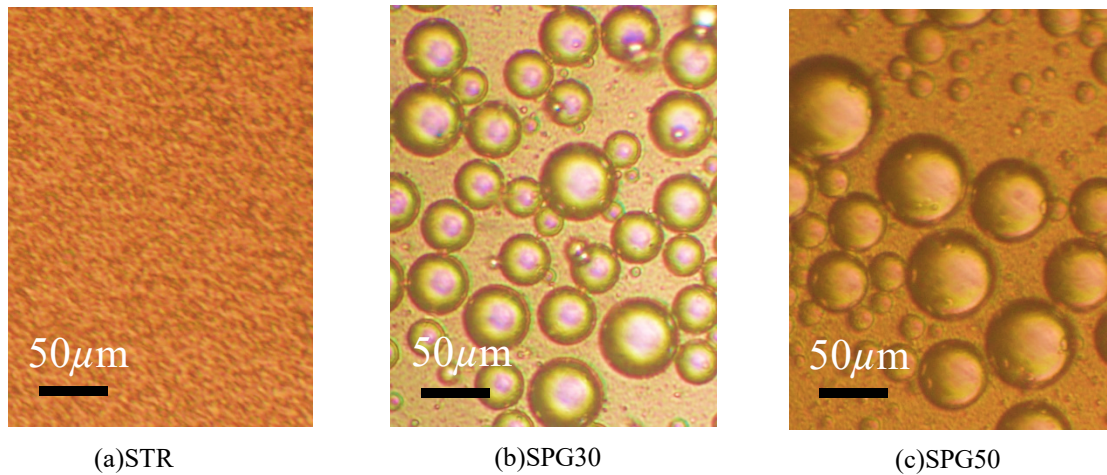


Fig. 4 Images of water droplets by optical microscope.

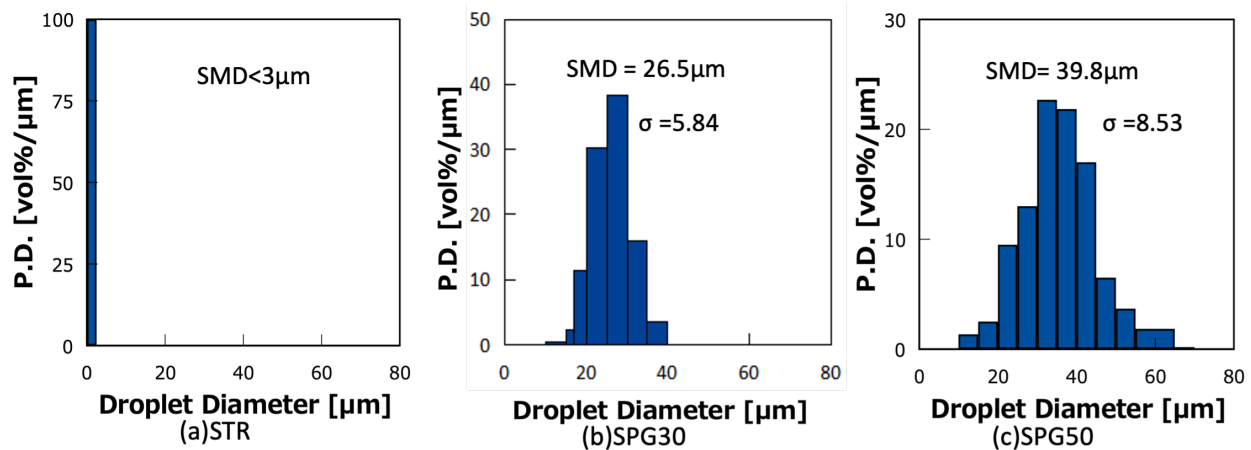


Fig. 5 Probability distribution (P.D.) of dispersed water droplets.

The distribution of water droplet sizes in emulsified fuels varies based on the emulsification method as can be observed in Fig. 5. The strong stirring method (STR) produces very small droplets, mostly under $3\ \mu\text{m}$, as stated previously. The porous glass membrane methods (SPG30 and SPG50) generate more uniform droplet sizes. SPG30, with $30\ \mu\text{m}$ pores, produces droplets with an average size (SMD) of $26.5\ \mu\text{m}$ and a tighter distribution, while SPG50, with $50\ \mu\text{m}$ pores, results in larger droplets (SMD = $39.8\ \mu\text{m}$) and a wider diameter range. Membrane emulsification offers better control compared to stirring, with smaller pores (SPG30) providing more consistent droplet sizes.

3.2 Influences of water emulsification onto engine performance

Low combustion temperature, long ignition delay and lower heat input of emulsified fuels can affect the engine performance. To better understand the relationship between water droplet size, water content, and these combustion behaviors, the engine performance was investigated while manipulating the water content and droplet diameters. The engine's operating speed was set at a fixed value of 2300 rpm, while the governor opening fixed at 7/8. This approach ensured consistent fuel injection conditions across all fuel variations in the jerk pump direct injection system. The fuel injection quantity was $12.6 \pm 0.5 \text{ mm}^3/\text{cycle}$. This study focuses on the output power and thermal efficiency as parameters to evaluate the engine performance. The results are illustrated in Fig. 6.

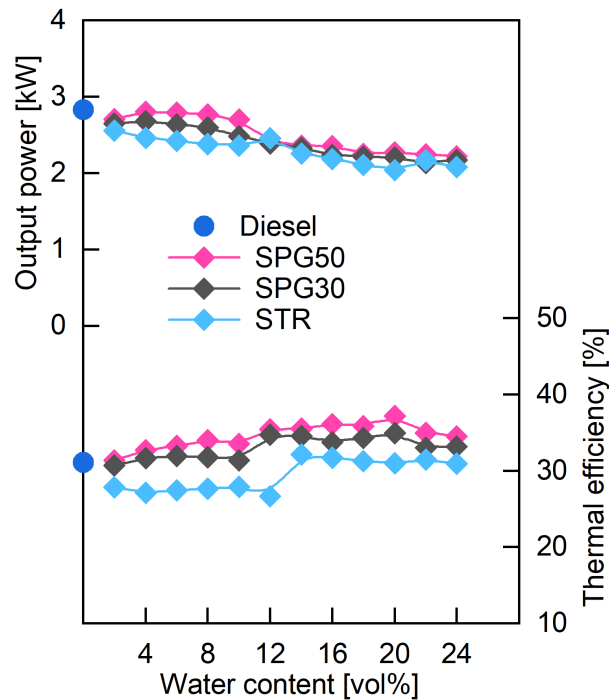


Fig. 6 Output power and thermal efficiency of emulsified fuels and diesel.

It could be observed that the output power decreases continuously for all the emulsified fuels when the water content is increased, with the most rapid decrement obtained for STR emulsified fuels, and retarded decrement is observed for the output power of SPG50 emulsified fuels. The decrement of power is due to the latent heat of water, which reduce the heat released and mainly due to the decrease of heat input due to lower diesel fraction.

Regarding thermal efficiency, an increasing trend was observed for all SPG30 and SPG50 emulsified fuels as the water content increased up to 20 vol%. In contrast, STR-emulsified fuels exhibited lower thermal efficiency compared to diesel, although an improvement was noted up to 14 vol% water content. Among the fuels tested, STR fuels showed the slowest increase in thermal efficiency, while SPG50 fuels displayed the most significant improvement. To better understand these results, the in-cylinder temperature, pressure, and heat release rate are illustrated in Fig. 7.

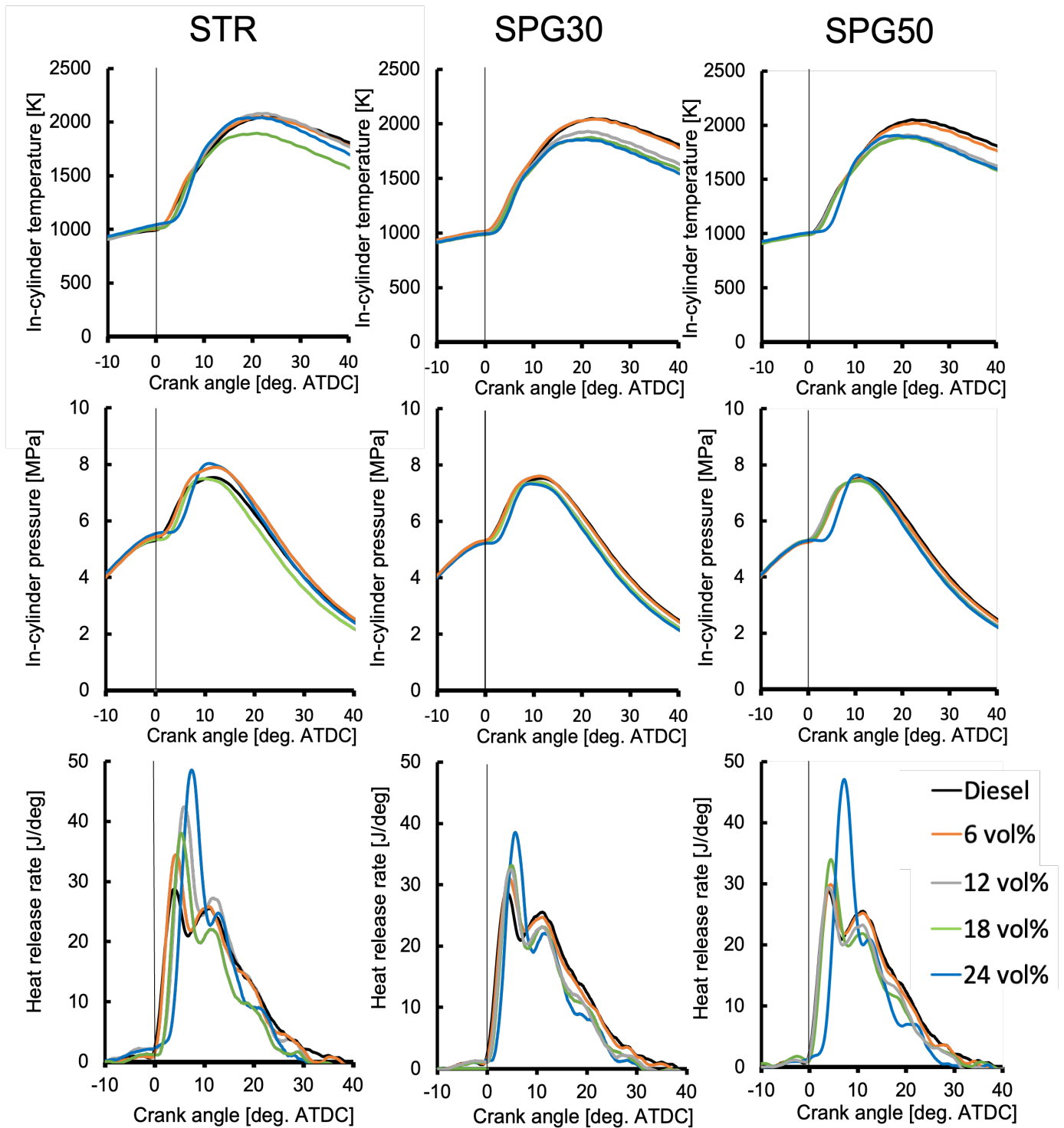


Fig. 7 Variations of heat release rate and average in-cylinder temperature versus crank angle of emulsified fuels.

3.3 Influences of water emulsification onto combustion behavior

Figure 7 shows in-cylinder temperature, pressure, and heat release rate during combustion for different emulsified fuels compared to pure diesel. From left, the combustion behaviors of STR, SPG 30 and SPG50 emulsified fuels are illustrated respectively. The x-axis represents the crank angle (CA). The upper part of the graph displays the in-cylinder temperature, the middle part shows the in-cylinder pressure, and the lower part represents the heat release rate. These parameters help illustrate the combustion characteristics of each fuel type as the engine operates. The heat release rate exhibits a dual stage for all fuels, in which the first peak is the heat release from premixed-like combustion, and the second peak is the diffusion-controlled combustion. Heat release rate rises earlier during diesel combustion than emulsified fuels due to higher net diesel and local temperature. The heat release rate for emulsified fuels with higher water content rises later because of the latent heat of the water and lower diesel content, which retard the ignition timing. It is difficult to evaluate the retarded ignition from Fig. 7; the ignition delay value is measured and plotted in Fig. 8 later. As the ignition is retarded, more fuel vaporizes and mixes with the surrounding air, ensuring more gaseous fuel during premixed-like combustion (Fahd et al., 2013; Badran et al., 2010; Chaudhari and Deshmukh, 2022). Therefore, a higher peak is observed during premixed-like combustion of emulsified fuels with higher water content.

In general, the delayed timing of the HRR peak as water content increases leads to a reduction in peak pressure. This delayed peak pressure reduces the engine's power output, especially as water content rises. In the case of 24 vol% water content, although the premixed combustion produces a significantly higher HRR peak, the ignition timing is too delayed, occurring as the piston is already entering the expansion stroke. As a result, despite the high peak pressure, the power output is reduced due to the late combustion. Among the emulsified fuels, STR demonstrates the highest peak pressures across all water content levels, which corresponds to its higher HRR peaks. This could be attributed to the slightly significant ignition delay of the STR fuels as will be explained later under the discussion for Fig. 8.

Increasing water content decreases the average in-cylinder temperature, with a significant decrease between 6% and 12%, especially in SPG30 and SPG50 fuels. Based on the decreasing magnitude, it could be concluded that the main reason for the temperature decrement is the reduction of diesel fraction, which significantly decreases the heat input. At the same volume, the latent heat of water only contributes to 6% of reduction from the calorific value of diesel. This decreasing temperature trend due to lower heat input describes the decrement of NO_x of all emulsified fuels. The high peak heat release rate during premixed combustion affects the in-cylinder temperature during the first half. This trend can be seen at a water content of 24 vol% for SPG50 and at several water content conditions for STR fuels. However, the low heat input and latent heat of the water as well as a lower peak during diffusion-controlled combustion eventually decrease the combustion temperature; hence the temperature shows a decreasing trend during the second half of combustion, in which higher water content emulsified fuels exhibit lower temperatures.

The increment of ignition delay due to the increment amount of water which results in more heat is absorbed during water vaporization is shown in Fig. 8. The effect of water droplet diameter is not significant until 12 vol% water content. Beyond that point, STR fuels show drastic increment, while SPG50 exhibit the slowest increment of ignition delay. The higher water droplet content in a single spray of smaller water droplet emulsified fuels is ascribed to this matter. The longer ignition delay contributes to a higher peak of heat release rate, which contributes to higher thermal efficiency, but the decrement of thermal efficiency for emulsified fuels after 20 vol% water content. For SPG30 and SPG50 emulsified fuels, and after 14 vol% for STR emulsified fuels could not be explained by ignition delay. The trend is contrary to the previous report, in which the elongated ignition timing helps to improve thermal efficiency (Badran et al., 2010). Therefore, it is assumed that the extremely long ignition delay, which retard the timing for the peak heat release rate, could affect the thermal efficiency. To clarify this matter, the burn ratios of the fuels are plotted as well in Fig. 8. Burn ratio mainly divides the combustion phase, which is the ratio of diffusion-controlled combustion (CA₉₀-CA₅₀) to the premixed-like combustion period.

Burn ratio increases with water content, and different water droplet diameters of fuels exhibit different increasing rates, with SPG50 emulsified fuel showing the slowest increasing rates. The burn ratio exhibits a trend similar to the ignition delay but with a gentler slope. During the combustion of SPG30 and SPG50 emulsified fuels, the burn ratio seems constant until 20 vol% water content, while a significant increase can be seen at 22 vol% and 24 vol% water. For STR, the burn ratio increases from 14 vol%. It can be concluded that both ignition delay and burn ratio correlates with thermal efficiency, in which a higher ignition delay increases the thermal efficiency by increasing the peak heat release rate, while higher burn ratio resulted in lower thermal efficiency. The behavior of the burn ratio depends on the

increment magnitude of ignition delay, which regards the combustion phasing of heat released rates. Therefore, the combustion phases are studied, in which the CA10, CA50 and CA90 of every combustion are determined and analyzed in Fig. 9.

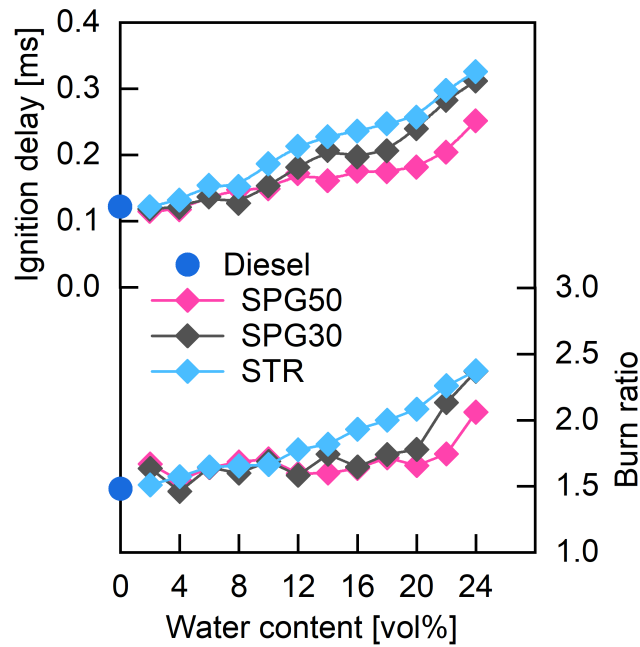


Fig. 8 Variations of water content versus ignition delay and burn ratio of water-emulsified fuels.

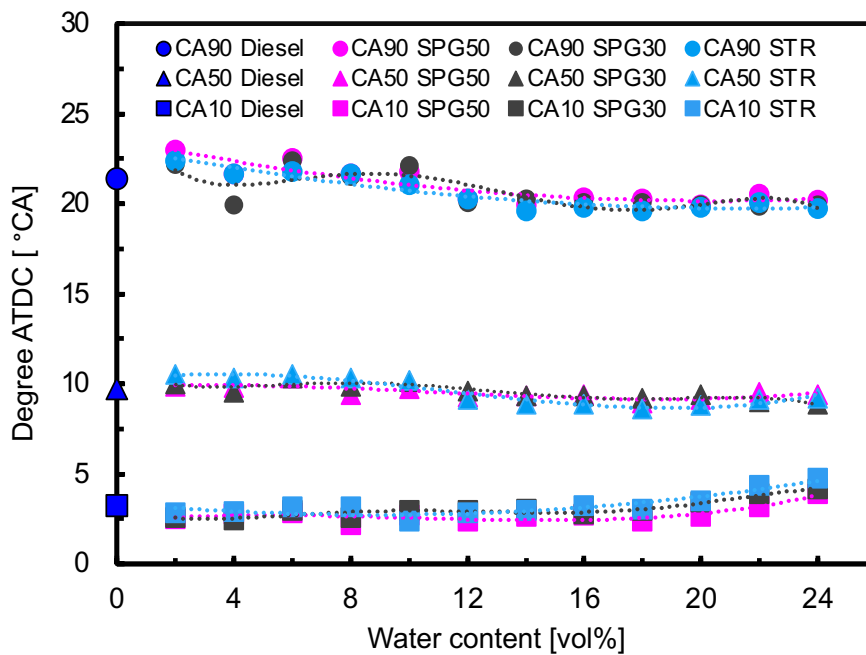


Fig. 9 Combustion phases of test fuels.

Combustion phases of the heat release rates are shown in Fig. 9. CA10 is considered the combustion starting point. It is noted that CA10 water content is increased with linear retardment for STR fuels from the water content of 14 vol% due to longer ignition delay as water content increases. Almost no retardment is observed at lower water content for SPG30 and SPG50 fuels from low water content until 20 vol%, and retardments are observed from 20 vol% to 24 vol% for SPG30 and SPG50 emulsified fuels. Comparing the minimum water content that regards the CA10, as in Fig. 9 and the water content which increases the burn ratio, as in Fig. 8, it can be considered that CA10 dominates the role of controlling the burn ratio in this study.

CA50 is considered the center of the heat release rate. Small advancements in CA50 are observed during STR fuel combustion, while almost no change can be seen for SPG30 and SPG50. Therefore, it can be concluded that the retardment of CA10 mainly causes the premixed combustion duration (CA50-CA10) to decline.

CA90 reflects the duration of total combustion. As the water content increases in all emulsified fuels, the combustion characteristics exhibit an advancement in CA90. This can be attributed to the decrease in the net diesel content and an increase in ignition delay, resulting in accelerated combustion rate and reduction in the duration of combustion. The decrement of the combustion duration improves the degree of constant volume combustion. This explains the improved thermal efficiency at certain water contents. For STR fuels from 14 vol% onwards, SPG30 and SPG50 fuels with 22~24 vol% the decreasing magnitude of CA90 is smaller than the retardment of CA10, as well as the advanced CA50 in certain points which causes the premixed-like combustion duration (CA50-CA10) to progress faster and the diffusion-controlled combustion (CA50-CA90) duration to be longer than the conventional diesel situation. Consequently, the ratio of these combustion phases, referred to as the burn ratio increases. A longer duration of diffusion-controlled combustion paired with a shorter duration of premixed-like combustion, compared to conventional conditions, leads to greater fuel energy loss (Chaudhari and Deshmukh, 2022). This means that more heat is produced after the piston begins its power stroke, which diminishes the efficiency of constant volume combustion. As a result, the increase in burn ratio reduces energy conversion efficiency. Additionally, the lower temperatures caused by the latent heat of the water and reduced heat input significantly decrease output power, further contributing to this issue.

3.4 Influences of water emulsification onto emission

Previous studies have highlighted the significant impact of introducing water into combustion through emulsification on combustion behavior, including the generation of pollutants such as NO_x, soot, and CO (Alahmer et al., 2010; Fahd et al., 2013). To better understand the relationship between water droplet size, water content, and these combustion behaviors, the emission characteristics of these pollutants were investigated while manipulating the water content and droplet diameters.

As water content is increased until 24 vol%, the emission of NO_x shows an almost linear decreasing trend from the combustion of all emulsified fuels as shown in Fig. 10. A little difference due to water droplet diameter effects is observed at low water droplets. However, rather significant differences were found in different water droplet diameter emulsified fuels at higher water content from 12 vol% or 14 vol% to 24 vol%. The maximum reduction is obtained through STR emulsified fuel combustion at 24 vol%, with approximately 40% reduction of NO_x is achieved compared to diesel. The decreasing trend of NO_x for these emulsified fuels as the water content increases is due to the latent heat of water during vaporization in the combustion chamber and the decrements of diesel fraction, which produce up to 30% less heat input, hence reducing the NO_x which is produced by thermal NO mechanism. The low temperature directly influences NO formation by suppressing the chemical reaction rates, as explained in Zeldovich mechanism reactions (Alahmer et al., 2010).

Increasing trends are observed for CO emissions as the water content is increased. The increasing trends are due to the increment of water fraction, which reduce the heat produced and lower the temperature. The decrement of diesel fraction, which reduces the carbon input, restricts the increasing intensity of CO. Overall, the slowest increment can be seen during SPG50 emulsified fuel combustion. Larger water droplet diameter leads to a decrease in the number density of water droplets, and more droplets without water are present in the fuel spray. It is assumed that droplets without water ignite and burn similarly to diesel fuel, leading to combustion behaviors of emulsified fuels with larger water droplet diameters that closely resemble those of diesel. The highest emission of CO is from STR emulsified fuel, during water content of 24 vol%, which emits about 380 ppm, four times the emission of CO over diesel combustion.

Soot is emitted lower for all emulsified fuel combustion than diesel combustion, as shown in Fig. 10. This is due to the lower diesel input as the source of the soot itself. Soot emission is reduced linearly for all emulsified fuels except STR fuels when water content increases. For STR emulsified fuels combustion, the decrement of soot levels off at water content of 14 vol%, which reached the minimum value, and soot emission stays constant until 24 vol%. This trend is probably due to the dispersion of small water droplets in all the spray droplets, in which the water vapor dispersed throughout the fuel vapor region. Whereas the water dispersion could not be proven, the soot measurement device's precision in this research must also be considered. The soot measurement device has significant uncertainty, leaving the possibility of small decrements, but the magnitude is exceptionally small that it is unreadable by the device. The soot emissions of other emulsified fuels decreased as the water content increased up to 24 vol%, and the soot emissions of all the emulsified fuels were almost the same at the water content of 24 vol%.

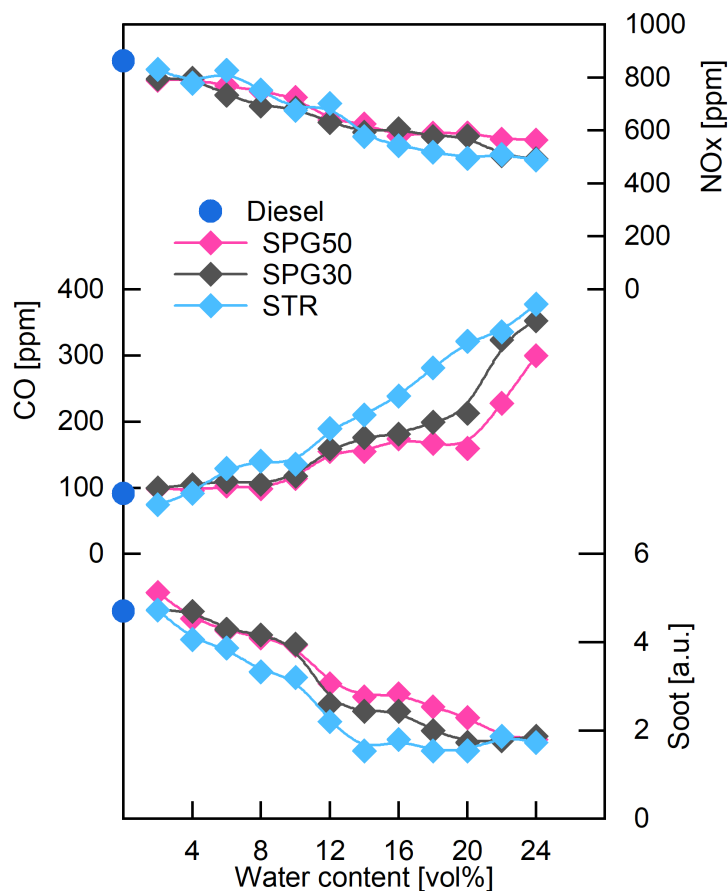


Fig. 10 Water content of emulsified fuels versus NOx, CO and soot emission.

As the output power is also reduced when the water content is increased, the brake specific emission, i.e. brake specific NOx (BsNOx) and brake specific CO (BsCO) is plotted in Fig. 11. Despite the decrease in output power, BsNOx emissions decrease for all emulsified fuels when the water content is increased. Comparing with NOx emission, BsNOx is reduced gentler, with the maximum reduction of BSNOx is about 28%. Among the emulsified fuels, SPG30 and SPG50 show similar and more stable trends with lower NOx compared to STR at lower water content. The STR emulsified fuels initially has comparable NOx values but shows more fluctuation and an eventual increase, suggesting less effective NOx reduction at lower water content, likely due to poorer droplet uniformity and inconsistent combustion. BsCO emissions increase significantly with the rise in water content for all emulsified fuels. Comparing with CO emission in Fig. 10, almost no change is observed in the increasing magnitude. Despite the decrease in carbon input through the reduction of neat diesel in the emulsified fuels when the water content is increased, the incomplete combustion due to lower temperature in the combustion chamber, which lead to incomplete oxidation of carbon to CO₂

(Elsanusi, 2017), results in a significant increase in CO emission at higher water contents.

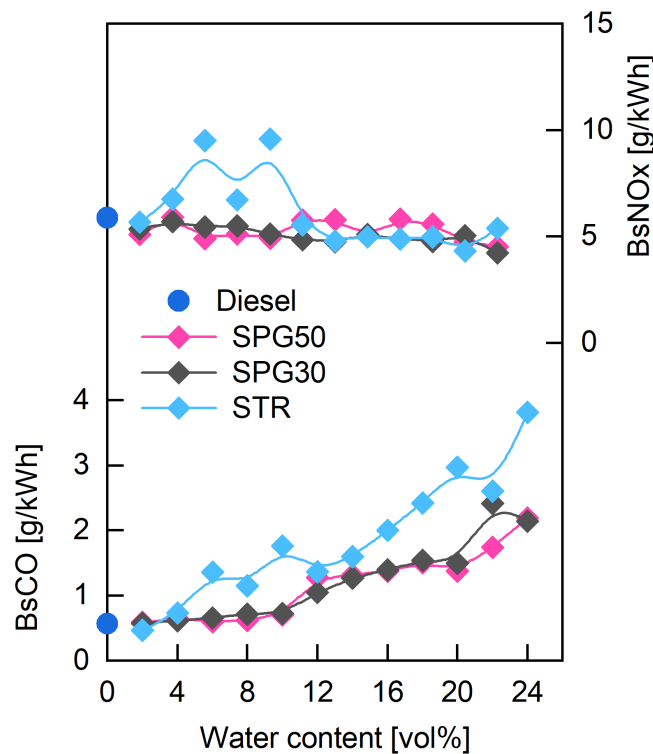


Fig. 11 Water content of emulsified fuels versus BsNOx and BsCO.

4. Conclusion

The influences of water content and water droplet diameter in W/O emulsified fuels were experimentally investigated in an air-cooled direct-injection single-cylinder diesel engine with a constant speed of 2300 rpm. By manipulating the water content up to 24 vol% with a 2 vol% increase and the water droplet size, the following conclusions can be reached:

1. Increasing water content improves pollutant emission, in which a significant reduction of NOx and soot is achieved due to low combustion temperature and carbon input. However, CO emission displays a trade-off relationship.
2. Lower heat input at higher water content deteriorates the output power for all fuels, but this behavior could be slightly improved by increasing the water droplet size.
3. Water content of 20 vol% is a favorable condition to improve thermal efficiency when larger water droplet emulsified fuel is used due to increment of ignition delay, which increases the peak rate of heat release, and this trend agrees with some previous studies in which the maximum efficiency is achieved at 20 vol% (Abu-Zaid, 2004; Kannan and Udayakumar, 2009). For small water droplet fuel (STR), maximum thermal efficiency is reached at 14 vol%. The thermal efficiency decreases after those water content conditions due to the increment of burn ratio, which increases the effective energy loss (late premixed combustion timing).
4. The burn ratio increases with both water content and droplet size because these factors extend the ignition delay, shifting more combustion into the diffusion-controlled phase. However, there is an optimal range for both water content and droplet size where the burn ratio stays low, maintaining a balance between premixed and diffusion combustion for higher thermal efficiency.
5. Larger water droplet diameter leads to a decrease in the number density of water droplets, and more droplets without water are present in the fuel spray. It is assumed that droplets without water ignite and burn similarly to diesel fuel, leading to combustion behaviors of emulsified fuels with larger water droplet diameters resemble those of neat diesel.

6. Considering the effects of water on engine emission and performance, it can be concluded that the maximum water content of 20 vol%, with the largest water droplet diameter, is the best fuel property from this research. Hence SPG50 fuel with a water content of 20 vol% is regarded to have the most potential.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- Abu-Zaid, M., Performance of single cylinder, direct injection diesel engine using water fuel emulsions, *Energy Conversion and Management*, Vol. 45, No. 5(2004), pp. 697-705, DOI: 10.1016/S0196-8904(03)00179-1.
- Alahmer, A., Yamin, J., Sakhrich, A. and Hamdan, M. A., Engine performance using emulsified diesel fuel, *Energy Conversion and Management*, Vol. 51, No. 8(2010), pp. 1708-1713, DOI: 10.1016/j.enconman.2009.11.044.
- Armas, O., Ballesteros, R., Martos, F. J. and Agudelo, J. R., Characterization of light duty Diesel engine pollutant emissions using water-emulsified fuel. *Fuel*, Vol. 84, No. 7-8(2005), pp. 1011-1018, DOI: 10.1016/j.fuel.2004.11.015.
- Badran, O., Emeish, S., Abu-Zaid, M., Abu-Rahmeh, T., Al-Hasan, M. and Al-Ragheb, M., Impact of emulsified water/diesel mixture on engine performance and environment, *International Journal of Thermal and Environmental Engineering*, Vol. 3, No. 1 (2011), pp. 1-7, DOI: 10.5383/ijtee.03.01.001.
- Chase, M.W., NIST-JANAF Thermochemical tables fourth edition (1998).
- Chaudhari, V.D. and Deshmukh, D., Fuel flexibility study of various fuels with charge dilution and high compression ratio for medium-load operating RCCI engine, *Fuel*, Vol. 310, Part B, No. 122163(2022), DOI: 10.1016/j.fuel.2021.122163.
- Dan, T., Basic Characteristics of emulsion fuel and its effect on combustion, *Journal of the Japan Institute of Marine Engineering* (in Japanese), Vol. 51, No. 3 (2016), pp. 307-314, DOI: 10.5988/jime.51.307.
- Elsanusi, O. A., Roy, M. M. and Sidhu, M. S., Experimental investigation on a diesel engine fueled by diesel-biodiesel blends and their emulsions at various engine operating conditions, *Applied Energy*, Vol. 203(2017), pp. 582-593, DOI: 10.1016/j.apenergy.2017.06.052.
- Fahd, M. E. A., Yang, W., Lee, P. S., Chou, S. K. and Yap, C. R., Experimental investigation of the performance and emission characteristics of direct injection diesel engine by water emulsion diesel under varying engine load condition, *Applied Energy*, Vol. 102(2013), pp. 1042-1049, DOI: 10.1016/j.apenergy.2012.06.041.
- Fu, W. B., Hou, L. Y., Wang, L. and Ma, F. H., A unified model for the micro-explosion of emulsified droplets of oil and water, *Fuel Processing Technology*, Vol. 79, Issue 2 (2002), pp. 107-119, DOI: 10.1016/S0378-3820(02)00106-6.
- Griffin, W. C., Classification of surface-active agents by HLB, *Journal of the Society of Cosmetic Chemists*, Vol. 1(1949), pp. 311-326.
- Kannan, K. and Udayakumar, M., NO_x and HC Emission control using water emulsified diesel in single cylinder diesel engine, *ARNP Journal of Engineering and Applied Sciences*, Vol. 4, No. 8(2009), pp. 59-62.
- Khatrri, D. and Goyal, R., Performance, emission and combustion characteristics of water diesel emulsified fuel for diesel engine: a review, *Materials Today: Proceedings*, Vol. 28, Part 4(2020), pp. 2275-2278, DOI: 10.1016/j.matpr.2020.04.560.
- Mizutani, Y., Fuchihata, M., Matsuoka, Y. and Muraoka, M., Observation of micro-explosions in spray flames of light oil-water emulsions, *Transactions of the JSME* (in Japanese), Part B, Vol. 66, No. 646 (2000), pp. 1544-1549,

DOI: 10.1299/kikaib.66.646_1544.

- Mizutani, Y. and Taki, A., Combustion, emission characteristics and combustion mechanism of water emulsified fuel spray (1st report, emulsion properties and combustion, emission characteristics), Transactions of the JSME (in Japanese), Part B, Vol. 47, No.424 (1981), pp. 2379-2385, DOI: 10.1299/kikaib.47.2379.
- Nakagawa, H. and Tateishi, M., Emulsified fuel spray combustion in D. I. diesel engine, Journal of the Society of Mechanical Engineers (in Japanese), Vol. 81, No. 720 (1978), pp. 1201-1207, DOI: 10.1299/jsmemag.81.720_1201.
- SPG Technology Co., Ltd., SPG emulsification technical bulletin (in Japanese), (2013), pp.1-5.
- Suzuki, Y., Harada, T., Watanabe, H., Shoji, M., Matsushita, Y., Aoki, H. and Miura, T., Visualization of aggregation process of dispersed water droplets and the effect of aggregation on secondary atomization of emulsified fuel droplets, Proceedings of the Combustion Institute, Vol. 33 (2011), pp. 2063-2070, DOI: 10.1016/j.proci.2010.05.115.
- Takeda, S., Fuchihata, M. and Ida, T., Observation of micro explosions in spray flames of light oil-water emulsions (3rd Report, influence of the diameter of dispersed water droplets on the spray flame structure), Transactions of the JSME (in Japanese), Part B, Vol. 74, No. 743 (2008), pp. 1649-1654, DOI: 10.1299/kikaib.74.1649.
- Tentora, T. and Fuchihata, M., Effect of dispersed water droplet diameter in light oil-water emulsion fuel on diesel engine operating performance, Transactions of the JSME (in Japanese), Vol. 85, No. 875 (2019), DOI: 10.1299/transjsme.18-00399.
- Willems, R., Willems, F., Deen, N. and Somers, B., Heat release rate shaping for optimal gross indicated efficiency in a heavy-duty RCCI engine fueled with E85 and diesel, Fuel, Vol. 288, No. 119656 (2021), DOI: 10.1016/j.fuel.2020.119656.
- Yahaya Khan, M., Abdul Karim, Z. A., Hagos, F. Y., Aziz, A.R. and Tan, I. M., Current trends in water-in-diesel emulsion as a fuel, Scientific World Journal (2014). DOI: 10.1155/2014/527472.
- Zhang, L., Matsumoto, R. and Shimizu, K., Micro-explosion of emulsion fuel droplet under high pressure, Journal of the Marine Engineering Society in Japan (in Japanese), Vol. 24, No. 1 (1989), pp. 37-43, DOI: 10.5988/jime1966.24.37.