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# Study on Combustion and Emission Characteristics of Marine Diesel Oil and Water-In-Oil Emulsified Marine Diesel Oil

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**Abstract:** Compression ignition engines used as marine engines are the most efficient internal combustion engines. They are well-established products, and millions are already on the market. Water-in-MDO (marine diesel oil) emulsions are the best alternative fuel for compression ignition engines and can be utilised with the existing setup of 2.0 L automotive common rail direct injection (CRDI) engines. They have benefits for the simultaneous reduction of both $NO_x$ and smoke (black carbon). Furthermore, they have a significant impact on the improvement of combustion efficiency. Micro-explosions are the most important phenomenon of water-in-diesel emulsions inside an internal combustion engine chamber. They affect both the emission reduction and combustion efficiency improvements directly and indirectly in accordance with the brake mean effective pressure (BMEP) and rpm. Owing to the influence of micro-emulsions on the combustion and emissions of water-in-diesel emulsion fuel, the reduction ratios of $NO_x$ and smoke in a used engine are approximately 30% and 80%, respectively. The effect of the operating parameters on micro-emulsions is presented.

**Keywords:** micro-explosions; CRDI engine; emulsion; water-in-MDO emulsion; marine diesel oil (MDO)

## 1. Introduction

The global use of fossil fuels has been increasing owing to economic development and industrialisation, and currently fossil fuels are playing a core role in modern living. Fossil fuels provide comfort, but they also discharge pollutants.

Regulations on land transportation, such as passenger cars, trucks, large trucks, and buses, were re-enforced in the forms of EURO 4 in 2006 and EURO 5 in 2011. However, the legal emission standards for ships are lower than those for automobiles. The International Maritime Organization (IMO) decided to apply the Tier 3 exhaust gas regulations from 2016 to strengthen the emission allowance standards for ships to the level of those for automobiles. For ships built after 1 January 2016, 80% of the allowed emission standards must be reduced compared with those built before 31 December 2010 [1,2].

IMO enacted and adopted the MARPOL annex (regulations for preventing air pollution from ships) at the 37th Marine Environment Protection Committee (MEPC) convention held at the IMO headquarters in London, U.K. on 26 September 1997 to regulate ozone-depleting substances, nitrogen oxides ($NO_x$), sulphur oxides ($SO_x$), volatile organic compounds, exhaust gas from the incinerators of ships, and the quality of fuel oil. In addition, the enforcement conditions of Annex VI included the acceptance of 15 or more countries and stated that the bottoms of the merchant ships of the accepting countries had to be more than 50% of the volume of the global merchant ship bottoms. The determined effective date was one year from the date when the enforcement conditions were satisfied. As the conditions were satisfied on 18 May 2004 when Samoa accepted the annex as the 15th country, the MARPOL Annex VI (regulations for preventing air pollution from ships) came into effect on 19 May 2005, that is, one year later. Table 1 shows Tiers I–III according to the $NO_x$ emission regulations [3,4]. Exhaust gas can be removed largely in two ways. The first is a pre-treatment method [5–14], which uses specific treatments before using fuels, including the removal of sulphur or metal powders emitting hazardous exhaust gas, combustion facility improvement, fuel injection timing delay, combustion-chamber shape modification, and fuel injection system improvement, in addition to the use of exhaust recirculation, water injection, and emulsion fuels that utilise diesel oil–water emulsions. The second is a post-treatment method, such as catalytic decomposition, catalytic reduction, or absorption, to remove $NO_x$ included in exhaust gas. In the case of ship oil, even if the post-treatment devices [15–17], such as selective catalytic reduction (SCR), which is the most commonly used of the post-treatment methods, are used to reduce $NO_x$, large amounts of smoke, $SO_x$, and $NO_x$ are discharged in exhaust gas owing to the high content of sulphur compounds. As this significantly reduces the durability of SCR, pre-treatment of the fuel is necessary.

**Table 1.** $NO_x$ limits in MARPOL Annex VI.

| Tier | Effective Date | $NO_X$ Limit (g/kWh) | | |
|---|---|---|---|---|
| | | $N < 130$ | $130 \leq N < 2000$ | $N > 2000$ |
| Tier I | 2000 | 17 | $45 \times n^{-0.2}$ | 9.8 |
| Tier II | 2011 | 14.4 | $44 \times n^{-0.2}$ | 7.7 |
| Tier III | 2016 | 3.4 | $9 \times n^{-0.2}$ | 1.96 |

As thermal $NO_x$ represents most of the $NO_x$ emitted from ship diesel engines, technologies to control the amount of this thermal $NO_x$ are important. The primary $NO_x$ reduction methods include water emulsion fuels [7], engine adjustment [12–14], and exhaust gas recirculation (EGR) [7–9], which are pre-treatment $NO_x$ reduction technologies capable of reducing $NO_x$ by changing the characteristics of internal combustion engines and combustion chambers, including the combustion time and temperature. The secondary methods include $NH_3$ and urea SCR technologies, which are engine post-treatment technologies to reduce and separate $NO_x$ included in exhaust gas into $N_2$ and $H_2O$.

Among them, emulsion fuels are practical and economical $NO_x$ reduction technologies compared with expensive large-scale denitrification facilities (such as SCR). In particular, as the generation of $NO_x$ and soot (unburned fine carbon particles) from heat engines that use low-quality liquid fuels accounts for a high proportion of air pollution, the use of emulsion fuels, which is one of the methods to suppress the generation, reduces the combustion temperature using the latent heat of water and accomplishes complete combustion using the micro-explosion phenomenon, which is a characteristic unique of emulsion fuels alone, thereby improving the efficiency of heat engines and effectively reducing $NO_x$. In addition, the use of emission fuels requires no additional devices, unlike the existing pre- and post-treatment technologies, and thus, studies to commercialise emulsion fuel technology have been actively conducted [18–20].

For the application of alternative fuel technologies to existing engines, studies are being actively conducted to overcome limitations such as output degradation, corrosiveness, and fuel viscosity. Among the alternative fuel technologies, emulsion fuels can be easily obtained from existing fuels, such as diesel. These are fuels in which water and an emulsifier are mixed at a certain ratio. In addition, as fuels contain water, they can reduce the combustion temperature in the combustion chamber, owing to the absorption of latent heat of evaporation caused by the vaporisation of water during combustion, and promote fuel atomisation with micro-explosions caused by rapid evaporation. Therefore, they can reduce $NO_x$, $SO_2$, and soot simultaneously. Furthermore, they require no additional device, unlike the existing engine technologies, new engine combustion technologies, and post-treatment technologies. As they can be applied to the existing engines without additional modification, the related studies have attracted attention [21–24].

In this study, when Bunker-A, used as ship oil, was converted into an emulsion fuel using an emulsifier, the performance of the emulsion fuel was investigated. Its calorific value during combustion and whether the emulsion fuel satisfied the quality criteria were examined, and the combustion and exhaust characteristics according to the cylinder pressure and heat release characteristics were analysed through an engine applicability test in which the brake mean effective pressure (BMEP) and rpm were varied. In addition, the reduction in $NO_x$ and smoke density generated during combustion and the combustion stability were analysed using the emulsion fuel and marine diesel oil (MDO) used in this study.

## 2. Experimental Apparatus and Methodology

### *2.1. Emulsion Oil Properties*

The MDO used in this study was ship oil, and emulsified marine diesel oil (EMDO) was the water-in-oil-type emulsion fuel fabricated by mixing MDO and water at a ratio of 80:20 and by adding less than 1% of an emulsifier. The component analysis of MDO and EMDO was performed by the Korea Petroleum Quality and Distribution Authority to identify the properties of the fuels according to the water content. The results are shown in Table 2. As the water content increased, the calorific value decreased, whereas the viscosity and density increased. On the basis of these fuel properties, it appeared that fuel consumption would increase to achieve the same combustion performance. However, the cylinder pressure and heat release were expected to increase owing to the improvement of the combustion performance caused by fuel atomisation, which was promoted by micro-explosions as a result of the water contained in the fuel. In addition, it appeared that the reduction in the exhaust temperature owing to the absorption of the latent heat of evaporation caused by the vaporisation of water would reduce $NO_x$ and smoke simultaneously.

**Table 2.** Specifications of fuel oil used in this study.

| Item/Classification | Marine Diesel Oil (MDO) | Emulsified Marine Diesel Oil (EMDO) |
|---|---|---|
| Lower calorific value (J/g) | 41,060 | 32,990 |
| Gross calorific value (J/g) | 43,670 | 36,050 |
| Sulphur content (wt %) | 0.15 | 0.1 |
| Density at 15 °C (kg/m$^3$) | 923.6 | 929.7 |
| Viscosity at 15 °C (cP) | 21.7 | 34.3 |
| Moisture (vol %) | 0.5 | 16.8 |
| Flash point (°C) | 104 | 86 |

### *2.2. Experimental Apparatus*

Figure 1 shows the engine constructed to investigate the combustion and exhaust characteristics of MDO and EMDO. The engine was a 2.0 L class four-cylinder common-rail diesel engine with a turbocharger capable of high-pressure injection (max: 1600 bar). As shown in Figure 1, it consisted of an engine generator, a control panel, a data collection system, and a sensor. The experimental equipment also included a generator system made using a FUSHINO dynamometer (AC 110 kW). Pressure sensors for cylinder pressure measured using the piezoelectricity (Kistler model 6056 A, Winterthur, Switzerland) of the cylinder pressure. The charge output from this transducer was converted to an amplified voltage using an amplifier (Kistler model 5015, Winterthur, Switzerland), recording at a 0.5° crank angle (CA) resolution, and the sampling signal was formed from a shaft encoder. The heat release rate was calculated by a zero-dimensional combustion model corresponding to the in-cylinder pressure averaged over 100 cycles for each operating point.

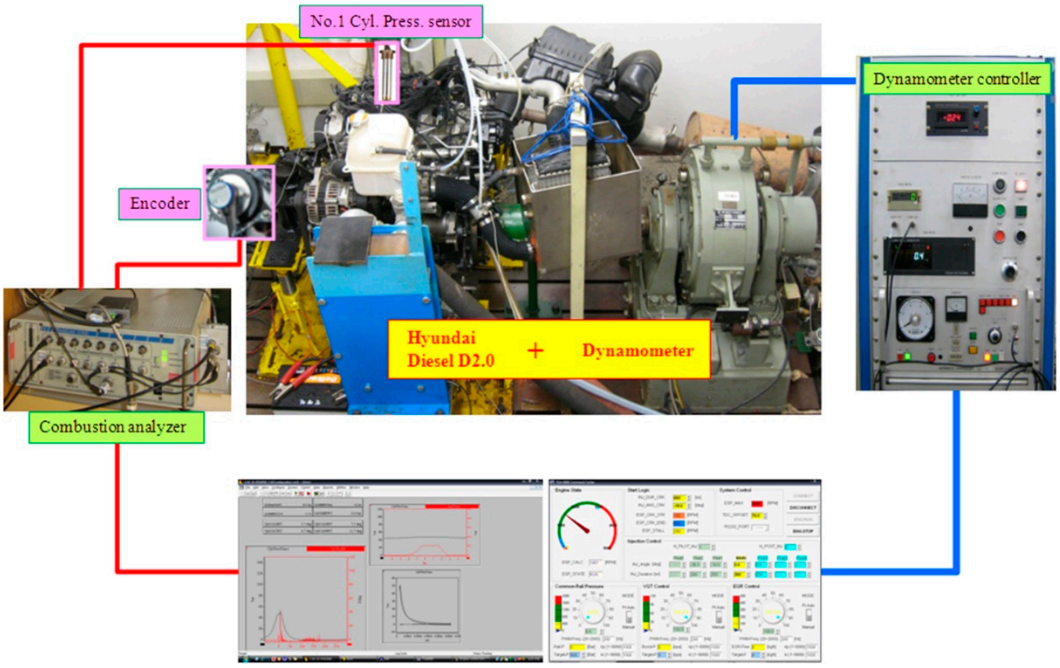



**Figure 1.** Engine and engine dynamometer.

The engine used this research was based on a single-cylinder, direct-injection, four-stroke diesel engine. The specifications of the main engine are listed in Table 3.

**Table 3.** Specifications of the test engine.

| Item/Description | Specifications |
|---|---|
| Engine type | Four-stroke turbo-charged direct injection diesel engine |
| Number of cylinders | 4 |
| Bore × stroke (mm) | 83 × 92 |
| Displacement (cc) | 1991 |
| Fuel injection system | Common rail (max: 1600 bar) |
| Max power (ps/rpm) | 146/4000 |
| Max torque (kg m/rpm) | 32/1800–2500 |

As shown in Table 4, the exhaust gas compositions of CO, HC, and $NO_x$ emissions were measured by a gas analyser (Horiba, MEXA 7100, Kyoto, Japan), and the smoke opacity was measured by a smoke meter (AVL 415, Graz, Austria).

**Table 4.** Specifications of the engine dynamometer and exhaust analyser.

| Item | Specifications |
|---|---|
| Dynamometer | HUSHINO ESF-H-150; eddy current type; 110 kW at 10,000 rpm |
| Exhaust gas analyser | Horiba, MEXA 7100 |
| Smoke meter | AVL 415 |

### 2.3. Experimental Conditions

To investigate the combustion and exhaust characteristics of MDO and EMDO in the engine, the rpm (1500, 2000, and 2500) and load conditions (BMEP of 3, 6, 9, and 12 bar) including the maximum torque performance interval, which are commonly used during driving, were selected, as shown in Table 5.

**Table 5.** Engine test conditions.

| Fuel | MDO/EMDO |
| --- | --- |
| Engine speed (rpm) | 1500, 2000, 2500 |
| Brake mean effective pressure (BMEP) | 3, 6, 9, 12 |

## 3. Results and Investigations

### 3.1. Cylinder Pressure and Heat Release Characteristics of MDO and EMDO

Figures 2–4 show the results of comparing the cylinder pressure and heat release characteristics according to the engine rpm and fuel properties.

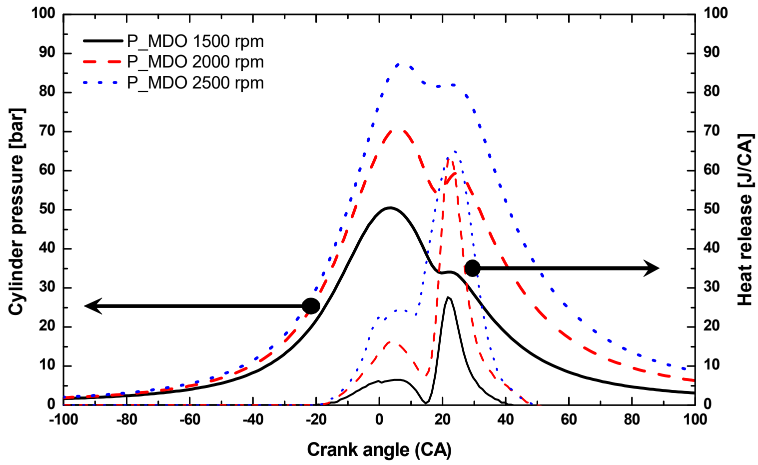



**Figure 2.** Characteristics of the cylinder pressure and heat release according to rpm for marine diesel oil (MDO).

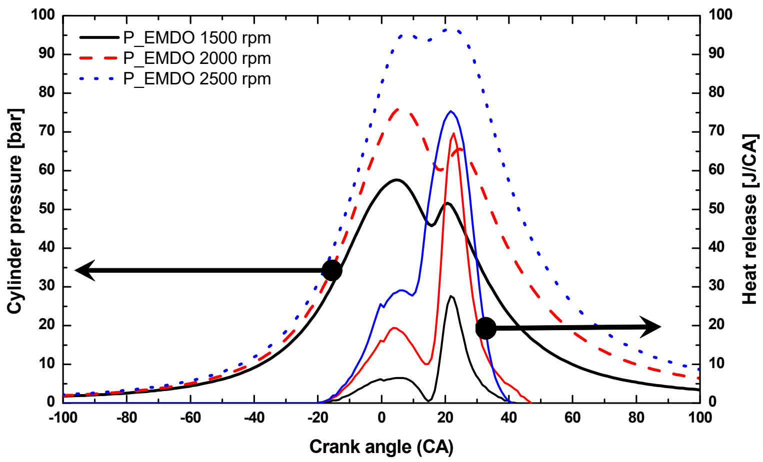



**Figure 3.** Characteristics of the cylinder pressure and heat release according to rpm for emulsified marine diesel oil (EMDO).

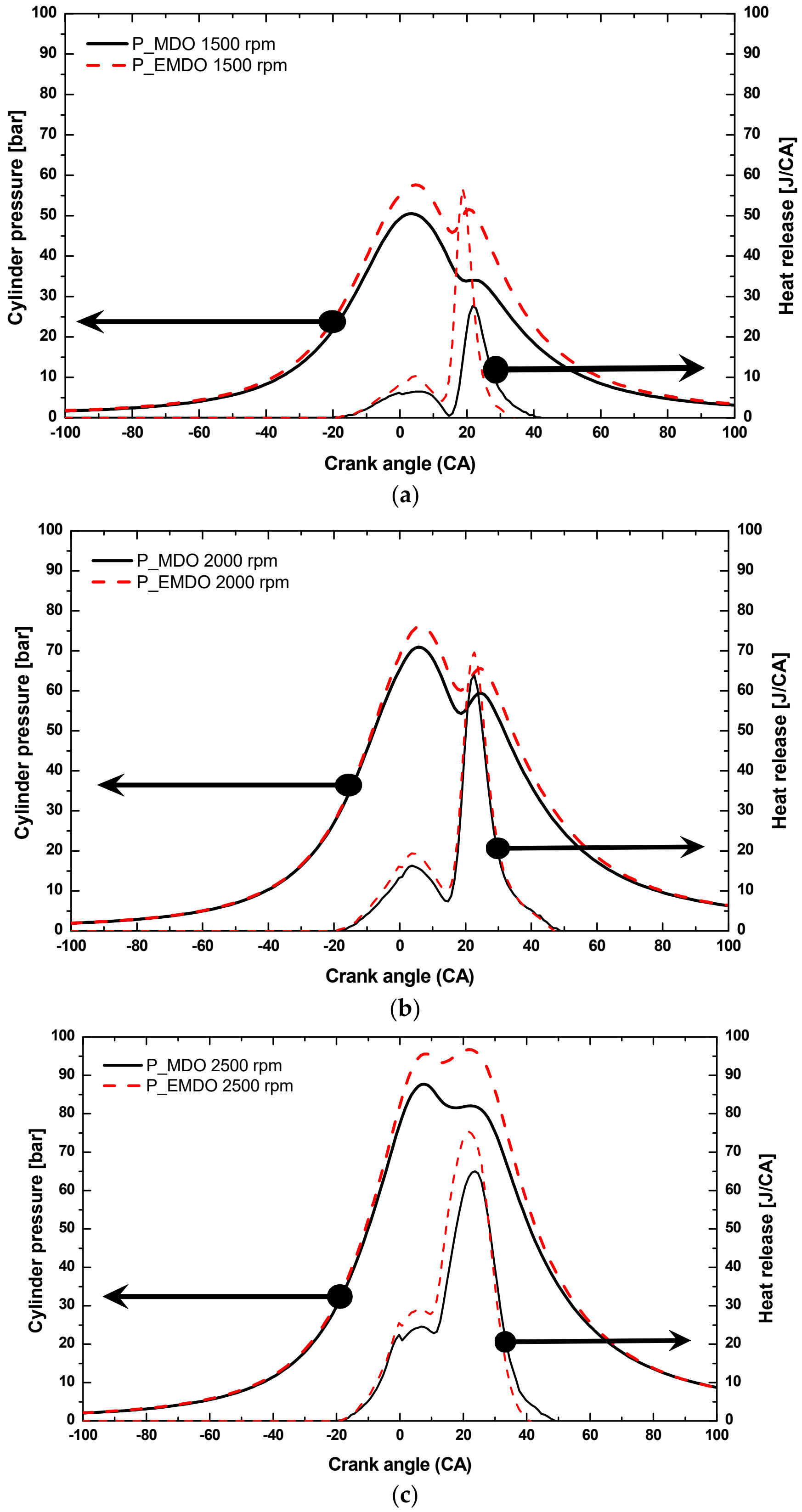



**Figure 4.** Characteristics of the cylinder pressure and heat release with marine diesel oil (MDO) and emulsified MDO (EMDO) in accordance with changing rpm: (**a**) 1500 rpm; (**b**) 2000 rpm; (**c**) 2500 rpm.

Figures 2 and 3 show the results of the analysis of the combustion and heat release characteristics of MDO and EMDO. Figure 2 shows the results for the combustion chamber pressure and heat release rate characteristics of the MDO fuel. Injection timing was constant at BTDC of 18 CA, and according to the changing rpm and BMEP, the injection amount was controlled. The results for EMDO are shown in Figure 3.

Figure 3 shows that, in EMDO, the overall cylinder pressure increased and the heat release exhibited a sudden increase. Therefore, it appeared that the fuel atomisation and combustion improvement owing to the micro-explosions and evaporation of the water contained in EMDO increased the cylinder pressure and heat release.

As shown in Figure 4, although the characteristics of combustion and heat release showed similar tendencies overall, the cylinder pressure and heat release were higher when EMDO was used than when MDO was used. As shown in Figure 4a–c, the cylinder pressure in the case of EMDO was higher than that of MDO. This appeared to be because combustion was activated owing to the micro-explosions caused by the water contained in the fuel.

### *3.2. Combustion Duration Characteristics of MDO and EMDO*

Figure 5 shows the results of the analysis of the combustion duration of MDO and EMDO according to the BMEP and rpm. From the results in Figure 5, when commercial EMDO emulsion fuel was used, the combustion period was shorter than when burning EMDO. This was considered to have promoted combustion by micro-explosions of water contained in the emulsion.

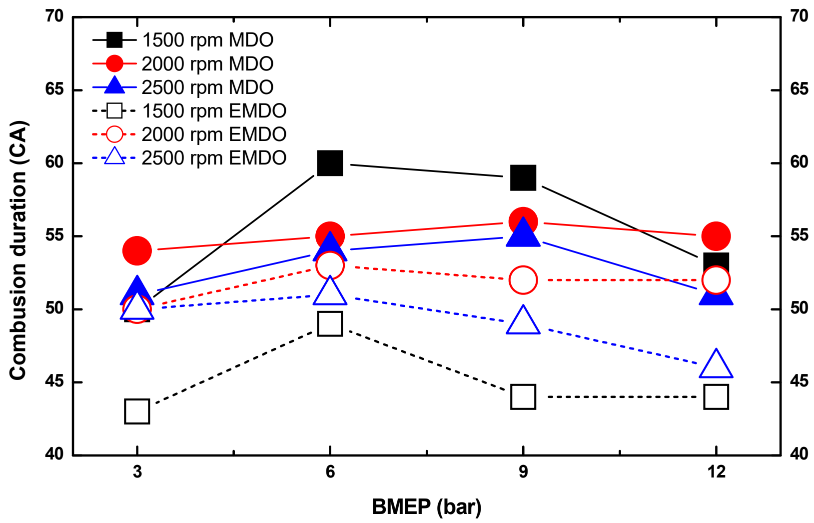



**Figure 5.** Characteristics of the combustion duration according to brake mean effective pressure (BMEP) and rpm.

Figure 6 shows the results of a comparison of the mean values of each fuel under different load conditions at each value of rpm. The ratio of combustion duration between the EMDO and MDO fuels was calculated as follows:

$$\text{Ratio of combustion duration } (\%) = \text{ combustion duration} \left[ \frac{\text{MDO} - \text{EMDO}}{\text{MDO}} \right] \times 100 \tag{1}$$

For 1500, 2000, and 2500 rpm, the reduction ratios of the combustion duration in EMDO decreased by 20%, 6%, and 9%, respectively, compared with MDO. Under all rpm conditions, the combustion duration of EMDO was shorter than that of MDO. This appeared to be because the fuel atomisation and improved air–fuel mixing owing to the micro-explosions and evaporation of the water contained in EMDO caused faster combustion than for MDO, thereby reducing the combustion duration. On the basis of these results, it appears that soot will decrease owing to the short combustion duration and that $NO_x$ will be reduced owing to the decrease in the combustion temperature caused by the latent heat of evaporation of water. Under low rpm and low load conditions, the ignition delay increased with MDO according to the water content of EMDO, but the ignition delay of EMDO tended to be shorter than for MDO as the rpm increased.

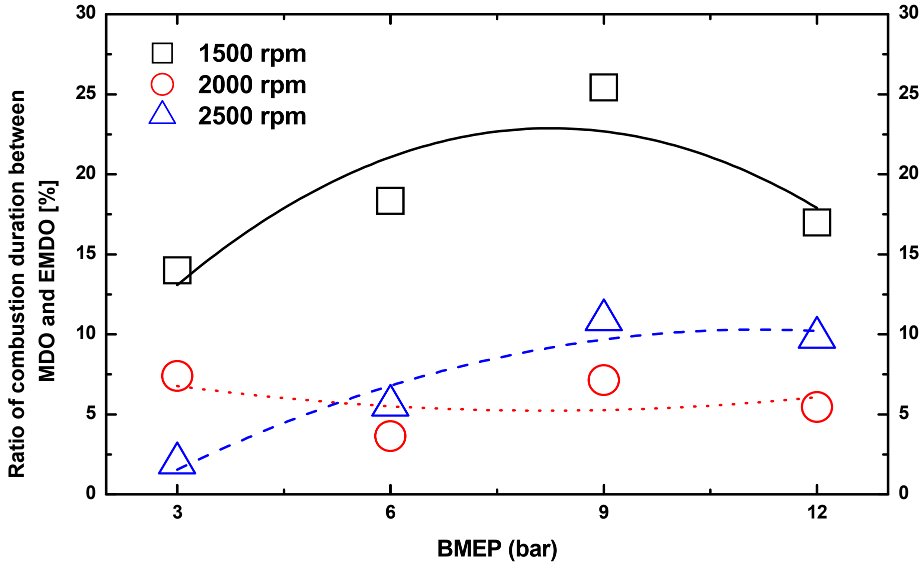



**Figure 6.** Ratio of combustion duration between marine diesel oil (MDO) and emulsified MDO (EMDO) according to brake mean effective pressure (BMEP) and rpm.

Figure 7 shows the mean heat release of MDO and EMDO according to the BMEP and rpm. As the rpm increased, the mean heat release increased. The heat release was higher when EMDO was used than when MDO was used. This appeared to be because the fuel atomisation and improved air–fuel mixing owing to the micro-explosions and evaporation of the water contained in EMDO enhanced the combustion.

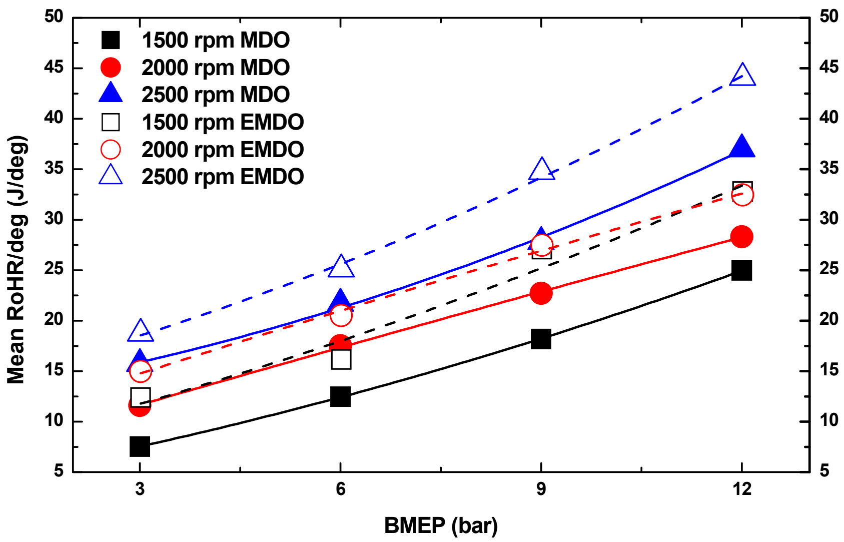



**Figure 7.** Characteristics of the mean heat release according to brake mean effective pressure (BMEP) and rpm.

Figure 8 shows the results of the comparison of the mean heat release between MDO and EMDO. The results show that the differences in heat release between MDO and EMDO were 43%, 20%, and 19% for 1500, 2000, and 2500 rpm, respectively. The burning period of EMDO was shorter than that of MDO; the water content of EMDO is micro-explosions of fuel atomisation due to the evaporation of water, the mixing of air and fuel was improved, the combustion was improved, and the combustion progressed more rapidly than for MDO. It was concluded that the period would be shortened.

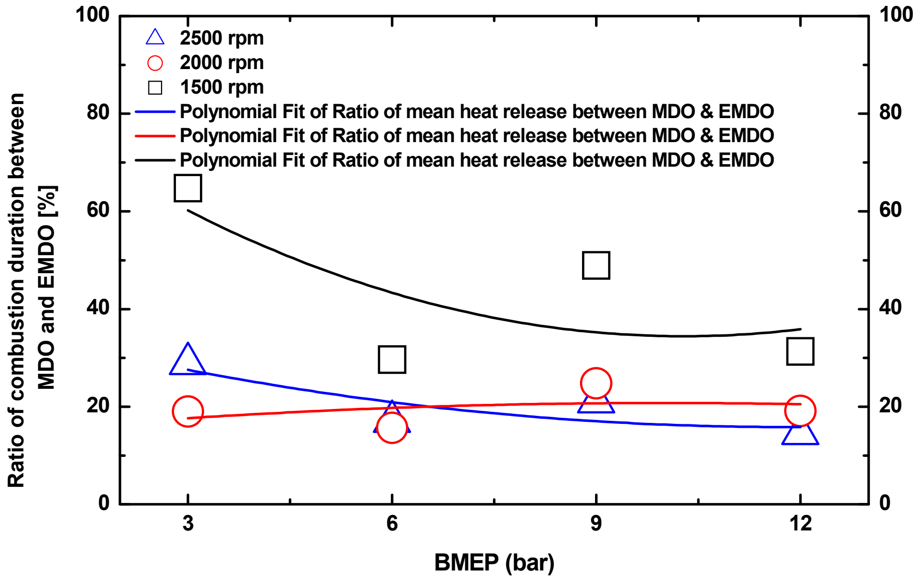



**Figure 8.** Ratio of mean heat release between marine diesel oil (MDO) and emulsified MDO (EMDO) according to rpm.

### 3.3. Comparison of Fuel Consumption Characteristics by Water Content between MDO and EMDO

Figures 9 and 10 show the pure fuel consumptions when water was either included or excluded. Figure 9 shows the consumptions of the fuels with water. The results indicate that the consumption of EMDO increased to achieve the same output.

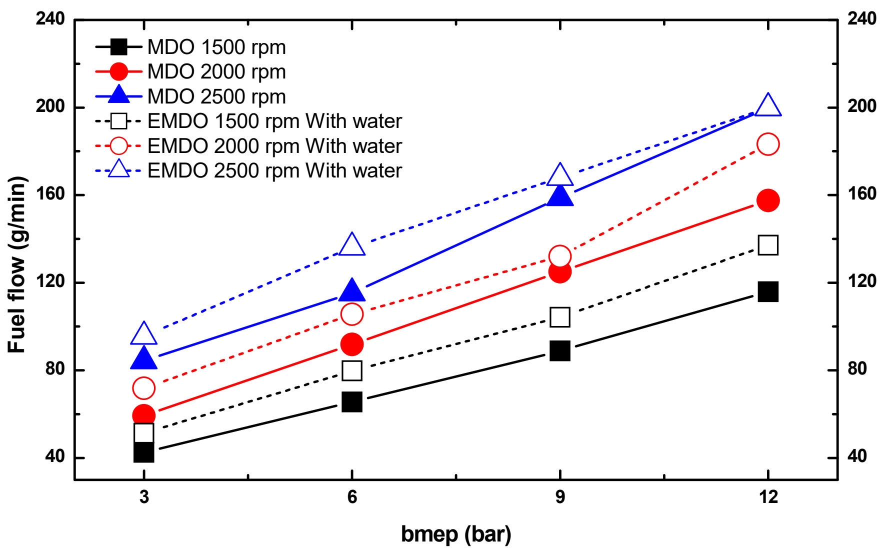



**Figure 9.** Fuel consumption with marine diesel oil (MDO) and emulsified MDO (EMDO) fuels according to rpm.

However, Figure 10 shows the results of the analysis of the fuel consumption excluding the water content, and the fuel consumption reduction characteristics are shown in Figure 11. The results show that the pure fuel consumptions decreased by 4.4%, 8.4%, and 12.6% for 1500, 2000, and 2500 rpm, respectively. This appeared to be consistent with the results of the combustion and heat release analysis described above.

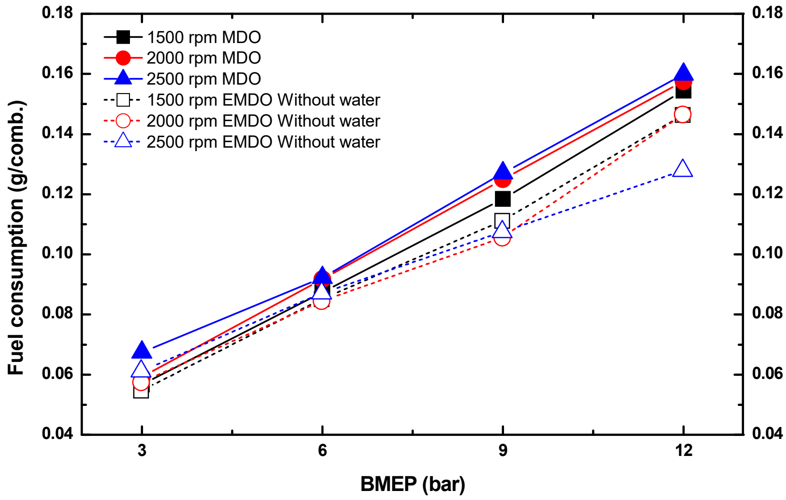



**Figure 10.** Fuel consumption without water content for marine diesel oil (MDO) and emulsified MDO (EMDO) fuels according to rpm.

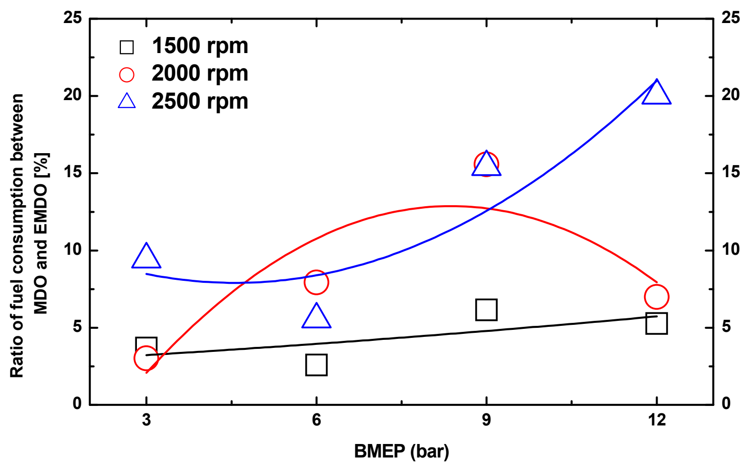



**Figure 11.** Ratio of fuel consumption without water content for marine diesel oil (MDO) and emulsified MDO (EMDO) fuels according to rpm.

### *3.4. Combustion and Exhaust Characteristics by Water Content in MDO and EMDO*

Figure 12 shows the exhaust characteristics for $NO_x$ reduction according to the BMEP and rpm. Figure 12 presents a graph showing the $NO_x$ emission characteristics of MDO and EMDO under the respective experimental conditions. $NO_x$ emissions of EMDO were reduced in all areas, and $NO_x$ emissions of EMDO were reduced by up to 50% compared to MDO at 1500 rpm. It is considered that this was because $NO_x$ generation was suppressed owing to the combustion period being shortened as a result of a decrease in the combustion temperature due to the latent heat of evaporation of water in EMDO, a reduction in the oxygen concentration in the combustion chamber due to steam, and an improvement of combustion due to micro-explosions.

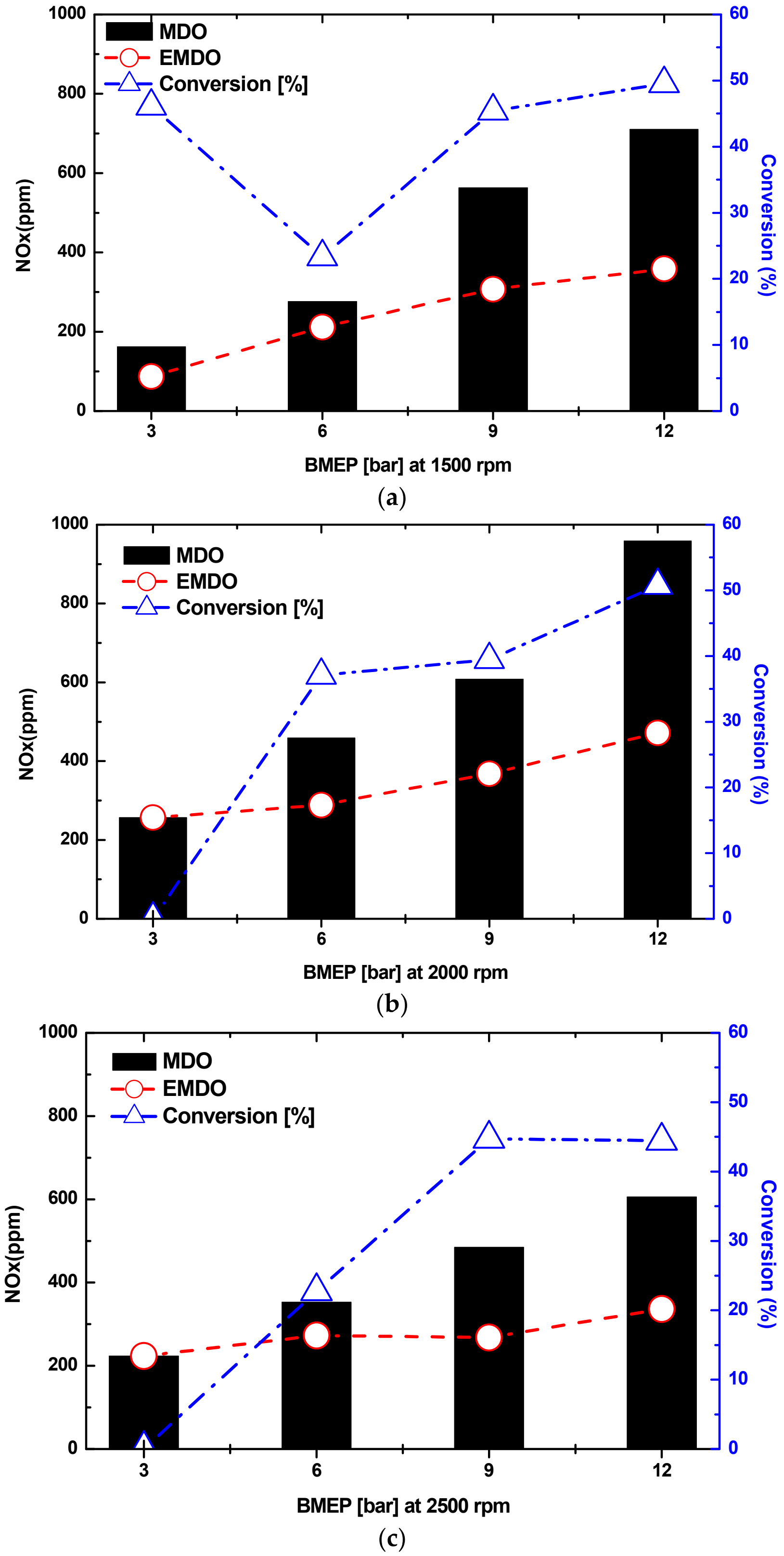



**Figure 12.** $NO_x$ reduction characteristics according to rpm and brake mean effective pressure (BMEP): (**a**) 1500 rpm; (**b**) 2000 rpm; (**c**) 2500 rpm.

The conversion of the $NO_x$ reduction is defined by the following equation:

$$\text{Conversion } (\%) = \left[\frac{\text{ppm of } (\text{MDO} - \text{EMDO})}{\text{ppm of MDO}}\right]_{\text{NOx}} \times 100 \quad (2)$$

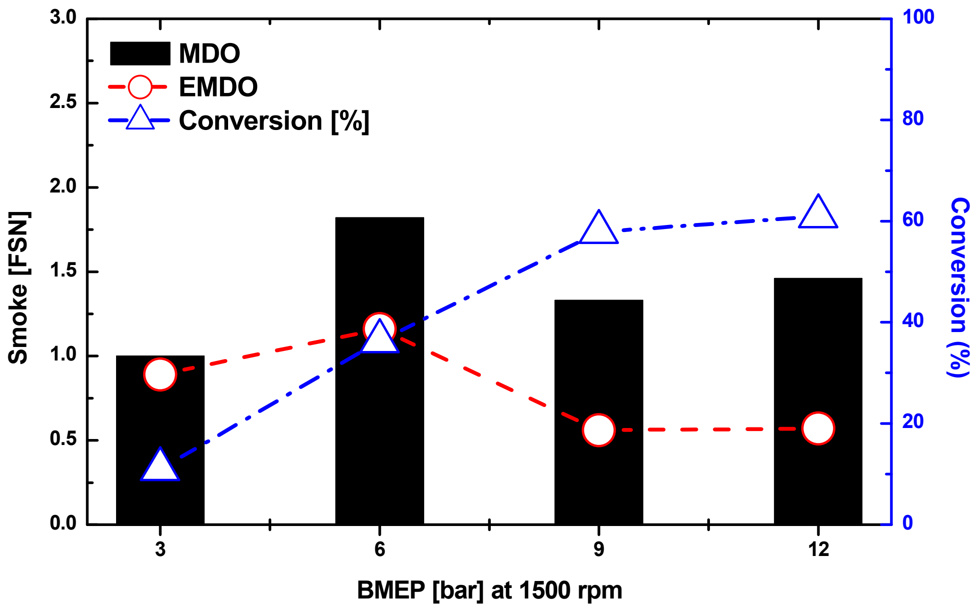
As the BMEP increased, the $NO_x$ reduction rate increased. This appeared to be because $NO_x$ was reduced in the combustion chamber as the combustion temperature in the combustion chamber was reduced by the micro-explosions and latent heat of evaporation caused by the water contained in the fuel. Overall, $NO_x$ was reduced by approximately 30% on average.

Figure 13 shows the exhaust characteristics for smoke reduction according to the BMEP and rpm. Figure 13 is a graph showing the smoke emission characteristics of MDO and EMDO under the respective experimental conditions. The smoke of EMDO was less than for MDO in the entire load range. As the engine load increased, the ignition delay as a result of water content in the diesel emulsions of the ship, the reduction in diesel inflow, and fuel particle formation due to micro-explosions improved the combustion, and smoke was reduced.

The conversion of the black carbon reduction is defined by the following equations:

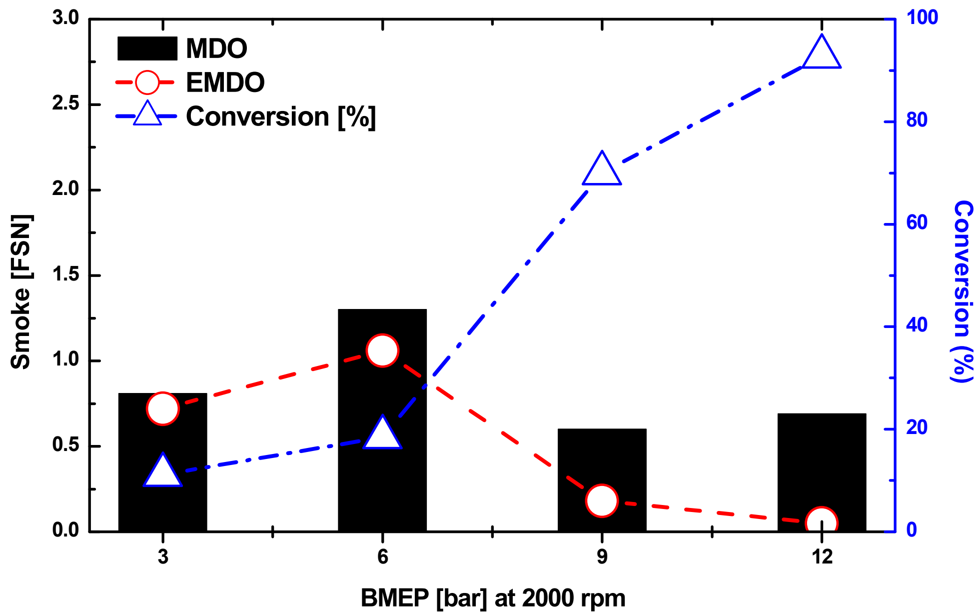
$$\text{Conversion } (\%) = \left[\frac{\text{FSN of } (\text{MDO} - \text{EMDO})}{\text{FSN of MDO}}\right]_{\text{NOx}} \times 100 \quad (3)$$

While smoke showed a tendency to decrease as BMEP increased in Figure 13a–c, it gradually decreased as rpm increased (as rpm is increased Figure 13a to Figure 13c. This appeared to be because smoke occurrence in the case of MDO was suppressed by the reduction in the combustion duration and the increase in heat release owing to the micro-explosions and absorption of evaporation (latent heat) caused by the water contained in EMDO.

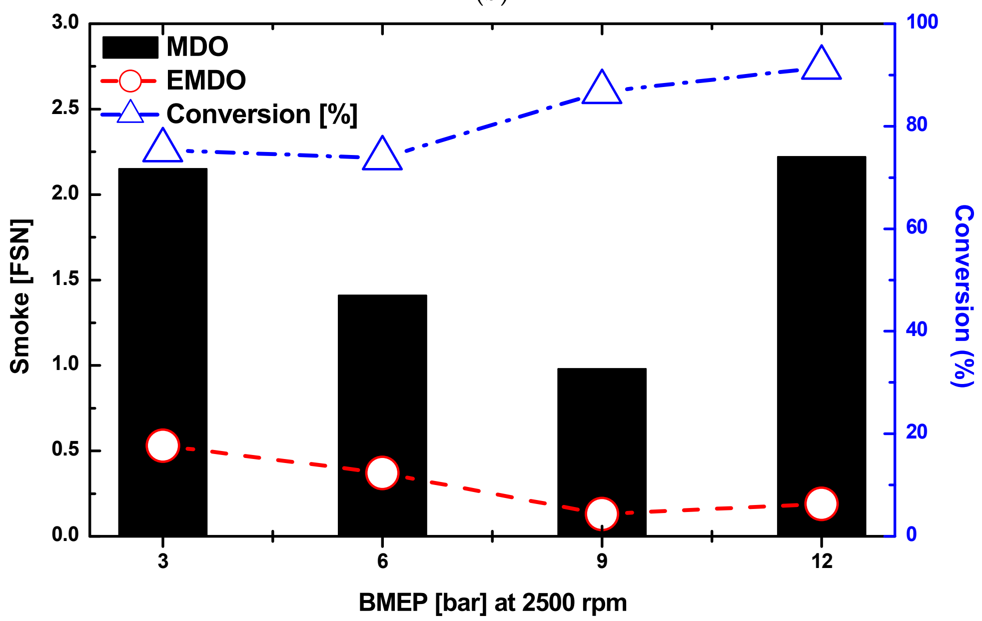



(a)

**Figure 13.** *Cont.*




(**b**)




(**c**)

**Figure 13.** Smoke reduction characteristics according to rpm and brake mean effective pressure (BMEP): (**a**) 1500 rpm; (**b**) 2000 rpm; (**c**) 2500 rpm.

The emulsified fuel used in this research was in such a form that it was wrapped in water as a dispersion, but such a water/oil (W/O)-type emulsified fuel causes micro-explosions in the combustion chamber and breaks the fuel up finely. It was concluded that it had the effect of decreasing the main given smoke, which was close to perfect combustion, and also the effect of depriving the water of vaporizing heat in the combustion chamber to lower the temperature inside the combustion chamber and suppress the generation of $NO_x$. In addition, as for the emulsified fuel, the smoke and $NO_x$ decreased as the moisture content increased; it turned out that these decreased more at the low BMEP than at the high BMEP as shown in all result of Figure 13a–c—as with $NO_x$. The cause of smoke reduction is due to the activation of combustion by promoting atomization of fuel due to the evaporation of water. The cause of nitrogen oxide reduction is reduced by the ambient temperature of the combustion chamber due to the latent heat of vaporization due to water evaporation. Therefore, the cause of this is reduced nitrogen oxides and smoke due to micro-explosion of the fuel. This was concluded to be due to the effect of ignition delay.

As the water content of the emulsified fuel increased, the smoke density decreased and the smoke levels decreased. As the moisture content of the MDO increased, the smoke density decreased. The reduction in smoke levels as the water content increased was achieved (1) a reduction in combustion temperature, (2) a promotion of the mixing of air and fuel by the increasing surface area of droplets due to micro-explosions of the emulsion, (3) an increase in water vapor concentration, and (4) the effect of the aqueous reaction of water and carbon.

Figure 14 shows the combustion stabilities of MDO and EMDO according to the rpm and BMEP. The combustion stability for EMDO was lower than that of MDO because of the low viscosity of EMDO and because the combustion temperature inside the combustion chamber at the low load had a BMEP of 3 bar. However, as the BMEP increased to a load of more than 6 bar, the combustion stabilities of MDO and EMDO became similar. Therefore, Overall, a stable combustion state was observed except for the case in which the BMEP was 3 bar. It appeared that an initial cold start could be a problem.

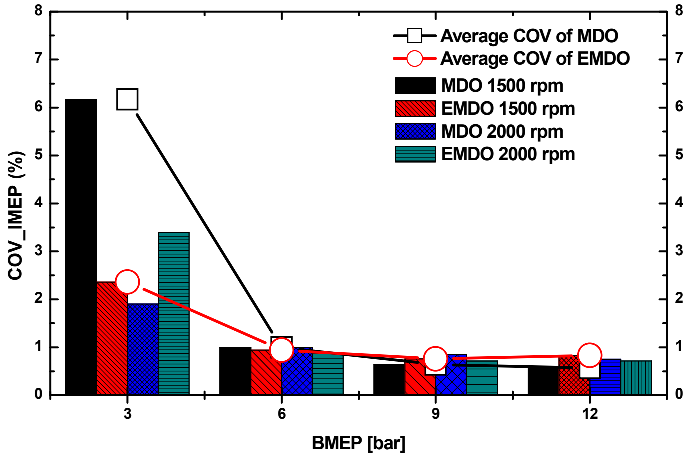



**Figure 14.** Combustion stability characteristics according to rpm and brake mean effective pressure (BMEP).

## 4. Conclusions

In this study, a water-in-oil ship diesel oil emulsion was applied to an automotive diesel engine using the MDO used for ships, and its combustion and exhaust characteristics were investigated. The following are the conclusions of this study.

(1) Under 3, 6, and 9 bar at 2500 rpm, EMDO exhibited higher cylinder pressure and heat release than MDO. In the case of ignition delay, EMDO was slightly faster than or similar to MDO. Rapid combustion reduced the combustion duration.

(2) As for the cylinder pressure and heat release, EMDO exhibited a higher cylinder pressure and shorter combustion duration than MDO under the experimental conditions. EMDO exhibited a 27% higher heat release and a 14% higher total release than MDO for the CA.

(3) EMDO exhibited a 14% higher fuel consumption than MDO. Comparing their pure fuel consumptions when excluding the water content, EMDO showed approximately 5% less fuel consumption than MDO.

(4) As a result of the experiment using EMDO and MDO according to the changes in load and rpm, the $NO_x$ and smoke reduction rates were 30% and 80%, respectively. Over the entire load area, drastic exhaust emission reduction performance was observed. In addition, in terms of the stability of the coefficient of variation for the indicated mean effective pressures of the two fuels, a stable combustion state was observed over the entire load area, but poor characteristics were observed over the low-load area.

(5) As the water content of the emulsified fuel increased, the smoke density decreased and the smoke levels decreased. As the moisture content of the MDO increased, the smoke density decreased and the smoke levels decreased. The reduction in smoke levels as the water content increased was from (1) a reduction in combustion temperature, (2) the promotion of the mixing of air and fuel by the increasing surface area of droplets due to micro-explosions of the emulsion, (3) an increase in the water vapor concentration, and (4) the effect of the aqueous reaction of water and carbon.

**Author Contributions:** M.K. and C.L. conceived and designed the experiments; M.K. performed the experiments; J.O. analyzed the data; M.K. contributed reagents/materials/analysis tools; C.L. wrote the paper.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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