

Article

Comparison of NO_x and Smoke Characteristics of Water-in-Oil Emulsion and Marine Diesel Oil in 400-kW Marine Generator Engine

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Abstract: Currently, the exhaust gas of a ship is regulated for nitrogen oxides and sulphur compounds; however, there is no IMO regulation on smoke under discussion. This study investigated the reduction of exhaust gas through ship emulsion fuel, which can simultaneously reduce nitrogen oxides and smoke in ship engines before smoke regulations are established. The combustion and exhaust characteristics were investigated according to the moisture content of emulsion fuel using a 400-kW generator engine. As the water content of the emulsion and the temperature of the combustion chamber increase, micro explosion increases and the combustion period decreases. The nitrogen oxide and smoke from the emulsion fuel used in this study decreased by 7% and 75%, respectively. The nitrogen oxides and soot reductions obtained by the use of emulsion fuel were boosted by micro-explosion of water contained in the fuel during combustion.

Keywords: micro explosion phenomena; marine diesel engine; emulsified oil; water-in-oil; MDO

1. Introduction

Large amounts of fuels are consumed in off-road or road vehicles, shipping, agriculture, forestry, and industrial generators. In such cases, diesel engines are preferred over gasoline engines because of their low fuel consumption, high output, rigid structure, and high brake thermal efficiency (BTE) [1]. As such, diesel engines are an important power source for automobiles. However, they are associated with the emission of pollutants, such as carbon monoxide, hydrocarbons, nitrogen oxides, and smoke [2]. Currently, the negative effects of such emissions on the human body such as pneumonia, breast and lung cancer will continue unless technologies for emission reduction are developed [3,4].

Lin et al. [5] investigated diesel engine performance and emission characteristics with oil-in-water emulsion fuel and emulsified fuel containing diglyme (a combination enhancer). They found that the CO level of water/diesel (W/D) emulsified fuel increased because of incomplete combustion caused by steam from water present in the emulsion fuel, but it can be reduced by adding diglyme, which assists combustion. The presence of moisture reduces NO_x emissions. Lin et al. [6] investigated diesel engine performance using two-phase and three-phase emulsion fuels. They used moisture contents of 10% and 20% in preparing the emulsified fuel and found that emulsified fuel increased the CO level, but decreased NO_x emissions by 56.82% compared to diesel fuel. Subramanian [7] found that reductions in NO_x and smoke in water–diesel emulsion fuel were lower compared to those of the injection method. However, the carbon monoxide and hydrocarbon levels were higher with emulsified oil.

Lin et al. [8] investigated the effects of NO_x and smoke emission characteristic on the emulsion oil type in water-in-oil and oil-in-water multiple emulsions. The specific fuel consumption, CO emissions

from the exhaust and the performance of this engine increased, whereas NO_x emissions decreased. Yang et al. [9] used a novel emulsified fuel with organic addition and found that CO and HC emissions slightly increased, whereas NO_x emissions decreased by 30.6%. Ogunkoya et al. [10] investigated the stabilization of emulsified oil with woody lignin. They stated that the emulsified oil increased the BTE, brake specific fuel, carbon monoxide and hydro carbon levels, whereas NO_x emissions decreased. Sadhik et al. [11] used diesel oil and water/diesel (W/D) and WD as nanoparticle additives, and found that specific fuel consumption (SFC) increased for W/D fuel and nanoparticle mixture. Furthermore, NO_x can be decreased by diesel water fuel and nanoparticles, but carbon monoxide and hydro carbon in the W/D fuel increased. These emissions can be reduced by adding alumina nanoparticles.

Research interests on additives of the main bases have continued to increase owing to improved combustion in the combustion process [12,13]. The additives mainly include copper, cerium, and platinum. Some researchers have reported that the addition of gold bases can improve the fuel quality and reduce BSFC and exhaust gas [14–16]. For example, Vellaiyan showed that HC, CO, and NO_x emissions can be reduced by adding 50 ppm and 100 ppm of lead oxide to water diesel emulsion (WDE) [17]. Farfaletti et al. investigated the addition of CeO₂ to new WDE mixed fuel and found that PM, HC, and CO emissions can be decreased [18]. In addition, Keskin [19] investigated the effect of adding gold on the combustion and exhaust gas of a diesel engine and noted that carbon monoxide and soot release decreased by 56.4% and 30.4%, respectively.

A multiple emulsion system consists of three phases separated by internal and external phase dispersed phases. Emulsified fuel is recommended for fuel preparation and oil/water/oil (W/O/W) emulsion is recommended for pharmaceutical use [20,21]. The 3-phase emulsion is prepared using methods such as phase transfer, mechanical stirring and two-step emulsion. The two-step emulsified technology is widely used for O/W/O emulsions and has been reported in many studies [22–25]. A 2-phase oil/water (O/W) emulsified oil is first prepared using hydrophilic additives and then a 3-phase emulsion is formed using lipophilic surfactant. Many researchers have investigated the effects of the characteristics of a marine ship's engine with a compression ratio (CR) of 17 on combustion and exhaust gas of a three-phase emulsion [10,26–30] and found that the 3-phase emulsion exhibits low specific fuel consumption, and low carbon monoxide and NO_x emissions. Furthermore, the exhaust gas temperature of 2-phase emulsified oil and basic diesel (BD) can be used in all loading conditions. They concluded that the complexity and high processing cost of analysing the microbubble behaviour of O/W/O emulsions is an undesirable characteristic of the 3-phase emulsion.

In this study, we investigated the combustion efficiency and exhaust performance of MDO and emulsified MDO (EMDO) by applying emulsified fuel according to the composition ratio of additive and moisture content. The characteristics of the fuel composition according to the water content, as well the stability characteristics of the fuel were investigated. The mechanisms of NO_x and soot reduction were analysed through an engine applicability test in which the engine loads and the moisture content of EMDO were varied. In addition, the reduction characteristics of nitrogen oxides and soot produced during combustion were investigated, and the fuel consumption rate characteristics of MDO and water containing emulsified fuel were compared to analyse SFC, nitrogen oxide and soot reduction characteristics.

2. Experimental Apparatus and Methodology

2.1. Emulsion Oil Properties

In this study, ship oil was used as the MDO, and EMDO was used as the water-in-oil-type emulsion fuel. The EMDO was prepared by mixing MDO, moisture and less than 1% additives. Component analyses were performed in used emulsified oil by Korea Petroleum Quality and Distribution Authority (KPQCA) to determine the characteristic of emulsified oils according to the moisture content. Table 1 presents the composition of the MDO and emulsion fuels containing 10%, 13% and 16% moisture.

As the moisture content increased, the calorific value and sulphur content tended to decrease, whereas the density and flash point increased.

Table 1. Specifications of fuel oil used in this study.

Items/Classifications	MDO	10% EMDO	13% EMDO	16% EMDO
Lower calorific value (J/g)	41,860	36,760	34,610	34,430
Gross calorific value (J/g)	44,810	39,990	37,880	37,690
Hydrogen (m/m %)	13.06	13.06	12.87	12.73
Carbon (m/m %)	85.90	79.08	77.55	78.97
Sulphur content (Weight %)	0.19	0.15	0.14	0.13
Density @ 20 °C (kg/m ³)	858.9	872.3	878.5	882.3
Moisture (Volume %)	0.3	11.0	14.5	15.2
Flash point (°C)	104	102	114	118

As the ambient temperature increases, the duration of micro-explosion increases and the frequency of occurrence increases nearly three times [31]. The lower the atmospheric temperature, the lower the frequency of occurrence of micro explosions. It takes a long time for the droplets to be heated and burned, the evaporation of the droplets occurs in advance, and the size of the droplets is reduced. As the mixing ratio of water and the ambient temperature increase, the frequency of micro-explosions increases.

2.2. Experimental Apparatus

Figure 1 shows a schematic diagram for studying the combustion and exhaust characteristics of three types of emulsion fuel and MDO in an actual ship according to the water content. The 4-stroke turbocharger engine used in this study is a 400-kW generator engine. As shown in Figure 1, the 4-stroke engine consists of a generator engine, a controller panel, a data acquisition system, an exhaust gas analyser, and a pressure sensor. The engine load was adjusted using a load cell in the ship. The pressure sensor was mounted on the No. 6 cylinder through a hole in the combustion chamber, and signals from the data acquisition device, the flow meter and the encoder were simultaneously acquired from the sensor (model 6056 A, Kistler, Winterthur, Switzerland). The resolution of the encoder used in this study is 1CA. The heat generation rate was calculated by applying a zero-dimensional combustion model and averaging combustion data of 100 cycles.

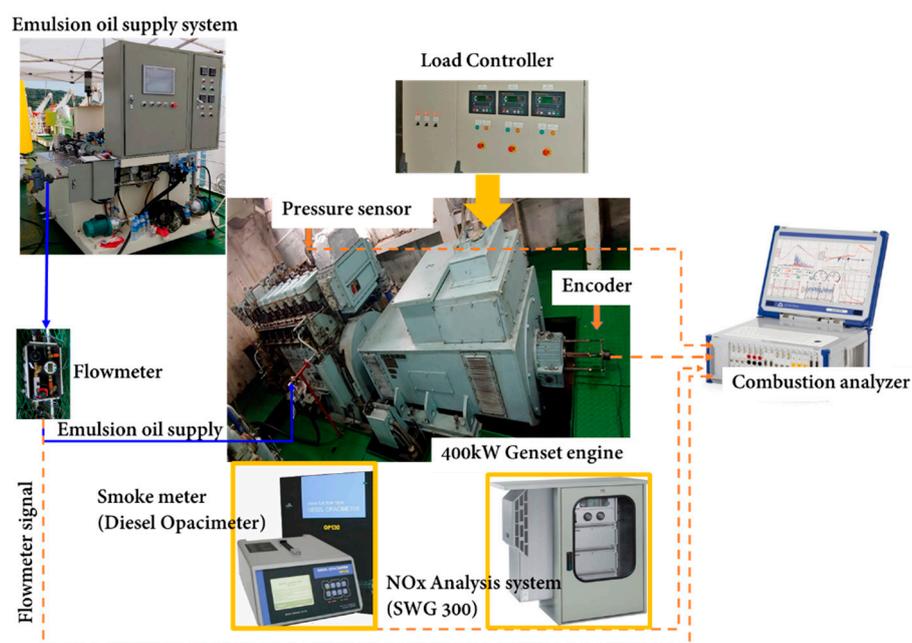


Figure 1. Schematic diagram of the marine engine and engine dynamometer.

The specifications of the engine used in this study, which consists of a six-combustion chamber, a mechanical pump and a four-stroke cycle diesel engine, are presented in Table 2.

Table 2. Specification of the test engine.

Items/Descriptions	Specifications
Engine type	4-stroke turbo-charged DI marine generator engine
Number of cylinders	6
Bore × Stroke (mm)	165 × 210
Displacement (cc)	18,000
Fuel injection system	Mechanical pumping system (Max. 1400 bar)
Engine's maximum continuous rating (MCR) (kW/rpm)	400 kW/1200 rpm

Table 3 presents the specifications of the exhaust gas analyser used in this study. The SWG 300 model was used to measure nitrogen oxides exhaust gas, whereas a diesel opacimeter was used to measure smoke.

Table 3. Specifications of the engine dynamometer and exhaust analyser.

Items	Specification
Dynamometer	Load controller (in a marine ship)
Exhaust gas analyser	SWG 300
Smoke meter	Diesel opacimeter (OP 130D)

2.3. Experimental Conditions

In this study, the combustion and exhaust characteristics of three types of emulsion oil and MDO were investigated for loads of 100 kW, 200 kW and 300 kW, and moisture contents of emulsion fuel of 10%, 13% and 16%. The experimental conditions of this study are listed in Table 4.

Table 4. Engine test conditions.

Fuel	MDO, EMDO (10%, 13% and 16%)
Engine speed (rpm)	1200
Load (kW)	100 (25%), 200 (50%), 300 (75%)

3. Results and Investigations

3.1. Characteristics of Combustion and Heat Release Rate of Emulsion Fuel According to Moisture Content

Figure 2 shows the results of comparison of the cylinder pressure and heat release characteristics for a conventional marine diesel engine according to the ratio of emulsified fuels and engine loads. The cylinder pressure and the rate of heat release increased with increasing engine load. The result in Figure 2 shows the characteristics of a conventional marine diesel engine. The figure also shows results of analysis of the combustion and heat release characteristics according to the variation of emulsified MDO with water concentrations of 10%, 13%, and 16%.

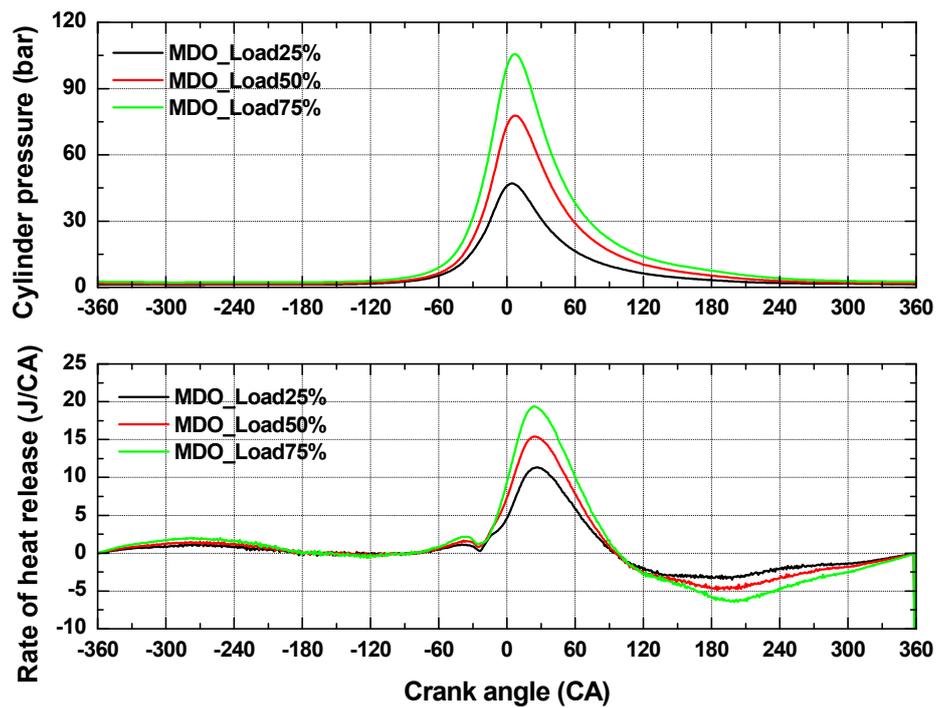
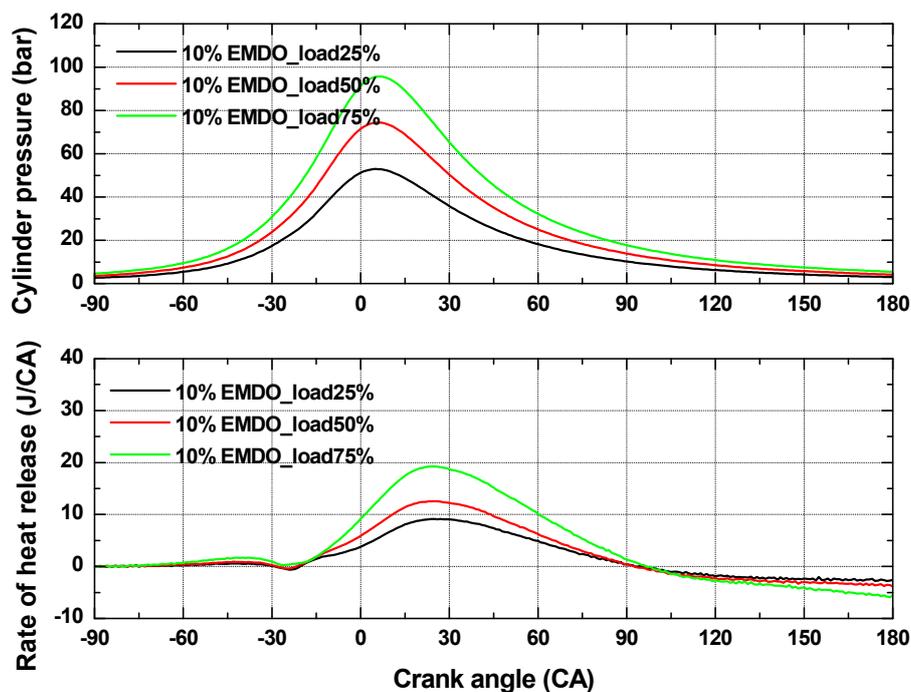


Figure 2. Characteristics of the cylinder pressure and heat release in a conventional marine engine with MDO.

Figure 3 shows a comparison of the combustion pressure and heat generation rate with increasing load using emulsion oil with 10% water content. As the water content in the emulsion oil increases, the combustion pressure tends to increase. This is because micro-explosion increases as the ambient temperature increases [32]. Results from this study show that micro-explosion is mostly caused by increase in the combustion pressure and temperature as the load increases.



(a)

Figure 3. Cont.

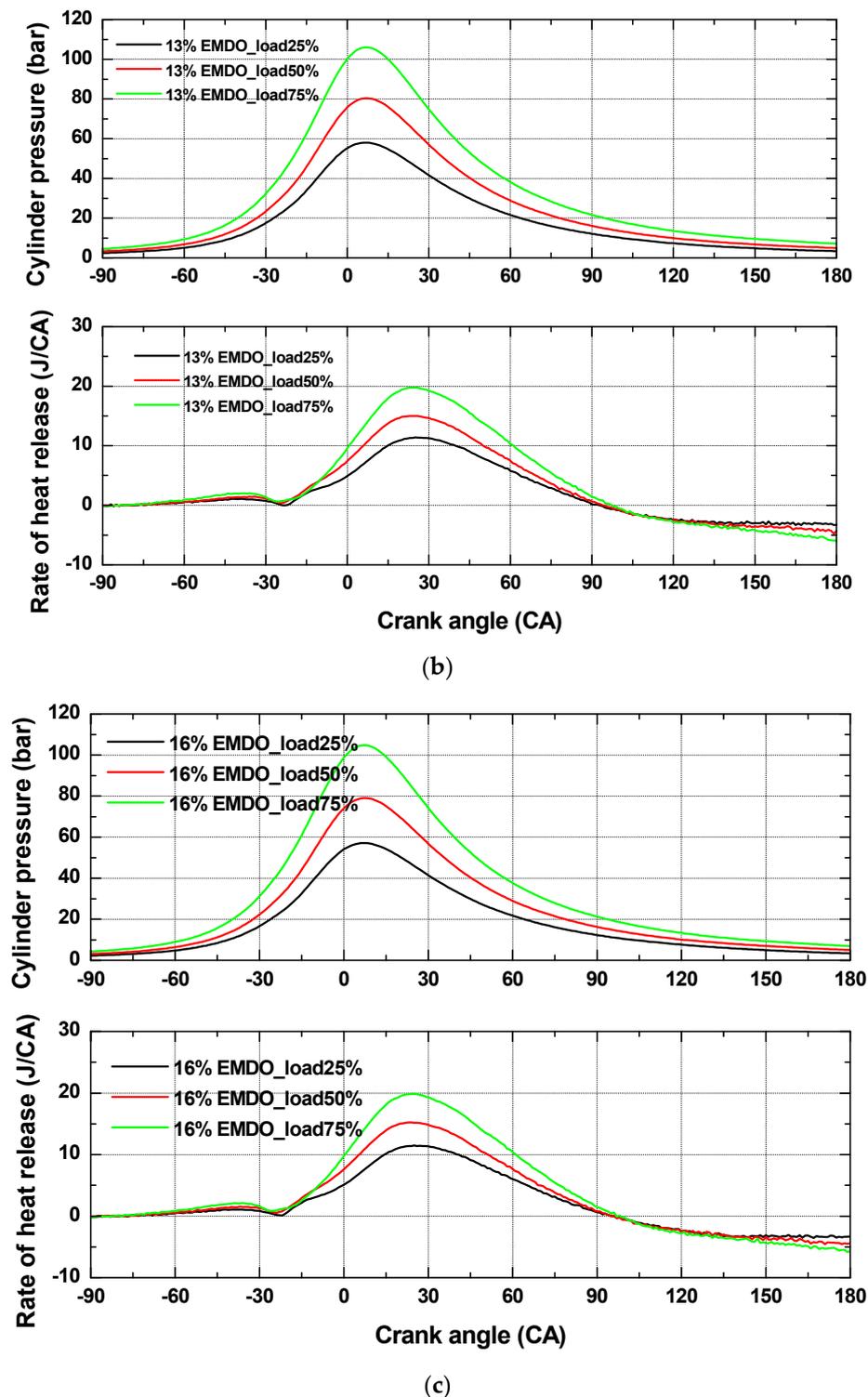
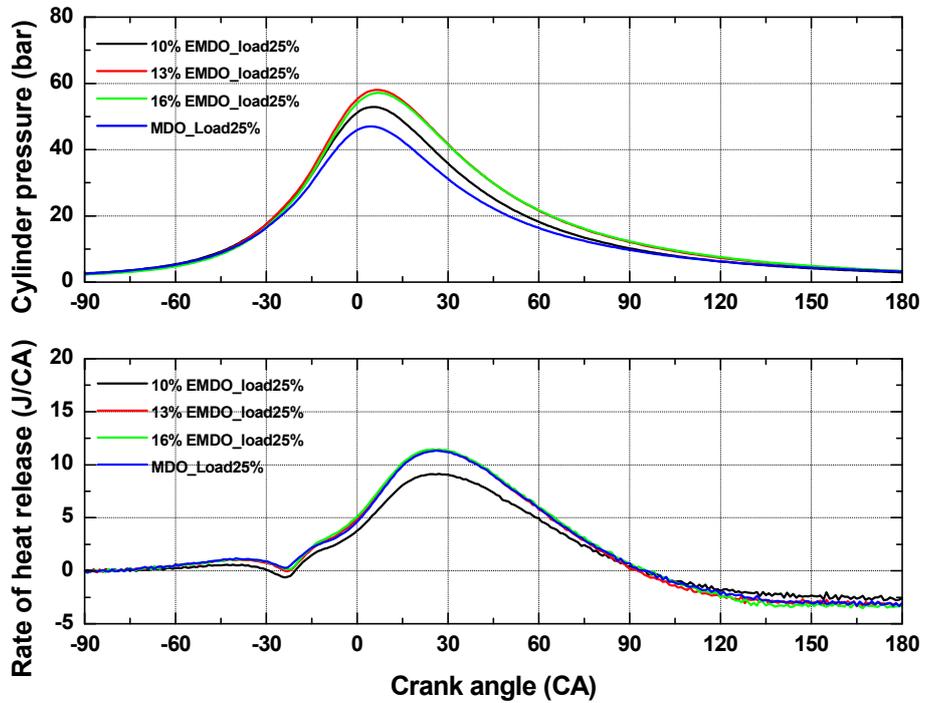


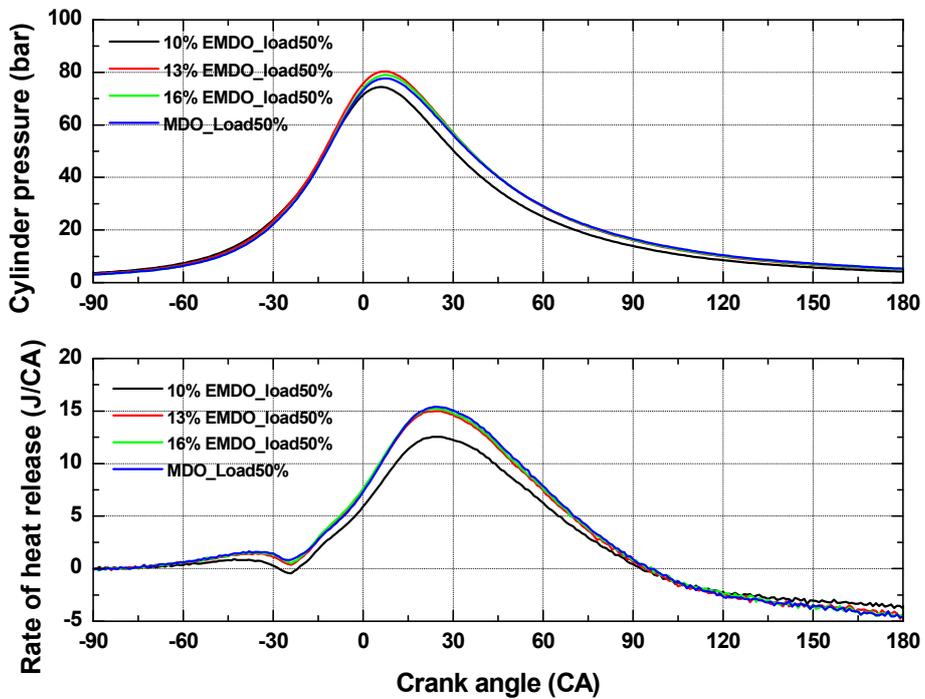
Figure 3. Characteristics of cylinder pressure and heat release of emulsified fuel according to moisture content: (a) Emulsion ratio 10%; (b) Emulsion ratio 13%; (c) Emulsion ratio 16%.

Figure 4 shows the combustion pressure and heat generation rate according to the water content of the emulsion under the same load conditions. Overall, the use of emulsion oil with water content of 16% yields the highest combustion pressure. The combustion pressure generally increased due to increase in the moisture content. In particular, emulsion oil with 10% moisture content exhibits very poor heat generation characteristic compared to MDO. The reason for this is unclear; however, it

is determined that the engine condition was not satisfied with the current experimental conditions. As shown in Figure 4a–c, the cylinder pressure was higher for emulsion fuel containing water compared to MDO. This is possibly because the combustion of emulsified fuel containing 16% water is activated by micro-explosion. Furthermore, as the mixing ratio of water and the ambient temperature increase, the frequency of occurrence of micro-explosions increases.



(a)



(b)

Figure 4. Cont.

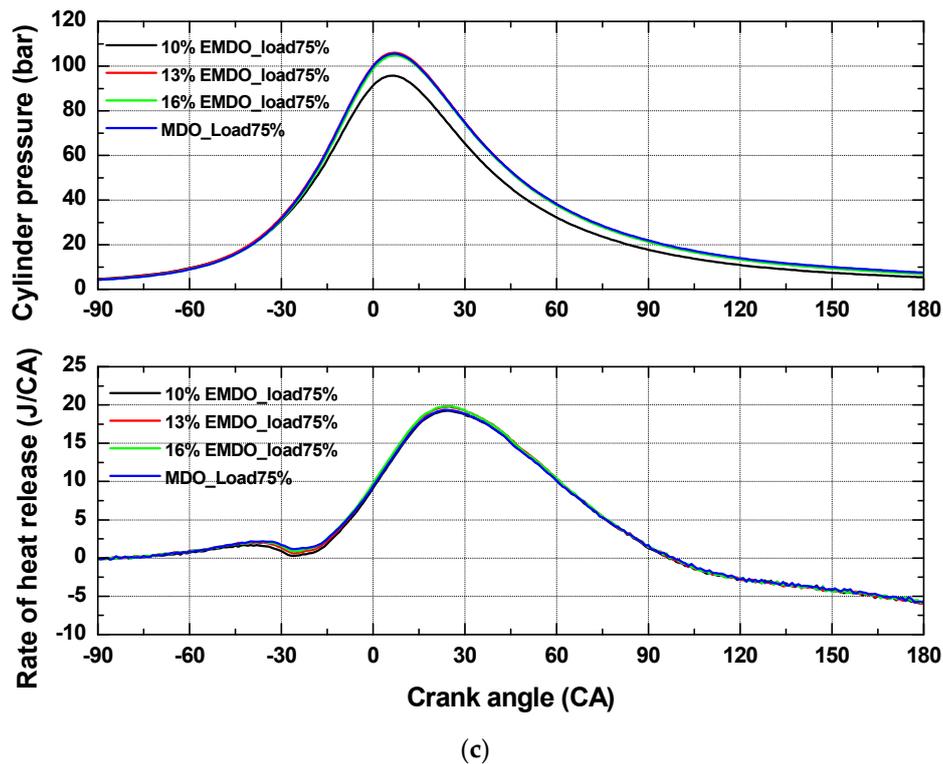


Figure 4. Characteristics of cylinder pressure and heat release with MDO and emulsified fuel according to moisture content: (a) Load 25%; (b) Load 50%; (c) Load 75%.

3.2. Combustion Duration Characteristics of MDO and EMDO

A zero-dimensional model [33] with air as the working fluid was used to predict the temperature and the net heat release (NHR) inside the cylinder. The total cumulative NHR was obtained by integrating the derivative of the NHR over the relevant crank angle rotation. The start of combustion (SOC) time was defined as the time when 10% of the accumulated heat release occurred. The point of combustion end was defined as 90% of the cumulative heat release. The combustion duration (CD) was defined as the crank angle rotation period between the SOC and the end of combustion.

Figure 5 shows the definitions of SOC and CD. In this study, SOC was used as the combustion timing indicator. Other parameters commonly used to quantify and characterize combustion onset are the maximum pressure (Pmax) timing and maximum pressure rate ($dP/d\theta$) max timing. All the pressure related parameters, including SOC, CD, Pmax, and ($dP/d\theta$) max, were calculated for 100 individual cycles at each point and then averaged. The heat release calculations indicate a strong correlation between calculated and actual pressure trace parameters.

Figure 6 shows the results of analysis of the combustion duration according to varying engine loads and moisture content of Emulsified Marine Diesel Oil (EMDO). The combustion period of commercial EMDO fuel was shorter compared to MDO. It is considered that moisture contained in the emulsion oil, as well as minute explosion during combustion boosted combustion. However, as the water content of EMDO increased, the combustion period tended to increase. The combustion period of 10% EMDO was shorter than those of 13% EMDO and 16% EMDO.

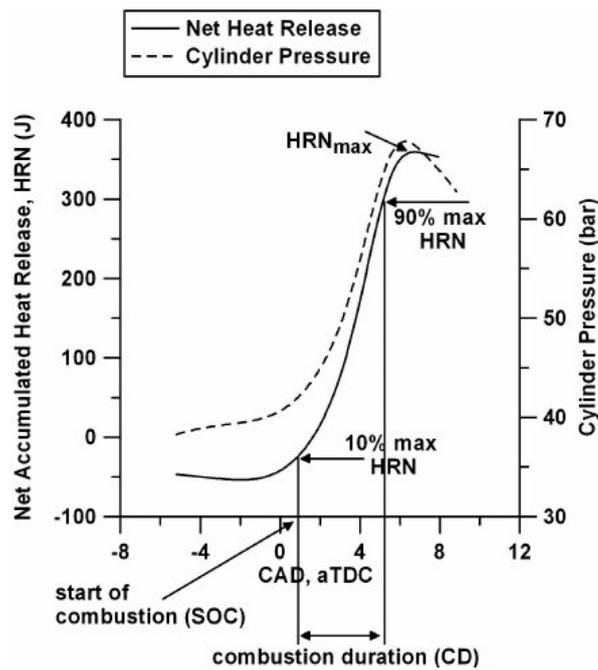


Figure 5. Start of combustion and combustion duration indicating net accumulated heat release and pressure history [34].

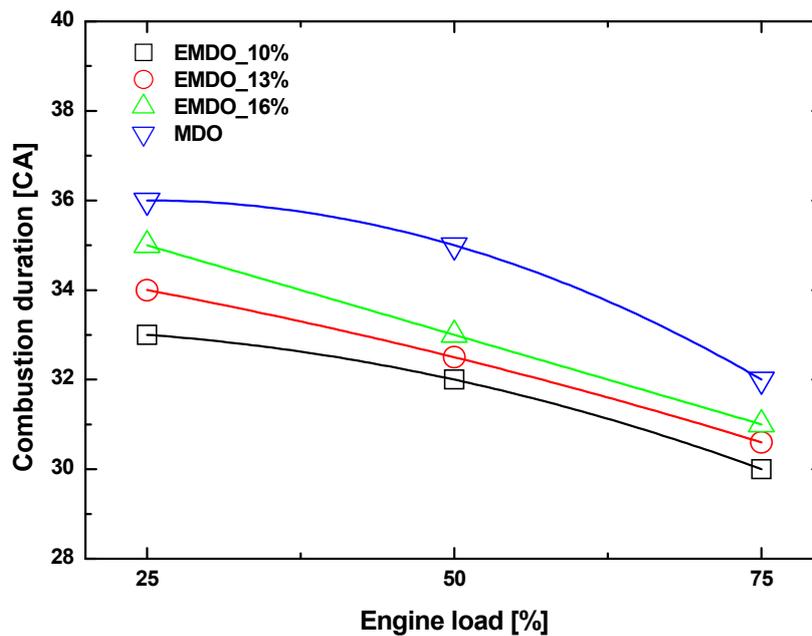


Figure 6. Characteristics of combustion duration according to engine loads.

Figure 7 shows the ratio of combustion of emulsion oil according to MDO combustion period and moisture content. The ratio of combustion duration of EMDO to MDO fuels is calculated using Equation (1):

$$\text{Ratio of combustion duration (\%)} = \text{Combustion duration} \frac{MDO - EMDO}{MDO} \times 100 \quad (1)$$

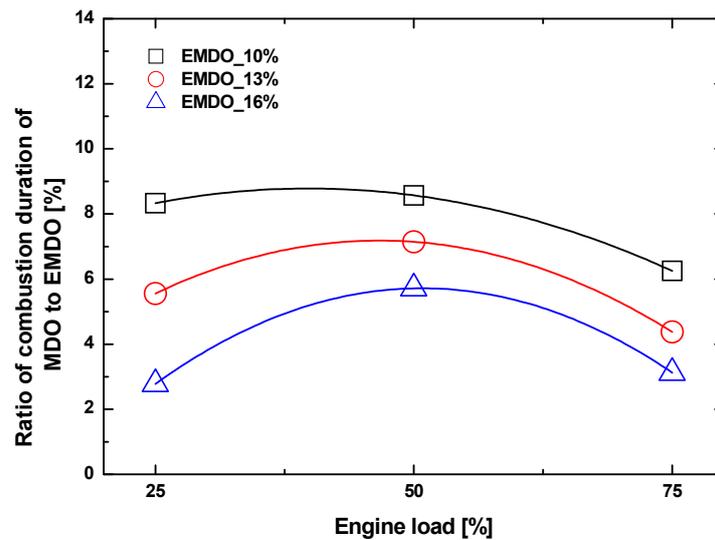


Figure 7. Ratio of combustion duration of MDO to EMDO according to BMEP and rpm.

The combustion duration of 10% EMDO yielded reduction ratios of 8.3%, 8.5% and 6.3%, that of 13% EMDO yielded 5.5%, 7.1% and 4.4%, and that of 16% EMDO yielded 2.7%, 5.7%, and 3.1% with loads compared to 10%, 13%, and 16% water concentration MDO. Overall, the characteristic of emulsion oil is such that the combustion period is shortened by 2–8% compared to that of MDO. This is because as the atmospheric temperature increases, micro explosion increases. As a result, the combustion pressure and temperature increase as the load increases. It can be observed that it occurs actively micro explosion phenomena.

3.3. Comparison of Specific Fuel Consumption of MDO and Emulsified Fuel According to Moisture Content

Figure 8 shows the fuel consumptions with and without water; Figure 8a shows the fuel consumption with water, whereas Figure 8b shows the fuel consumption without moisture content. The results show that to obtain the same output, the fuel consumption rate of the emulsified fuel was increased, depending on the water content. The low calorific value of the fuel presented in Table 1 indicates that the fuel consumption rate will increase.

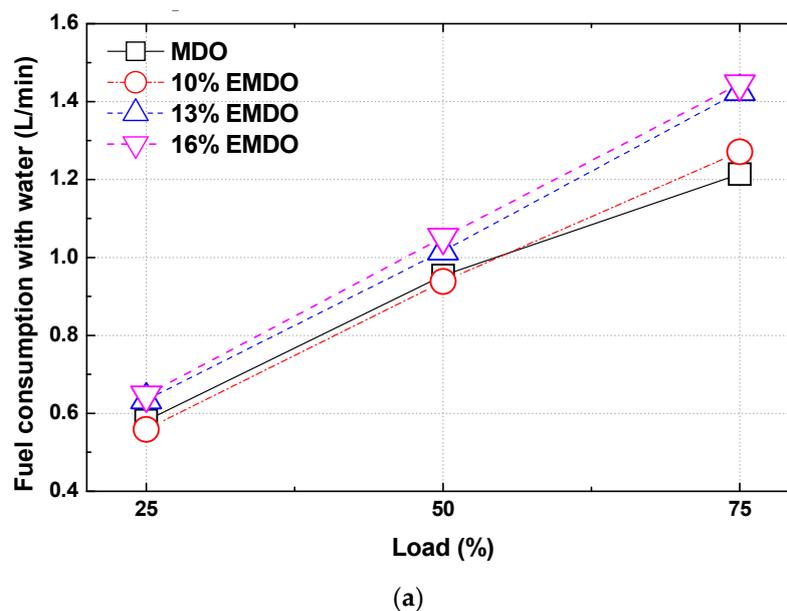


Figure 8. Cont.

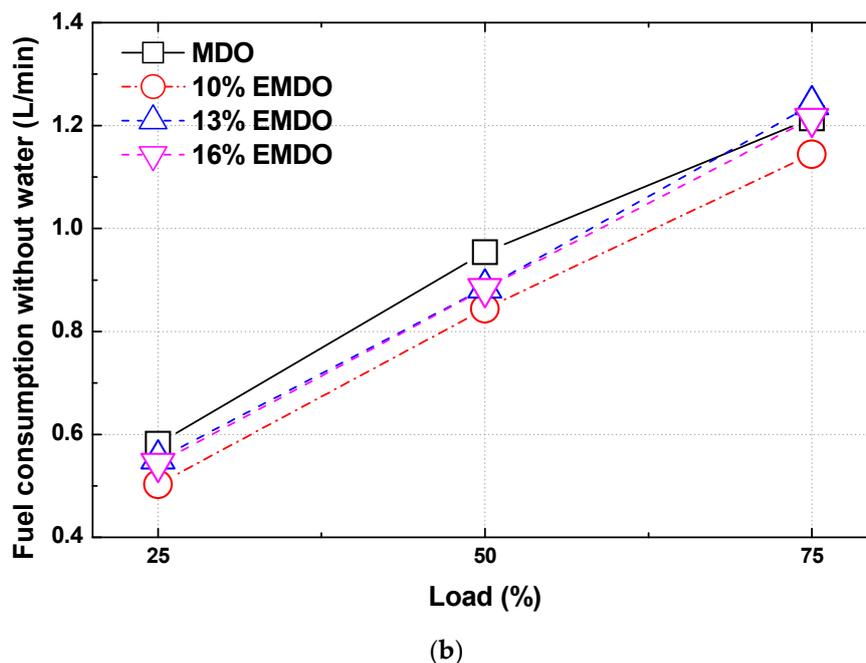


Figure 8. Fuel consumption of MDO and EMDO fuel according to emulsified fuel ratio: (a) With water; (b) Without water.

Figure 9 shows the fuel consumption rate characteristics according to the composition of the load and emulsified fuel. The specific fuel consumptions of 10% EMDO decreased by 13.5%, 11.5%, and 5.7%, those of 13% EMDO by 5.1%, 7.3%, and -2.1% , and those of 16% EMDO by 6.5%, 7.4%, and 0% with loads. However, at 75% engine load, the fuel consumption rate of 10% EMDO decreased, whereas the fuel consumption rates of 13% EMDO and 16% EMDO increased.

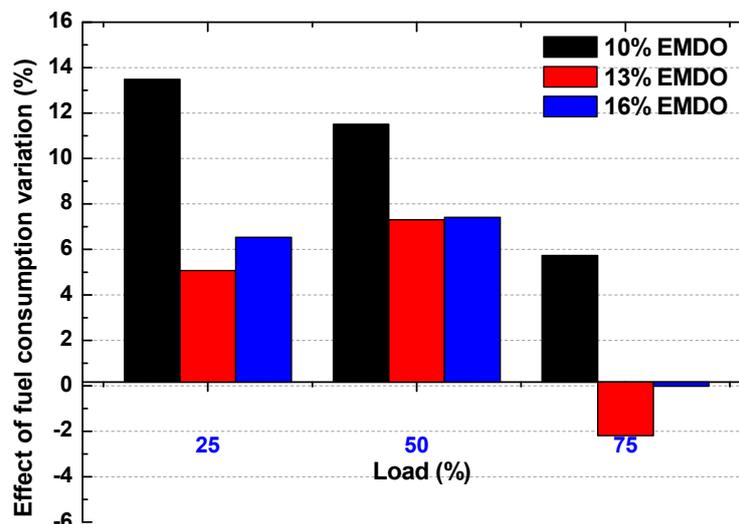


Figure 9. Fuel consumption without water with MDO and EMDO according to emulsified fuel ratio.

3.4. Combustion and Exhaust Characteristics of MDO and Emulsified Fuel According to Moisture Content

Figure 10 shows the results of nitrogen oxides reduction of MDO and EMDO, which is emulsion oil with moisture contents of 10%, 13%, and 16%. Nitrogen oxides decreased at 50% and 75% load conditions, but not at 25% load condition. Emulsion oil with 16% moisture content yielded the highest nitrogen oxides reduction. It is considered that this is due to the increase in micro explosion and

decrease in the combustion chamber temperature; as the ambient temperature increases, the latent heat of evaporation in the combustion chamber increases due to evaporation of water. This can be attributed to the suppression of NO_x generation owing to the shortened combustion period with decreased combustion temperature caused by evaporation of water, as well as improvement in combustion due to micro-explosion. The conversion of NO_x reduction is given as follows:

$$\text{Conversion (\%)} = \left[\frac{\text{ppm of (MDO - EMDO)}}{\text{ppm of MDO}} \right]_{\text{NO}_x} \times 100 \quad (2)$$

As the water concentration of MDO and load increased, the reduction rate of NO_x increased. Overall, the maximum NO_x reduction was approximately 9%.

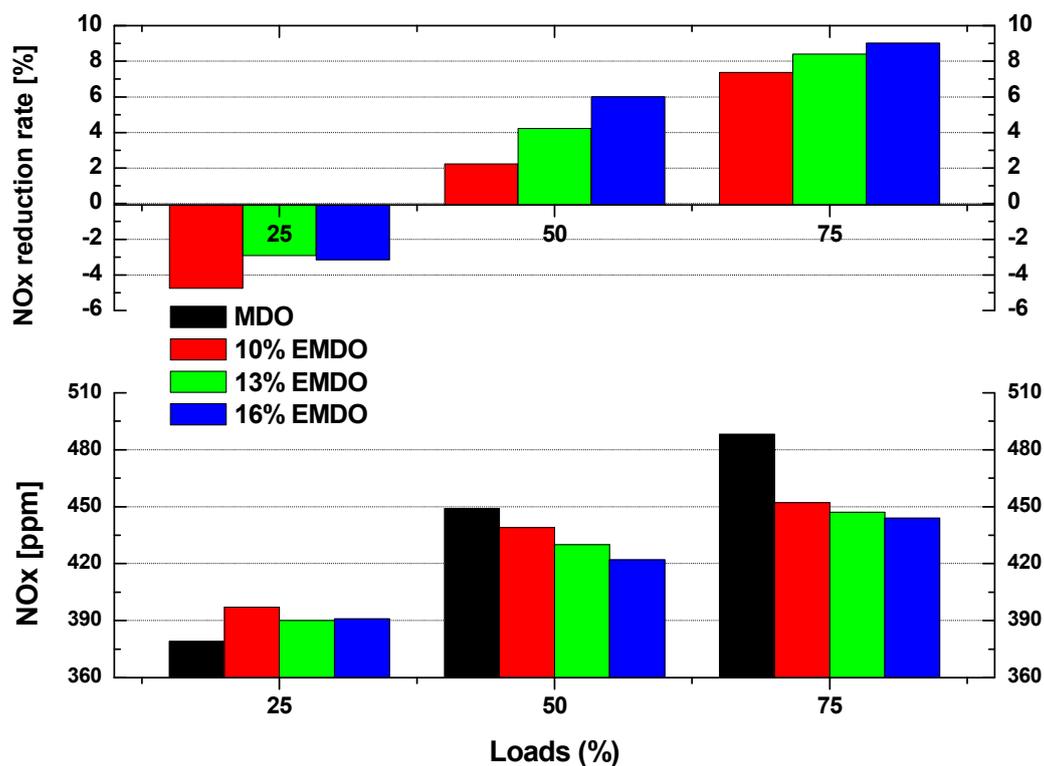


Figure 10. NO_x reduction characteristics according to load and rate of water concentration of MDO.

Figure 11 shows the exhaust characteristics for smoke reduction according to the load and water concentration of MDO. In the entire load range, smoke emissions were lower with EMDO than with MDO. The conversion of black carbon reduction is given as follows:

$$\text{Conversion (\%)} = \left[\frac{\text{Opacity of (MDO - EMDO)}}{\text{Opacity of MDO}} \right]_{\text{NO}_x} \times 100 \quad (3)$$

We observed that smoke exhibited a decreasing trend with increasing water concentration in MDO and gradually decreased as the loads increased. It is considered that the smoke decreased owing to shortening of the trailing edge due to micro explosion of water contained in emulsified fuel and decrease in combustion duration due to evaporation and increase in heat release.

The emulsified fuel used in this study was produced according to the moisture content. Such W/O type emulsified fuel is produced in the combustion chamber as a result of micro-explosion, thereby finely atomizing the fuel. This phenomenon reduces lead in smoke produced close to complete combustion, and also suppresses the formation of nitrogen oxides by lowering the temperature in the combustion chamber and eliminating the vaporization heat required by water in the combustion

chamber. In addition, smoke and NO_x emissions decreased as the water content of emulsified fuel increased. The decrease was found to be more significant with high load than with low load. The decrease in smoke and NO_x emissions with increasing moisture content suggests improvements in air and fuel mixing, increase in water vapor concentration, increase in water vapor due to decrease in the combustion temperature, and increase in the surface area of droplets due to micro-explosion.

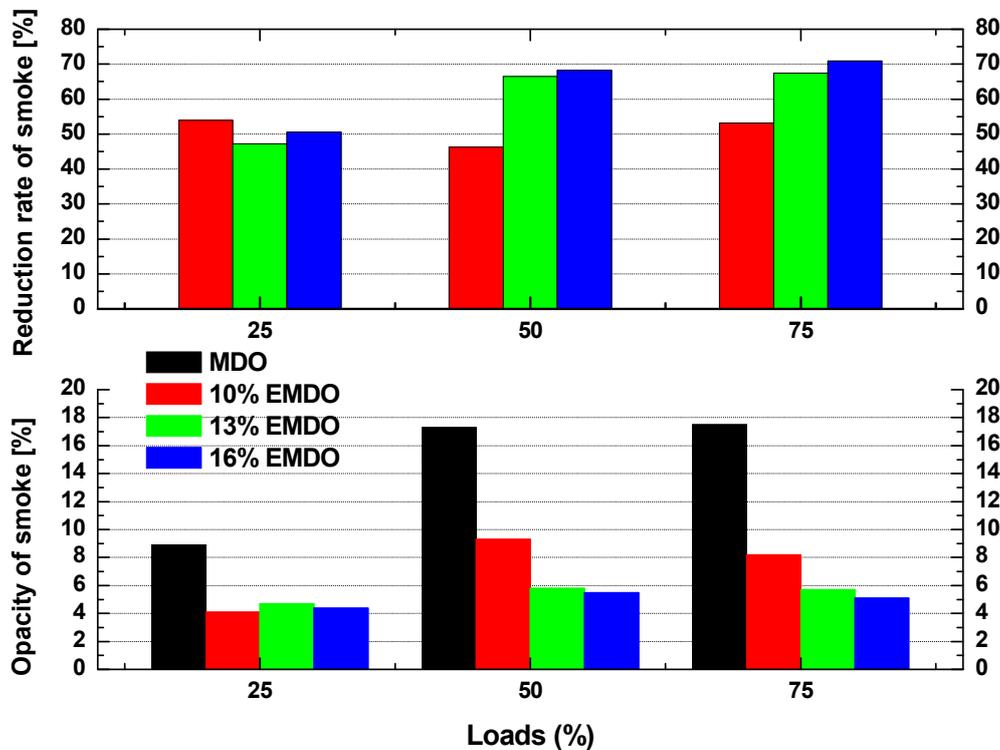


Figure 11. Smoke reduction characteristics according to load and water concentration of MDO.

4. Conclusions

In this study, a 400-kW marine diesel generator engine was investigated using marine MDO. In addition, the combustion and exhaust characteristics were investigated using diesel oil as oil-in-water emulsion. The following conclusions are drawn from this study:

- (1) EMDO exhibited higher cylinder pressure and shorter combustion duration than MDO. The combustion durations of 10% EMDO decreased by 8.3%, 8.5% and 6.3%, those of 13% EMDO by 5.5%, 7.1% and 4.4%, and those of 16% EMDO by 2.7%, 5.7% and 3.1% with loads compared to MDO with water concentrations of 10%, 13% and 16%.
- (2) The pure fuel consumptions of 10% EMDO decreased by 13.5%, 11.5%, and 5.7%, those of 13% EMDO by 5.1%, 7.3%, and -2.1%, and those of 16% EMDO by 6.5%, 7.4%, and 0% with loads compared to MDO. In the case of 75% engine load, the fuel consumption rate of 10% EMDO decreased, whereas those of 13% and 16% EMDO increased.
- (3) The NO_x emissions of EMDO fuel decreased by up to 8% at 75% load compared to MDO. The smoke reduction rate was 75% for 16% EMDO at 75% engine load.
- (4) As the water content of emulsified fuel increased, the nitrogen oxide emission and smoke exhaust decreased. The smoke density and emission also decreased with increase in the moisture content of MDO. The reduction of smoke with increasing water content could be attributed to the following factors: (1) reduction in the combustion temperature, (2) the mixture of the surrounding air and the fuel is boosted as the surface area of the droplet increases due to fine explosion of

the emulsion; (3) increase in the moisture content; and (4) effect of aqueous reaction of water and carbon.

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References

1. Dhinesh, B.; Lalvani, J.I.; Parthasarathy, M.; Annamalai, K. An assessment on performance, emission and combustion characteristics of single cylinder diesel engine powered by Cymbopogon flexuosus biofuel. *Energy Convers. Manag.* **2016**, *117*, 466–474. [[CrossRef](#)]
2. Sharma, A.; Kumar, N.; Vibhanshu, V.; Deep, A. *Emission Studies on a VCR Engine Using Stable Diesel Water Emulsion*; SAE Technical Paper; SAE International: Warrendale, WA, USA, 2013. [[CrossRef](#)]
3. Nadeem, M.; Rangkuti, C.; Anuar, K.; Haq, M.R.; Tan, I.B.; Shah, S.S. Diesel engine performance and emission evaluation using emulsified fuels stabilized by conventional and gemini surfactants. *Fuel* **2006**, *85*, 2111–2119. [[CrossRef](#)]
4. Şahin, Z.; Tuti, M.; Durgun, O. Experimental investigation of the effects of water adding to the intake air on the engine performance and exhaust emissions in a DI automotive diesel engine. *Fuel* **2014**, *115*, 884–895. [[CrossRef](#)]
5. Lin, C.Y.; Wang, K.H. Effects of a combustion improver on diesel engine performance and emission characteristics when using three-phase emulsions as an alternative fuel. *Energy Fuels* **2004**, *18*, 477–484. [[CrossRef](#)]
6. Lin, C.Y.; Wang, K.H. Diesel engine performance and emission characteristics using three-phase emulsions as fuel. *Fuel* **2004**, *83*, 537–545. [[CrossRef](#)]
7. Subramanian, K.A. A comparison of water–diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions. *Energy Convers. Manag.* **2011**, *52*, 849–857. [[CrossRef](#)]
8. Lin, C.Y.; Wang, K.H. Effects of diesel engine speed and water content on emission characteristics of three-phase emulsions. *J. Environ. Sci Health Part A Toxic Hazard. Subst. Environ. Eng.* **2006**, *39*, 1345–1359. [[CrossRef](#)]
9. Yang, W.M.; An, H.; Chou, S.K.; Vedharaji, S.; Vallinagam, R.; Balaji, M.; Mohammad, F.E.A.; Chua, K.J.E. Emulsion fuel with novel nano-organic additives for diesel engine application. *Fuel* **2013**, *104*, 726–731. [[CrossRef](#)]
10. Ogunkoya, D.; Li, S.; Rojas, O.J.; Fang, T. Performance, combustion, and emissions in a diesel engine operated with fuel-in-water emulsions based on lignin. *Appl. Energy* **2015**, *154*, 851–861. [[CrossRef](#)]
11. Sadhik Basha, J.; Anand, R.B. Effects of nanoparticle additive in the water-diesel emulsion fuel on the performance, emission and combustion characteristics of a diesel engine. *Int. J. Veh. Des.* **2012**, *59*, 164–181. [[CrossRef](#)]
12. Shukla, P.C.; Gupta, T.; Labhassetwar, N.K.; Khobaragade, R.; Gupta, N.K.; Agarwal, A.K. Effectiveness of non-noble metal based diesel oxidation catalysts on particle number emissions from diesel and biodiesel exhaust. *Sci. Total Environ.* **2016**, *574*, 1512–1520. [[CrossRef](#)] [[PubMed](#)]
13. Saraee, H.S.; Taghavifar, H.; Jafarmadar, S. Experimental and numerical consideration of the effect of CeO₂ nanoparticles on diesel engine performance and exhaust emission with the aid of artificial neural network. *Appl. Therm. Eng.* **2016**, *113*, 663–672. [[CrossRef](#)]
14. Saxena, V.; Kumar, N.; Saxena, V.K. A comprehensive review on combustion and stability aspects of metal nanoparticles and its additive effect on diesel and biodiesel fuelled C.I. engine. *Renew. Sustain. Energy Rev.* **2017**, *70*, 563–588. [[CrossRef](#)]
15. Ashok, B.; Nanthagopal, K.; Subbarao, R.; Johny, A.; Mohan, A.; Tamilarasu, A. Experimental studies on the effect of metal oxide and antioxidant additives with Calophyllum Inophyllum Methyl ester in compression ignition engine. *J. Clean. Prod.* **2017**, *166*, 474–484. [[CrossRef](#)]

16. Mitchell, M.R.; Link, R.E.; Kao, M.J.; Ting, C.C.; Li, B.F.; Tsung, T.T. Aqueous aluminum nanofluid combustion in diesel fuel. *J. Test. Eval.* **2008**, *36*, 186–190. [[CrossRef](#)]
17. Vellaiyan, S.; Amirthagadeswaran, K.S. Zinc oxide incorporated water-in-diesel emulsion fuel: Formulation, particle size measurement, and emission characteristics assessment. *Pet. Sci. Technol.* **2016**, *34*, 114–122. [[CrossRef](#)]
18. Farfaletti, A.; Astorga, C.; Martini, G.; Manfredi, U.; Mueller, A.; Rey, M.; De Santi, G.; Krasenbrink, A.; Larsen, B.R. Effect of water/fuel emulsions and a cerium-based combustion improver additive on HD and LD diesel exhaust emissions. *Environ. Sci. Technol.* **2005**, *39*, 6792–6799. [[CrossRef](#)] [[PubMed](#)]
19. Keskin, A.; Gürü, M.; Altıparmak, D. Influence of tall oil biodiesel with Mg and Mo based fuel additives on diesel engine performance and emission. *Bioresour. Technol.* **2008**, *99*, 6434–6438. [[CrossRef](#)]
20. Kovacs, A.; Csoka, I.; Konya, M.; Csanyi, E.; Feher, A.; Istvan, E. Structural analysis of W/o/W multiple emulsions by means of DSC. *J. Therm. Sci. Calori.* **2005**, *82*, 491–497. [[CrossRef](#)]
21. Dluska, E.; Hubacz, R.; Wronski, S.; Kamienski, J.; Dylag, M.; Wojtowicz, R. The influence of helical flow on water fuel emulsion preparation. *Chem. Eng. Commun.* **2007**, *194*, 1271–1286. [[CrossRef](#)]
22. Eckert, P.; Velji, A.; Spicher, U. Numerical Investigation of fuelwater emulsion combustion in DI-diesel Engines. In Proceedings of the International Council on Combustion Engines, CIMAC, Vienna, Austria, 21–24 May 2007.
23. Weber, J.; Peters, N.; Bockhorn, H.; Pittermann, R. Numerical simulation of the evolution of the soot particle size distribution in a DI diesel engine using an emulsified fuel of diesel-water. *SAE Trans.* **2004**, *113*, 2217–2233.
24. Kim, M.; Oh, J.; Lee, C. Study on Combustion and Emission Characteristics of Marine Diesel Oil and Water-In-Oil Emulsified Marine Diesel Oil. *Energies* **2018**, *11*, 1830. [[CrossRef](#)]
25. Ismael, M.A.; Morgan, R.; Heikal, A.; Aziz, R.A.; Crua, C. The Effect of Fuel Injection Equipment of Water-In-Diesel Emulsions on Micro-Explosion Behaviour. *Energies* **2018**, *11*, 1650. [[CrossRef](#)]
26. Lin, C.-Y.; Chen, L.-W. Comparison of fuel properties and emission characteristics of two- and three-phase emulsions prepared by ultrasonically vibrating and mechanically homogenizing emulsification methods. *Fuel* **2008**, *87*, 2154–2161. [[CrossRef](#)]
27. Fu, W.B.; Hou, I.Y.; Wang, L.; Ma, F.H. A unified model for the micro-explosion of emulsified droplets of oil and water. *Fuel Process. Technol.* **2002**, *79*, 107–119. [[CrossRef](#)]
28. Watanabe, H.; Matsushita, Y.; Aoki, H.; Miura, T. Numerical simulation of emulsified fuel spray combustion with putting and micro-explosion. *Combust. Flame* **2010**, *318*, 21305704.
29. Rashid, M.A.A.; Ithnin, A.M.; Yahya, W.J.; Ramlan, N.A.; Mazlan, N.A.; Sugeng, D.A. Integration of real-time non-surfactant emulsion fuel system on light duty lorry. In *IOP Conference Series: Materials Science and Engineering*; IOP: London, UK, 2017; Volume 257, p. 012051.
30. Ithnin, A.M.; Yahya, W.J.; Ahmad, M.A.; Ramlan, N.A.; Kadir, H.A.; Sidik, N.A.C.; Koga, T. Emulsifier-free Water-in-Diesel emulsion fuel: Its stability behaviour engine performance and exhaust emission. *Fuel* **2018**, *215*, 454–462. [[CrossRef](#)]
31. Mwangi, J.K.; Lee, W.-J.; Chang, Y.-C.; Chen, C.-Y.; Wang, L.C. An overview: Energy saving and pollution reduction by using green fuel blends in diesel engines. *Appl. Energy* **2015**, *159*, 214–236. [[CrossRef](#)]
32. Jung, I.C.; Lee, K.H. Characteristics of ignition and micro-explosion for droplets of water-in-fuel emulsion. *J. Korean Soc. Mar. Eng.* **2013**, *37*, 1–8. [[CrossRef](#)]
33. Heywood, J.B. *Internal Combustion Engine Fundamentals*; McGraw-Hill: New York, NY, USA, 1988.
34. Hosseini, V.; Checkel, M.D. *Using Reformer Gas to Enhance HCCI Combustion of CNG in a CFR Engine*; SAE Technical Paper 2006-01-3247; SAE International: Warrendale, WA, USA, 2006. [[CrossRef](#)]

