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FEASIBILITY STUDY ON THE BLACK CARBON REDUCTION OF THE USE OF EMULSION FUEL IN A DIESEL ENGINE

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Abstract

The performance and exhaust emission characteristics of a marine diesel oil (MDO) and a water emulsion fuel were analyzed in this study. Because an experiment with a ship's diesel engine would have involved numerous restrictions and expenses, a scaled-down diesel

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engine for automotive vehicles was used for this research. Some differences in basic combustion characteristics were anticipated because the automotive diesel engine was designed to use ultra-low-sulfur diesel (ULSD) fuel. Therefore, a preliminary experiment was conducted to investigate the differences in the combustion characteristics of the two fuels. Significant issues were observed, even when MDO was used in the automotive diesel engine, except in the low-load range. The test results showed that the combustion performance of the water emulsion fuel was superior to that of MDO. Latent heat from the evaporation of water particles in the fuel and a micro-explosion phenomenon resulted in improved exhaust emissions and combustion performance.

1. Introduction

Shipping accounts for the highest volume of global transportation, and although ships carry 80% of global freight, shipping consumes only 2% of the world's energy. Carbon dioxide (CO_2) emissions from global shipping account for only 3.3% of the total global emissions of CO_2. Thus, shipping is considered as an efficient and eco-friendly mode of transportation. However, environmental regulations concerning CO_2 exhaust from ships and demands for environmentally friendly ships continue to increase in stringency. Tier 3 of MARPOL 73/78 of the International Maritime Organization (IMO) came into effect in 2010, tightening the restrictions on exhaust emissions, including nitrogen oxide (NOx) and sulfur oxides (SOx). This regulation was applied to new ships by 2016, requiring reductions in NOx by as much as 85%.

Diesel engines are more thermally efficient than gasoline engines, and their CO_2 emissions are relatively low. Diesel engines are, therefore, widely used in transportation and in power plants to reduce CO_2 emissions. However, NOx and soot emissions remain critical issues because of the combustion characteristics of diesel engines. Combustion technologies, including high-pressure fuel injection and exhaust gas recirculation (EGR), have been developed to address this problem. After-treatment technologies, such as lean NOx traps (LNTs), diesel particulate filters (DPFs), and selective catalytic reduction (SCR), have also been developed to reduce exhaust emissions. In addition, alternative fuel technologies, such as water emulsion fuels, biodiesel, and dimethyl ether (DME), have attracted attention as candidates for lower-emission fuels. Research on these combustion and after-treatment technologies has been focused on two primary objectives: improving engine efficiency and reducing exhaust emissions. Some of these new technologies are already in common use. Research into alternative fuels for diesel engines has focused on minimizing their disadvantages, such as their low power density, corrosiveness, and high kinematic viscosity in comparison to diesel fuel.

The use of emulsion fuels involves the addition of surfactants to water and fuel that are not mixed with each other, forming a type of liquid dispersed as fine particles in another. Such fuels are primarily divided into two types: emulsions of oil in water and emulsions of water in oil. Current research on the viscosity and corrosiveness of emulsions in diesel engines has focused on emulsions of water in oil [1, 2].

In 2006, Lin and Chen published a paper in the journal named *Fuel* discussing a three-phase oil/water/oil (O/W/O) diesel emulsion fuel produced using an ultrasonic emulsification method. They analyzed the performance and exhaust emission characteristics of this fuel in diesel engines. While the levels of carbon monoxide (CO) and particulate matter (PM) emissions and the fuel consumption characteristics of the three-phase O/W/O emulsion fuel were improved over other diesel fuel to which it was compared, the brake thermal efficiency and the black smoke opacity were worse [3].

Jeong et al. conducted experimental research on the micro-explosion behavior caused by the auto-ignition of a single droplet of emulsion fuel, using 10% and 30% emulsion fuels. The sizes of single droplets were increased to permit analysis of the micro-explosion phenomenon. As the water content increased, the ignition delay and the strength of the micro-explosion increased [4].

In water emulsion fuel, fuel atomization is facilitated by the micro-explosion phenomenon as a result of the rapid evaporation of water, while the combustion temperature decreases because of the latent heat of vaporization during the combustion process. This results in simultaneous reductions of NOx and soot emissions. The use of water emulsion fuels has drawn attention because of their simplicity: unlike combustion and after-treatment technologies, the use of water emulsion fuels requires no additional or different equipment, except for the simple modification of a few conventional diesel engine parts [2, 5]. In addition, as oil prices continue to rise around the world, the possibility of using low-quality fuel in diesel marine engines becomes increasingly attractive.

In this study, an automotive diesel engine was used to conduct a scaled-down experiment because of the size and cost restrictions associated with using a ship engine in an experimental setting. Marine diesel oil (MDO) and a 20% water emulsion fuel (ME20%), which are lower-quality fuels than diesel fuel, were used in the experiment, and the combustion, exhaust emissions, and fuel consumption characteristics of the two fuels were analyzed. The differences between MDO and ME20% in terms of combustion and fuel consumption rates were examined. The effects of these alternative fuels on NOx and PM emissions were examined as well.

2. Experimental Apparatus and Procedures

2.1. Properties of MDO and MD emulsion fuel

A preliminary experiment was conducted using diesel fuel in an automotive engine. The combustion, fuel consumption, and exhaust emission characteristics were examined when MDO and ME20% were used as test fuels. Homogenizers were used in this study to produce the emulsion fuel. The ME20% fuel was produced as a water/oil (W/O) emulsion by mixing MDO and water with a surfactant at a mixing rate of 8:2. For the MDO and ME20%, a basic property test of calorific value and density was conducted. Table 1 lists the test procedures for measuring the basic properties of fuel.

Table 1. Test procedures for fuel characteristics

Contents	Test procedure
Lower calorific value	ASTM D 240:2009
Gross calorific value	ASTM D 240:2009
Moisture	KS M ISO 3733:2008
Sulfur content	KS M 2414:2011 (High-temperature method)
Ash	KS M ISO 3987:2012
Density	KS M ISO 12185:2003
Kinematic viscosity	KS M ISO 3104:2008
Deposit	KS M ISO 3735:2008
Copper strip corrosion	ASTM D 130:2012
Flash point	ASTM D 92:2005 (Cleveland open cup method)

2.2. Engine test system

The engine used in the experiment was a 2.0-L, common rail-type, direct-injection diesel engine for a passenger car. Because an experiment with a marine diesel engine would have been prohibitively expensive and time consuming, an automotive diesel engine was used in this preliminary experiment in which we studied the effects of the emulsion fuel. Table 2 lists the key specifications of the engine used in the experiment.

Figure 1 is a schematic illustration of the engine system used in the experiment, which utilized an eddy-current-type 110-kW dynamometer. The glow plug of the no. 1 cylinder was removed to analyze the combustion characteristics. A pressure sensor (Kistler 6045A) was installed in the cylinder's space. In addition, for synchronization with the crank signal, an encoder (Kistler 2613B) was attached to the engine crankshaft. The two signals were entered into a combustion analyzer (A&D Technology, Inc., E002.0094 CAS system) to determine the combustion characteristics of the fuel, such as the cylinder pressure, rate of heat release, and combustion duration. ETK-ECU for R&D was used to control the engine smoothly. The NOx and PM emissions were measured using an exhaust gas analyzer

(HORIBA MEXA-8120D) and a smoke meter (AVL 415S), respectively. Tables 3 and 4 show the specifications of the dynamometer and exhaust gas analyzer used in this study.

An additional fuel tank was prepared to supply the MDO and ME appropriately. A filter without an oil separator was added to the fuel supply line to prevent the flow from being separated in the fuel filter when the emulsion fuel was used. The fuel consumption was measured using of a fuel flow meter (Rheonik, RHE-08).

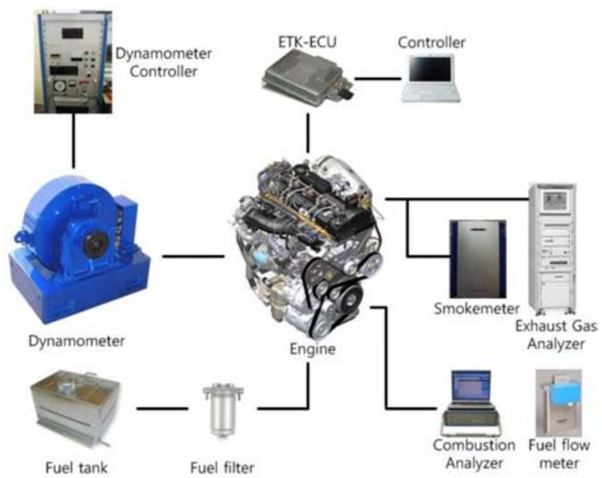


Figure 1. A schematic illustration of an engine test system.

Table 2. Specifications of an engine

Description	Specification
Engine type	4-stroke DI common-rail
Number of cylinders	4
Bore × stroke	83 × 92mm
Displacement volume	1991cc
Valve type	SOHC 4 valves
Max. power	146/4,000ps/rpm
Max. torque	32/1,800~2,500kg·m/rpm
Compression ratio	17.3
Connecting rod length	145.8mm

Table 3. Specifications of an engine dynamometer

Description	Specification
Model	FUCHINO ESF-H-150
Type	Eddy current, load-cell type
Max. power	110kW at 10,000rpm
Max. torque	35.8kg·m

Table 4. Specifications of exhaust emission analyzers

Emissions	Measurement principle	Model
NOx	Chemiluminescence	Horiba MEXA-8120D
Soot	Filter smoke number	AVL-415S

2.3. Experimental conditions and procedure

The engine test was conducted with diesel fuel. Because the engine used in the experiment was an automotive diesel engine, a preliminary experiment was conducted to compare the characteristics of diesel fuel with those of other fuels. Problems were anticipated with the use of MDO or ME because the engine was designed specifically for an ultra-low-sulfur diesel (ULSD) fuel. The feasibilities of using the MDO and then the ME in a diesel engine were evaluated. The experimental conditions used with the MDO and ME were the same as with the diesel fuel. The engine speed was set to achieve maximum torque performance and a stable combustion region for the selected diesel engine. Four engine load conditions (3, 6, 9 and 12 bar) were selected. The experimental conditions are summarized in Table 5.

Table 5. Experimental conditions

Conditions	Values
Engine speed	1500, 2000, 2500rpm
Engine load (BMEP)	3, 6, 9, 12 bar
Number of injections	3 (2-pilot, main)
Pilot injection timing	BTDC 26°, 14°
Main injection timing	BTDC 2.5°
Fuel	Diesel, MDO, ME20%
Fuel temperature	40°C
Coolant temperature	80°C

3. Results and Discussion

3.1. Comparison of fuel properties

Table 6 shows the results of the analysis of the fuel properties. The calorific value of the MDO was higher than that of diesel fuel, while the calorific value of the ME20% was considerably lower because of the water content. The sulfur content of the MDO was greater than that of ULSD because it functioned as a lubricant in the marine diesel engine. Both the fuels were higher in density than diesel, and the flash point was similar or higher. The kinematic viscosity, the effect of which on the injector's performance would dominate any other factors, was 57% higher for MDO and 67% higher for ME20% than for diesel. Therefore, in the use of MDO or ME in the diesel engine used in this study, differences in the combustion and exhaust characteristics were expected to be related to the differences in the kinematic viscosity. The presence of water in ME20% changes the properties of the fuel and the combustion rates, because of the micro-explosion of water particles and the temperature decrease associated with the latent heat of vaporization. We anticipated that the combustion and exhaust emission characteristics would change as a result.

Table 6. Specifications of diesel, MDO and ME20%

Characteristic	Diesel	MDO	ME20%
Lower calorific value (J/g)	40,101	41,060	34,990
Gross calorific value (J/g)	43,241	43,670	38,050
Moisture (volume %)	> 0.1	0.5	18.8
Sulfur content (weight %)	0.01	0.15	0.10
Ash (weight %)	-	0.012	0.007
Density@15°C (kg/m^3)	823.0	862.6	889.7
Kinematic viscosity (mm^2/s)	2.671	6.3	8.082
Deposit (volume %)	0.01	0.06	0.07
Copper strip corrosion (100°C, 3h)	-	1	1
Flash point (°C)	62~74	73~104	69~86

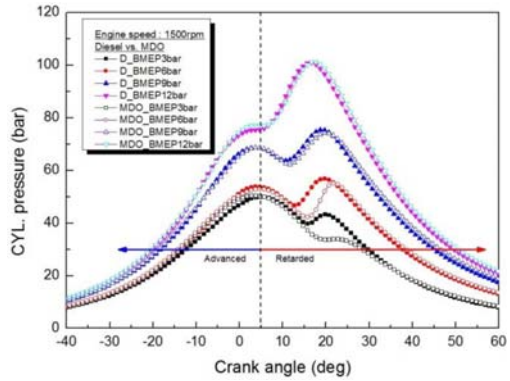
3.2. Combustion characteristics

Because of cost and experimental restrictions, MDO and ME20% were tested in an automotive diesel engine as a preliminary step in the analysis of marine diesel engine performance, and the combustion and exhaust characteristics were analyzed.

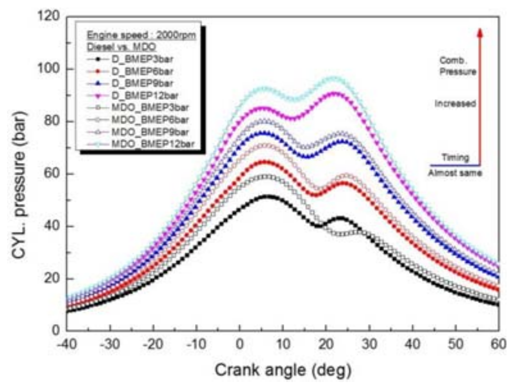
3.2.1. Comparison between diesel and MDO

Figures 2 and 3 show the combustion pressures and rates of heat release (RoHR) of diesel and MDO under four load conditions at engine speeds of 1500, 2000 and 2500rpm. As shown in these figures, the combustion pressure of MDO exceeds that of diesel under most of the load conditions, and the distribution of the cylinder pressure is wider as well. At an engine speed of 1500rpm and loads of 3 and 6 bar, as shown in Figure 2(a), the combustion pressure of MDO was slightly lower than that of diesel. Little difference between diesel and MDO was observed at the load conditions of 9 and 12 bar. This is most likely because the viscosity of MDO is higher than that of diesel and because the atomization characteristics deteriorate at low load levels, resulting in ignition delay. Similar trends were observed for the other conditions considered [6, 7]. As shown in Figure 2(b), the combustion pressure of MDO was higher than that of diesel under all load conditions, except when a local pressure drop of MDO appeared at 3 bar due to ignition delay.

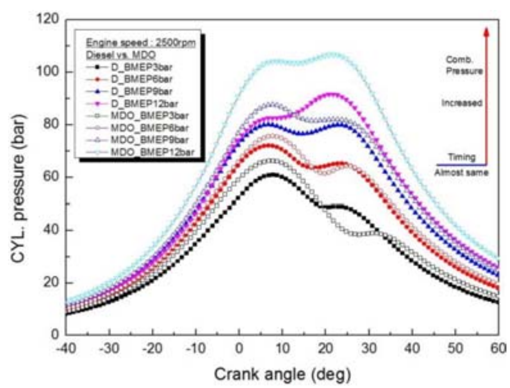
The maximum combustion pressure of MDO was higher than that of diesel at 1500rpm. Figure 2(c) shows that the combustion pressure of MDO increased at an engine speed of 2500rpm, while at loads of 3 and 6 bar, it failed to ensure sufficient time for fuel atomization in proportion to the high engine speed, which resulted in ignition delay and a local pressure drop. At 9 bar, the total combustion pressure of MDO exceeded that of diesel, and the difference in pressure was significant at 12 bar.



(a) 1500rpm

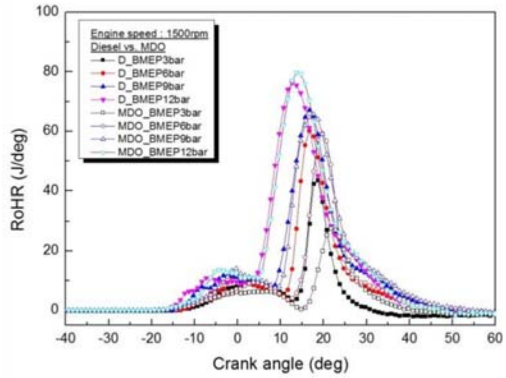


(b) 2000rpm

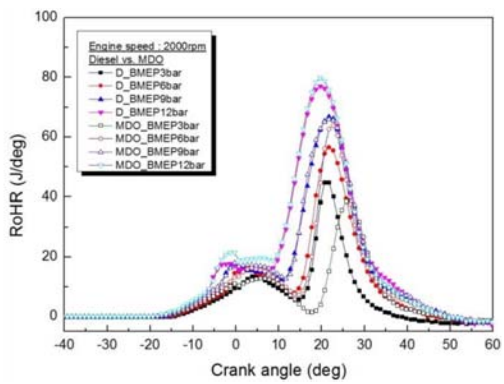


(c) 2500rpm

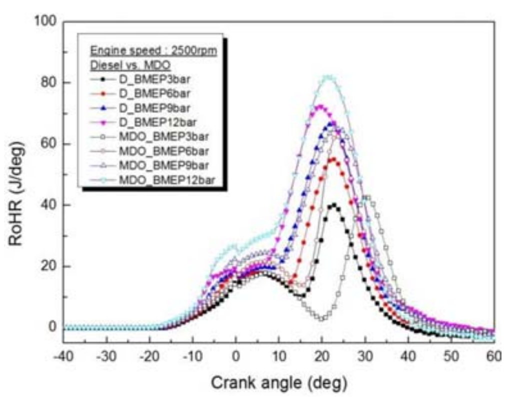
Figure 2. Combustion pressure in diesel and MDO for various engine speeds and loads.



(a) 1500rpm



(b) 2000rpm



(c) 2500rpm

Figure 3. Rate of heat release in diesel and MDO for various engine speeds and loads.

Figure 3 shows the trend in the heat release rates of diesel and MDO. Figure 3(a) shows that the primary ignition timing of MDO was retarded at loads of 3 and 6 bar at 1500rpm. At 3 bar, the heat release rate of MDO was lower than that of diesel and increased gradually as the load increased. The ignition delays at 3 and 6 bar resulted from pure fuel atomization due to the high viscosity of MDO, as mentioned earlier [6, 7]. Figure 3(b) shows that the ignition timing was delayed at 3 bar, for the same reasons outlined for Figure 3(a). At 2500rpm, ignition delay occurred in the low-load area of 3 and 6 bar. As the load increased, the difference in the ignition delay decreased while the heat release rate increased.

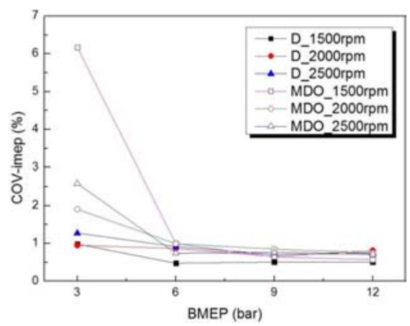
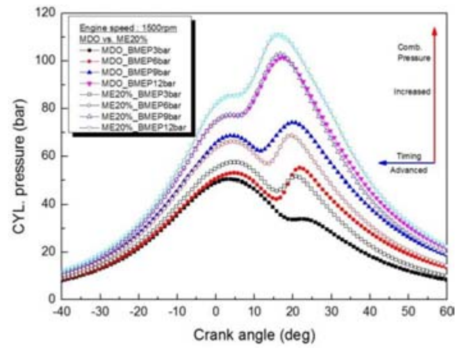


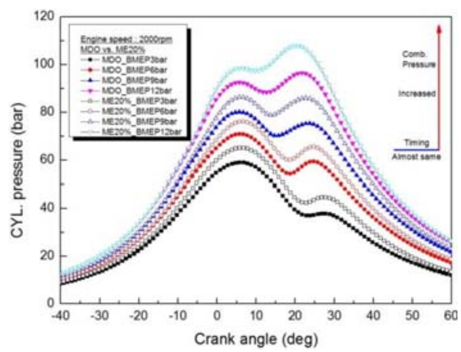
Figure 4. COV_{imep} of both diesel and MDO.

Figure 4 shows the coefficient of variation in indicated mean effective pressure (COV_{imep}) for each experimental condition. COV_{imep} is an indicator of a stable power output without fluctuation in combustion pressure, which can be explained in association with combustion stability. Diesel had a low COV_{imep}, because an automotive diesel engine was used in this experiment. On the other hand, MDO had the highest COV_{imep} at 1500rpm and 3 bar. In general, as the engine speed and load increased, the COV_{imep} decreased because of improved combustion. For the same reason, the COV_{imep} of MDO was higher than that of diesel. When the engine load exceeded 9 bar, the difference in COV_{imep} decreased drastically, which suggests that a marine diesel engine with a fixed high load could maintain better combustion stability. The combustion characteristics of diesel and

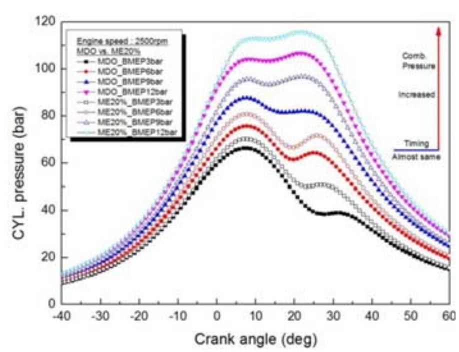
MDO were compared to establish a database for the application of MDO to an automotive diesel engine. The following sections compare the performance of MDO and ME20%.



(a) 1500rpm



(b) 2000rpm



(c) 2500rpm

Figure 5. Combustion pressure in MDO and ME20% for various engine speeds and loads.

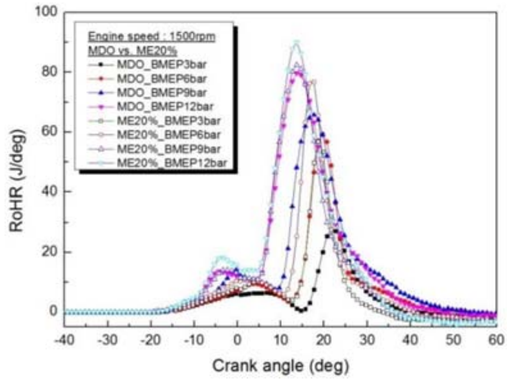
3.2.2. Comparison of MDO and ME20%

Figure 5 shows the combustion pressure characteristics under each load condition and at various engine speeds. As shown in the figure, the combustion pressure of ME20% was higher than that of MDO for every condition. When ME20% was used, the pressure exceeded that of MDO because the micro-explosion of water particles in the fuel enhanced the atomization process, which had a great effect on the combustion characteristics [2, 5, 8, 9].

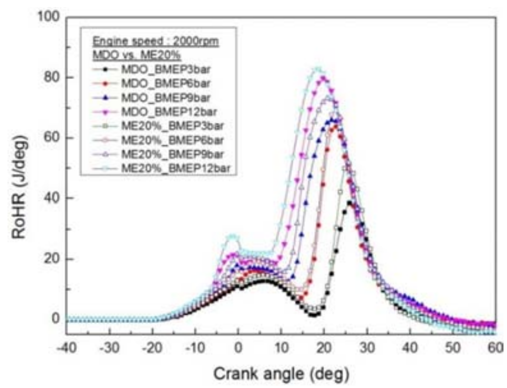
Figure 6 shows the characteristics of RoHR. In the case of RoHR, the ignition delay of ME20% was shortened under most of the conditions. The ignition delay of ME20% was the same as or shorter than that of MDO because water particle evaporation and micro-explosion in ME20% accelerated fuel atomization, despite the high kinematic viscosity, and as a result, the premixed combustion region was extended, shortening the ignition delay.

Figure 7 shows a comparison of the COV_{imep} of MDO and ME20%. At a load of 3 bar, the value of ME20% exceeded that of MDO, except at 1500rpm, indicating unstable combustion, because a low load condition was not sufficient to maintain the ambient temperature and pressure needed for the micro-explosion of water particles. However, the value of COV_{imep} under increased loads was lower than that of MDO, implying that the ambient conditions needed to evaporate water particles and drive micro-explosions were satisfied.

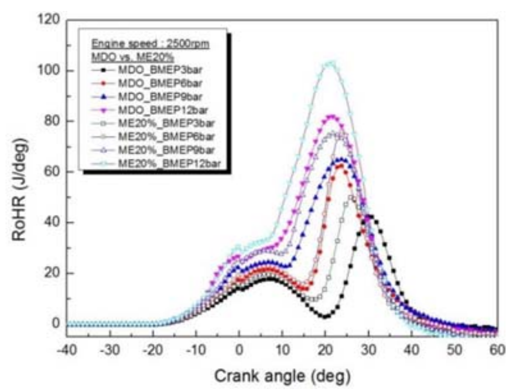
Figure 8 shows the combustion duration of MDO and ME20% under each experimental condition. The 0-10% and 10-90% ranges of the mass fraction burned (MFB) are defined as the ignition delay period and combustion period, respectively. In this study, the 90-100% range of MFB was ignored in considering the error in the heat release rate [10]. The combustion period of ME20% was 7.3% shorter than that of MDO because the micro-explosion after the evaporation of water in ME20% caused fuel atomization and shortened the combustion period due to the rapidity of the combustion caused by micro-explosion.



(a) 1500rpm



(b) 2000rpm



(c) 2500rpm

Figure 6. Rate of heat release in MDO and ME20% for various engine speeds and loads.

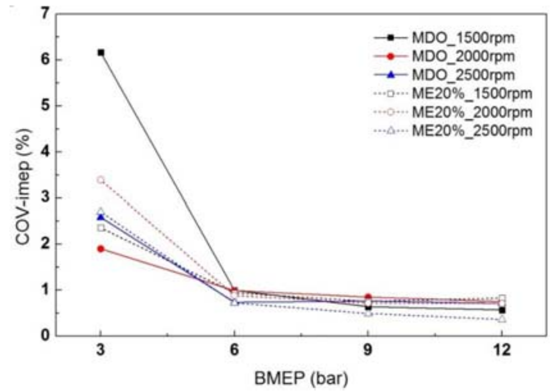


Figure 7. COV_{imep} of both MDO and ME20%.

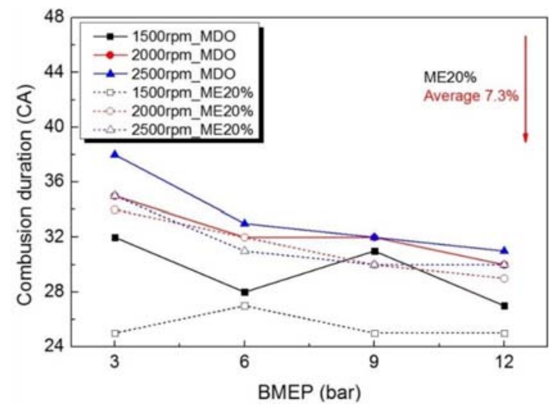


Figure 8. Combustion duration of MDO and ME20%.

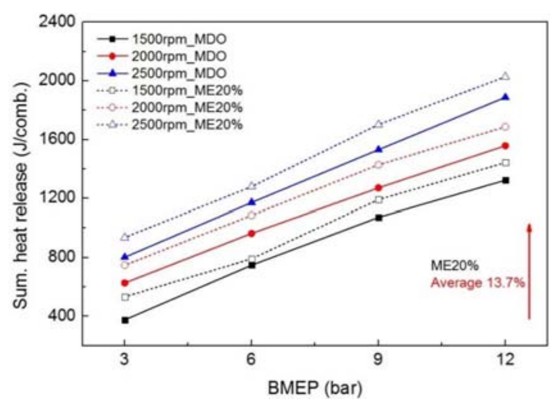


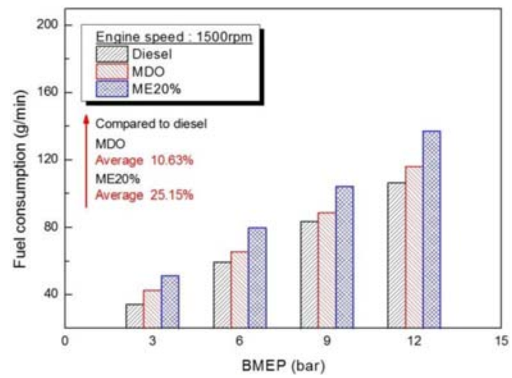
Figure 9. Sum of heat release for MDO and ME20% during combustion.

Figure 9 shows the total heat release of ME20% and MDO during the combustion period under various conditions. The total heat release of ME20% was approximately 13.7% higher than that of MDO. This result indicates that the fuel atomization due to the micro-explosion of water in ME20% improved the combustion characteristics and caused a higher level of heat release than that of MDO, despite the short combustion period [11].

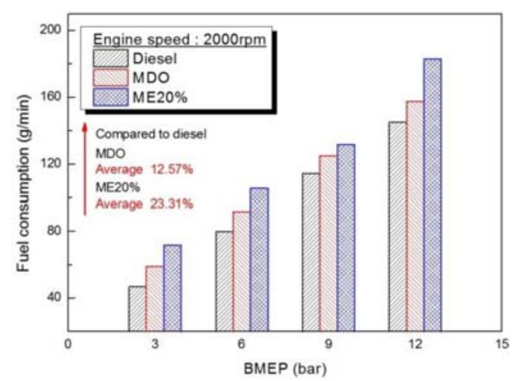
To summarize the process, ME20% exhibited a difference in ignition delay depending on the increase in the combustion pressure and patterns of heat release. ME20%, which is a combination of MDO and water, exhibited improved combustion characteristics owing to the micro-explosion of water particles when the proper ambient temperature and pressure conditions existed within the cylinder. The ignition delay of ME20% was almost the same as or shorter than that of diesel. These results suggest that ME20% would be useful in a marine diesel engine with a fixed engine speed and load.

3.3. Fuel consumption characteristics

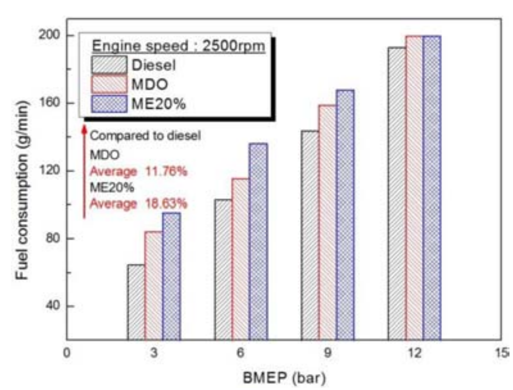
Figure 10 shows the characteristics of fuel consumption for each condition. Fuel consumption tended to increase linearly because the fuel was supplied in proportion to the engine speed and load. The fuel consumption was in the order of diesel < MDO < ME for every load condition. At 1500rpm, the rates of fuel consumption of MDO and ME20% were 10% and 25% higher, respectively, than that of diesel. At 2000rpm, the fuel consumption rates increased to 12% and 23% over the diesel rate for MDO and ME20%, respectively, and at 2500rpm, the consumption increases were 11% and 18%, respectively. These results show that the total consumption of ME20% exceeded that of other fuels, although the increase in the rate of consumption decreased as the engine speed increased. This is because the combustion temperature was low in the low-rpm region and was not sufficient to maintain the ambient temperature and pressure needed for water evaporation and micro-explosion, ultimately leading to unstable combustion. As a result, fuel consumption increased to maintain the same output. For the same conditions, the amount of fuel consumed, not including water, was lower than the amounts of MDO and diesel consumed, except in the low-load region.



(a) 1500rpm



(b) 2000rpm



(c) 2500rpm

Figure 10. Fuel consumption of diesel, MDO and ME20%.

Figure 11 shows the fuel consumption of ME20% without water. As the figure shows, the fuel consumption rate was reduced by approximately 5% on average per cycle, compared with MDO. The improvement in the fuel consumption rate stemmed from the micro-explosion of water particles caused by combustion, which accelerated fuel atomization and increased the surface area of fuel and air. This resulted in improved combustion rates and a shorter combustion duration. These results suggest that a smaller quantity of fuel can generate the same engine power; therefore, the fuel cost can be reduced when ME20% is used in a diesel ship engine.

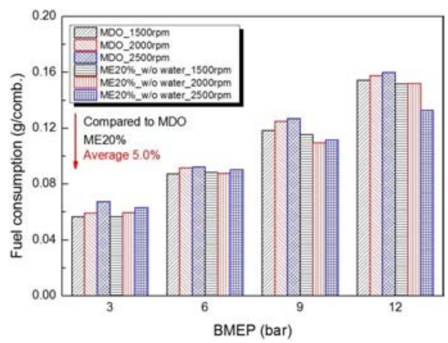


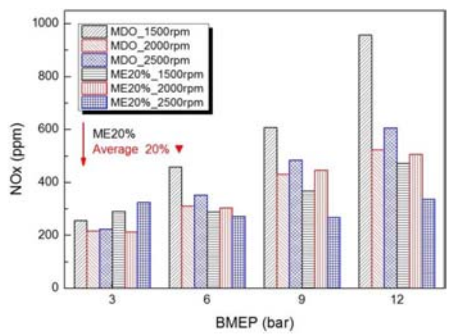
Figure 11. Fuel consumption of MDO and ME20% during combustion (w/o water).

3.4. Exhaust emission characteristics

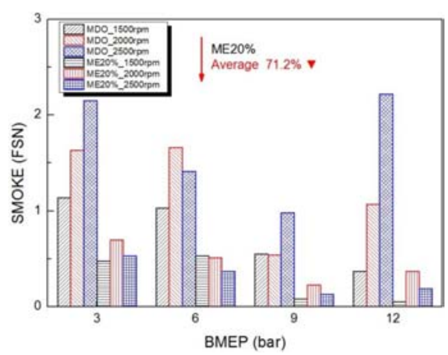
It is generally accepted that NOx is reduced when the combustion temperature of emulsion fuel decreases, because of the latent heat of vaporization and the reduction in PM emissions via the micro-explosion caused by evaporation [12-14]. The same trend was observed in ME20% produced with MDO. Figure 12 shows the characteristics of NOx and PM emissions under all of the experimental conditions considered.

As Figure 12(a) shows, the NOx emissions increased with the load level. In the low-load region, in which the combustion characteristics were inferior, the combustion was poor and thus the emissions of MDO and ME20% were relatively small. However, when the load exceeded 6 bar, the NOx emissions of ME20% were up to 20% lower than those of MDO. The NOx emissions of ME20% were relatively low, because as discussed, the heat absorption caused by water evaporation decreases the combustion temperature and restricts the thermal NOx production process.

Figure 12(b) shows a comparison of the PM emissions associated with MDO and ME20%. For nearly all the conditions considered, the value of MDO was high for two primary reasons. First, the test engine was designed for diesel fuel; second, the high kinematic viscosity caused the evaporation characteristics of MDO to be inferior. In the case of ME20%, the improvement was up to 71.2% over MDO because the evaporation of water particles in ME20% resulted in micro-explosions, allowing the fuel to mix with air and facilitating combustion. As mentioned earlier, however, PM emissions tended to increase in the low-load region in which combustion was unstable.



(a) NOx of MDO and ME20%



(b) PM of MDO and ME20%

Figure 12. NOx and PM emissions of MDO and ME20% at various engine loads.

4. Conclusions

In this study, MDO, a fuel of lower quality than conventional diesel fuel, and ME20% were used in an automotive diesel engine to examine their basic combustion and exhaust characteristics. Based on the experimental results, the following conclusions were drawn:

(1) The property analysis results showed that the caloric values decreased in the order of MDO > diesel > ME20%, and the kinematic viscosity decreased in the order of ME20% > MDO > diesel.

(2) The evaporation and combustion characteristics of the MDO were found to be inferior to those of the water emulsion fuel, and the COV_{imep} was found to be high in the low-load region. However, the combustion stabilized as the load increased, indicating that these fuels can be used in a marine diesel engine with a fixed engine speed and load.

(3) The combustion characteristics of the ME20% were slightly better than those of the MDO in the low-load region. On the other hand, the combustion duration of the ME20% was approximately 7.3% shorter than that of MDO because the fuel was easily atomized as a result of the micro-explosion of water contained in the ME20%, which led to rapid combustion. In addition, as a result of the micro-explosion phenomenon, the total heat release of the ME20% was approximately 13.7% higher than that of the MDO.

(4) The fuel consumption increased linearly in proportion to the engine speed and load, in the order of diesel < MDO < ME20%. However, if the 20% water component of ME20% were excluded, the fuel consumption could be reduced by 5% compared with MDO. Hence, when ME20% is used in a diesel ship engine, a lower cost is expected.

(5) Because of the micro-explosion and latent heat of vaporization of water particles, the NOx and PM emissions of ME20% were reduced by 20% and 71.2%, respectively, in comparison with MDO. Therefore, when the emulsion fuel is used in marine diesel engines, significantly reduced emissions are expected.

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