Article
Numerical Study on Nitrogen Oxide and Black Carbon Reduction of Marine Diesel Engines Using Emulsified Marine Diesel Oil

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Received: 16 October 2019; Accepted: 4 November 2019; Published: 12 November 2019

Abstract: In this study, the exhaust gas characteristics of marine diesel oil (MDO) and emulsion fuels, which are currently used to reduce nitrogen oxides and particulate matters emitted from ship engines, were investigated through experimental and numerical analyses. The moisture included in the emulsion fuel primarily promotes the atomization of fuel due to microexplosion, and lowers the combustion temperature due to the latent heat of evaporation from the evaporation of moisture, thus reducing nitrogen oxides and particulate matter. In the case of emulsion fuel containing a water content of 16%, the combustion temperature was lowered, and the reduction rate of nitrogen oxide and black carbon was about 60% and 15%, respectively. The proposed method is a combustion control technology that can reduce particulate matter as well as nitrogen oxides by using emulsion fuel.

Keywords: marine diesel oil (MDO); emulsified marine diesel oil; NOx emission; particulate matter; black carbon

1. Introduction

Recently, air quality in South Korea ranked 173rd among 180 countries worldwide, and for ultra-fine dust concentration, ranked 8th. Furthermore, fine dust is not an anticipated issue of the future in South Korea, but rather a current one (source: EPI, 2016) [1]. In addition, fine dust is a first-class carcinogen designated by the World Health Organization (WHO), and long-term exposure has been reported to cause various diseases such as cardiovascular, skin, and eye diseases, as well as respiratory diseases such as colds, asthma, and bronchitis, due to a decrease in immunity. Fine dust originates from various sources, among which fossil fuels, including coal and oil, artificially generate a large quantity. Moreover, a large amount of fine dust is also generated during various industrial processes such as thermal power plants and the chemical manufacturing industry. Fine dust is classified according to the size of grain into fine dust (PM10), which is 10 µm or smaller, and ultrafine dust (PM2.5), which is 2.5 µm or smaller.

Primary fine dust is mainly produced by carbon, and secondary fine dust is formed by photochemical reactions emitted to ammonia, nitrogen oxides, and sulphur oxides, and a technology for reducing such exhaust emissions is essential. According to a survey on the port area where exhaust pollution is the most serious, the number of premature deaths due to air pollution was higher in the port area than inland area. Among the air pollutants, the main source of SOx, NOx, and PM in the port area was identified as ships.

The diesel–water emulsified fuel used in this study is a water-in-oil-type fuel where water droplets are dispersed in diesel. Since water-in-oil-type fuel does not involve direct exposure of water upon fuel injection, there is a low risk of corrosion, an enhancement of spray atomization characteristics through the micro-explosion phenomenon, and a reduction of the combustion temperature as a result of the latent heat of water evaporation, which allows the simultaneous reduction of NOx and black carbon [2–4].
As shown in Figure 1a, the pollutants emitted from ships include those generated during shipbuilding, air pollutants generated during operation, water pollutants generated during operation, and pollutants generated when ships are decommissioned. In the micro-explosion phenomenon (Figure 1b), the difference in the boiling point between diesel and water upon fuel injection in a combustion chamber results in the evaporation of water droplets and a more thorough splitting of fuel droplets. As a result, secondary atomization contributes to enhancing the air–fuel mixture and reducing the incomplete combustion [5–7].

In particular, due to the rapid global warming, the International Maritime Organization (IMO) regulation of emissions related to global warming such as carbon dioxide (CO₂), nitrogen oxides (NOx), sulfur oxides (SOx), volatile organic components (VOCs), particulate matter (PM), black carbon (BC) among air pollutants has become stricter, and vessels that do not meet the requirements cannot be operated. The necessary tools and materials that meet the regulations for shipbuilding are shown in Figure 2.

International organizations such as the International Maritime Organization (IMO) and the International Association of Classification Societies (IACS) are tightening safety and environmental regulations such as air pollutants and greenhouse gas emissions from ships [8,9]. Furthermore, the Korean government is also emphasizing the development of core technologies for eco-friendly ships, such as emission control and material control technologies for CO₂/NOx/SOx/BC, aiming to become a global leader in the new maritime era of clean shipbuilding by 2020. Therefore, the market size is expected to expand in the future.

![Figure 1](image-url)

**Figure 1.** Causes and reduction methodology of black carbon. (a) Severity of fine dust from ships in port areas; (b) Mechanism of micro-explosion phenomenon [10].
In this study, a performance evaluation of a system installed before and after heavy engines using heavy fuel oil (HFO), which met IMO emission regulations and black carbon regulations by reducing NOx and Soot (Black carbon) components, was conducted.

Current technologies for reducing nitrogen oxides and black carbon include electrostatic precipitators, diesel particulate filters (DPF), diesel oxidation catalysts, selective catalytic reductions, exhaust gas recirculation, and a scrubber, among which the DPF is the most typical technology to reduce black carbon (Table 1). However, this technology requires additional equipment due to the increase in space area and water treatment in the vessel.

### Table 1. Summary of exhaust treatment as an abatement option (nr: not reported).

| Abatement Measure                  | CO₂ % | BC % | NOx | SOx | Remarks                        | Reference    |
|-----------------------------------|-------|------|-----|-----|--------------------------------|--------------|
| Electrostatic precipitators       | −5    | nr   | nr  | NOT available | Size, commercial availability for ships | [11–15]      |
| Diesel Particulate Filters        | −1    | −4   | −6  | NOT available | Commercial availability for ships. Requires low sulphur fuel | [16–20]      |
| Diesel Oxidation Catalyst         | nr    | nr   | nr  | NOT available | Often combined with DPF | [18,21,22]   |
| Selective Catalytic Reductions    | nr    | nr   | nr  | 0    | Yes | NOT available | [23,24]      |
| Exhaust Gas Recirculation         | nr    | nr   | nr  | 0    | Yes | NOT available | [25–27]      |
| Scrubbers – Sulphur               | −1.5  | −3   | −5  | 20   | Yes | Yes | Unit cost. Fuel S regulation motivations | [28,29]      |

Electrostatic precipitators (ESP) take advantage of this charge by flowing the exhaust between charged plates, leading to particle precipitation from the exhaust flow. This technology is commonly used in large stationary sources such as mines and factories. The method is an attractive option due to high collection efficiencies and low added energy use, as there only is a minimal pressure drop in the exhaust system. Collection efficiencies for PM sized 40 to 700 nm can range from 60% to 100% by
mass [11–15]. Diesel particulate filtration (DPF) is a technology that has been used extensively for reductions in BC emissions within the on-road vehicle sector. DPFs use ceramic or metal filters to trap the BC prior to exhaust emission and periodic cleaning is required. The BC is concentrated in the filter and then combusted via active or passive processes [16–20]. Diesel oxidation catalysts (DOCs) are commonly used in the on-road transportation sector. The technology utilizes precious metals on a honeycomb structure, through which the exhaust is passed to oxidize the exhaust components to less harmful species. BC reductions of 20% to 40% have been reported; however, this reduction is specific to particulate organic matter and has little effect on BC [18,21,22].

Table 2 shows the analysis results of the technologies used for reducing black carbon, nitrogen oxides, and sulfur oxides. It was found that LNG and water-in-fuel emulsion technologies are the most effective technologies to reduce sulfur oxide, nitrogen oxide, black carbon, and fuel. Furthermore, it was found that the technology that can fundamentally reduce black carbon and nitrogen oxides through combustion using emulsion fuel is the most effective technology. More technically, in the present study, a 1MW 4-stroke engine of the water–fuel emulsion can be used [31,32] to prepare for IMO Tier and exhaust regulations by reducing black carbon. Simultaneously, the stability of combustion and the reduction of harmful exhaust gases are studied in this study through an emulsified fuel system, a fuel pump, and an injection system in the marine engine.

| All Air Emission Parameters | Black Carbon only | Consolidated List |
|-----------------------------|-------------------|------------------|
| 1. LNG                      | 1. LNG            | 1. LNG           |
| 2. Water-in-fuel emulsion   | 2. Water-in-fuel emulsion | 2. Water-in-fuel emulsion |
| 3. Scrubbers—high sulphur   | 3. Scrubbers—high sulphur | 3. Scrubbers |
| 4. HFO—distillate           | 4. Diesel particulate filter | 4. Diesel particulate filter |
| 5. Scrubbers—low sulphur    | 5. HFO—distillate | 5. HFO—distillate |
| 6. Diesel particulate filter| 6. Scrubbers—low sulphur | 6. Scrubbers—low sulphur |
| 7. Slide valves             | 7. Biodiesel—100\% | 7. Biodiesel—100\% |
| 8. Slow steaming—de-rating | 8. Slide valves   | 8. Slow steaming—de-rating |
| 9. Biodiesel—100\%         | 9. Electrostatic precipitator | 9. Electrostatic precipitator |
| 10. Electrostatic precipitator| 10. Slow steaming—de-rating | 10. Slow steaming—de-rating |

The use of water–diesel emulsion in diesel engines as fuel shows several benefits [32,33]. These include improved combustion efficiency and reduced emission of various pollutants such as NOx, CO, HC, soot and particulate matter (PM). When emulsified diesel is injected into the high temperature combustion chamber of the IC engine, the water particles evaporate first and the diesel droplets surrounding water particles disperse into smaller fuel droplets. This phenomenon is called micro-explosion. Water vaporization increases fuel dispersion in the form of smaller droplets and the contact surface area between fuel and air is increased. As a result, combustion becomes more efficient. As water absorbs some heat in the form of latent heat for its vaporization, peak combustion temperatures are lowered. The improved combustion and the lowering of peak temperature reduce PM and NOx formation, respectively.

In this study, based on the results of experiments using emulsion fuels [31–34], nitrogen oxides are reduced as the combustion temperature due to latent heat of evaporation due to the phase change of moisture contained in the emulsion fuel is reduced. As the combustion time is shortened by facilitating atomization of fuel due to the micro-explosion of water contained in the fuel, the BC generated in the trailing edge is reduced. Based on the results of these experiments, the numerical results of emulsion fuel were analyzed using the AVL BOOST program. In addition, based on the numerical results, a study was conducted to reduce the exhaust gas of ships by deriving factors that can reduce NOx and BC.
2. Research Method

2.1. Experiment Method

In this study, a schematic of the system that reduces emissions of nitrogen oxides and black carbon in actual marine engines using emulsion fuel is shown in Figure 3.

![Figure 3. Schematic diagram for 4-stroke marine engine.](Image)

Figure 3 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 600-kW generator engine. As shown in Figure 3, the 4-stroke engine consisted of a generator engine, a controller panel, a data acquisition system, an exhaust gas analyzer, and a pressure sensor. The engine load was adjusted using a load cell in the ship. The pressure sensor was installed on the No. 6 cylinder through a hole in the cylinder head, 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.

In this paper, as shown in Table 3, a 600kW generator engine was used to study the characteristics of nitrogen oxide and black carbon reductions over the water content of emulsion fuel. In order to measure the number of nitrogen oxides and black carbon, exhaust gas components were measured using a measuring device that was approved for the accreditation process as shown in Table 4. Table 5 shows the experimental conditions for the study.
Table 3. Specification for test engine.

| Items/Descriptions                  | Specifications                                                                 |
|------------------------------------|-------------------------------------------------------------------------------|
| Engine type                        | 4-stroke turbo-charged DI marine generator engine                             |
| Number of cylinders                | 6                                                                             |
| Compression ratio                  | 15.9                                                                          |
| Bore × Stroke (mm)                 | 165 × 265                                                                     |
| Displacement (cc)                  | 20,000                                                                        |
| Fuel injection system              | Mechanical pumping system (Max. 1400 bar)                                     |
| Engine’s maximum continuous rating (MCR) (kW/rpm) | 600 kW/900 rpm                                                              |

Table 4. Exhaust gas instrument.

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

Table 5. Experimental condition.

| Fuel                  | MDO, EMDO (10%, 13%, and 16%)                      |
|-----------------------|----------------------------------------------------|
| Engine speed (rpm)    | 900                                                |
| Load (kW)             | 60 (10%), 150(25%), 300 (50%), 450 (75%), 600 (100%) |

The emulsion fuel, which was produced from the emulsion fuel supply system shown in Figure 3, was sampled before the test was performed. After that, compositions of the fuels containing marine diesel oil (MDO), 10%, 13%, and 16% of water, and additives for certified fuels were analyzed, and the results are shown in Table 6.

Table 6. Emulsified oil fuel properties used marine engine.

| Items/Classifications      | MDO          | 10% EMDO     | 13% EMDO     | 16% EMDO     |
|---------------------------|--------------|--------------|--------------|--------------|
| Lower calorific value (J/g) | 41,860       | 36,760       | 34,610       | 33,430       |
| Gross calorific value (J/g)| 44,810       | 39,990       | 37,880       | 36,690       |
| 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/m3)    | 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          |

Emulsion fuels were prepared with 10%, 13%, 16%, and 20% of water content in the MDO to test dispersion stability. Tubiscan equipment was used for the dispersion stability of the emulsified fuel and the dispersion stability was measured for 10 days. For the first three days, the backscattering was scanned every hour, and for the next seven days, the backscattering was scanned every six hours. The variation of the backscattering profile (Y-axis) at each scan time with respect to the height (X-axis) of the sample is plotted in the graph of the reference mode. The reference mode is a result that can be obtained by having the first backscattering (BS, %) profile as a reference, setting the obtained BS (%) profile value as 0% backscattering, and relatively moving the change of the remaining profiles. BS can be obtained as follows:

\[
BS \approx \left[ \frac{1}{P} \right]^\frac{1}{2}
\]

\[
P = \left[ \frac{2J}{3\pi^2(1-g)Q_2} \right]
\]
where \( l' \): photon transport means free path, \( g \): asymmetry factor, \( \varnothing \): concentration, \( Q_s \): scattering affix, \( d \): diameter.

### 2.2. Numerical Analysis Method

The software adopted for the simulation was the AVL BOOST version 2019.1, which provides a graphical user interface (GUI) composed of icons that represent components of ICE. Once selected and interconnected, the icons allow the opening of a window through which the geometrical and operational data of the engine, as well as the mathematical models that make up the simulation, are inserted. The 1D CFD model built in AVL Boost software is showed in Figure 4. Once all necessary data has been collected, the model is built in AVL Boost© [35]. This tool uses the conservation equations of mass, energy, and momentum for modelling intake and exhaust collector ducts. On the other hand, those equations are connected with contours conditions obtained from the modelling of other engine components, such as volumes, cylinder, turbocharger, valves or heat exchangers, each component has special modelling to consider the conservation equations and also its own special behaviour. In Figure 4, SB1 and SB2 are the inlet and outlet boundary; TC1 is the turbine and compressor (Charger); C1 through C6 represent six cylinders of the engine; CO1 represent the heat exchanger; PL1 is the manifold; MP1 through MP28 are measurement point. Model main elements are identified in Figure 4: air filters, compressors, air cooler, manifolds, cylinders and turbines, all connected by ducts. The engine configuration is modelled, considered the main characteristics, i.e., firing order C1-C2-C4-C6-C5-C3 and firing angle of each cylinder with respect to reference cylinder C1, the spatial distribution of cylinders, etc. Cylinder (C1) of the model in AVL Boost is connected with element Engine (E1), and it defines the type of engine used, operating speeds on it, moments of inertia, and break mean effective pressure (BMEP). The combustion method is chosen for the experimental MCC AVL combustion (mixing controlled combustion) model that predicts the rate of heat released (ROHR) and NOx emissions on the quantity of fuel in the cylinder and the turbulent kinetic energy introduced by the injection of fuel.

![Figure 4. AVL boost model for 4-stroke marine diesel engine.](image)

The first law of thermodynamics applied to the combustion cylinder is that the change of the internal energy in the cylinder is equal to the sum of piston works, fuel heat input, wall heat loses and
the enthalpy flow due to blow-by. This is applied AVK BOOST to calculate the thermodynamics state of cylinder.

\[
\frac{d(m_c \cdot u)}{d\alpha} = -P_c \frac{dV}{d\alpha} + \frac{dQ_F}{d\alpha} - \sum \frac{dQ_W}{d\alpha} - h_{BB} \frac{dm_{BB}}{d\alpha} \tag{3}
\]

where \(m_c\): mass in the cylinder; \(u\): specific internal energy; \(P_c\): cylinder pressure; \(V\): cylinder volume; \(Q_F\): fuel energy; \(Q_W\): wall heat loss; \(\alpha\): crank angle; \(h_{BB}\): enthalpy of blow-by; \(m_{BB}\): blow-by mass flows [35].

The heat transfer to the walls of the combustion chamber including cylinder head, piston, and cylinder liner can be calculated as follows [35]:

\[
Q_{wi} = A_i \cdot \alpha_c (T_c - T_{wi}) \tag{4}
\]

where, \(Q_{wi}\) is wall heat flow. \(A_i\) is surface area. \(T_c\) and \(T_{wi}\) are gas temperature in the cylinder and wall temperature, respectively.

The combustion in the direct injection compression ignition engines can be considered by two processes including premixed combustion (PMC) and mixing controlled combustion (MCC). The combustion model in this study used MCC [35].

\[
\frac{dQ_{total}}{d\alpha} = \frac{dQ_{MCC}}{d\alpha} + \frac{dQ_{PMC}}{d\alpha} \tag{5}
\]

where, \(Q_{total}\) is total heat release over combustion process (KJ). \(Q_{PMC}\) and \(Q_{MCC}\) are heat input for premixed combustion and cumulative heat release for the mixture-controlled combustion (KJ).

The NOx formation model is based on the well-known Zeldovich mechanism and BC formation is described by two steps including formation and oxidation. The net of rate of changes in soot mass \(m_{soot}\) is the difference between the rates of soot formed \(m_{soot \_form}\) and oxidized \(m_{soot \_ox}\) [35].

\[
\frac{dm_{soot}}{d\alpha} = \frac{dm_{soot \_form}}{d\alpha} - \frac{dm_{soot \_ox}}{d\alpha} \tag{6}
\]

3. Results and Investigations

3.1. Combustion Characteristic of Emulsified Marine Diesel Oil

Figure 5 shows the combustion chamber pressure and heat generation rate characteristics for the experimental and numerical results (Figure 4). The results of combustion analysis using MDO show very similar results to the numerical results of combustion analysis using AVL BOOST program. Through the test results and numerical analysis results, combustion and heat generation rate according to water content were compared after verification. The numerical results in Figure 5 showed that the maximum combustion pressure increases with increasing water content. Furthermore, based on the heat generation rate characteristics, the numerical results showed that the combustion pressure decreases as the water content increases, and combustion is actively performed. Reduction in nitrogen oxides and black carbon is expected due to rapid combustion.
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![Figure 5. Cont.](image-url)
Figure 5. Characteristics on the combustion pressure and heat release between experiment and numerical results.
Figure 6 shows the crank angle at which the maximum pressure occurs as a result of load variation for MDO and emulsion fuels. At a load of 50% or lower, it was found that the maximum combustion pressure position was advanced at a high moisture content in the emulsion fuel. However, at a load of 75%, the maximum combustion pressure position of the emulsion fuel was retarded when compared to the MDO. The retard in the combustion occurred due to the water content of the emulsion fuel when the load is 50% or lower, and fast combustion occurred due to the emulsion fuel when the load is 75% or higher. This is likely to be the cause of the reductions of nitrogen oxides and black carbon, and the rapid combustion from this phenomenon led to a reduction in the exhaust gas by shortening the post combustion period.

![Figure 6. Location of peak pressure in accordance with changing emulsified fuel oil.](image)

3.2. Specific Fuel Consumption Characteristic with Emulsified and Marine Diesel Oil

Figure 7 shows the comparative analysis results of the numerical and experimental results for the fuel consumption rate according to the load when MDO is used as the fuel. As a result of comparing the numerical results with the experimental results, although the numerical results showed lower fuel consumption rates, overall similar trends were observed.
Figure 7. Comparison on the specific fuel consumption with experimental and numerical results.

Figure 8 shows the fuel consumption for MDO and emulsion fuels. Figure 8a shows the fuel consumption according to the water content. From the results, it can be found that fuel consumption tends to increase as the water content increases. The fuel consumption was increased because more emulsion fuel is required than MDO to maintain the output of the same load. Figure 8b shows the fuel consumption of the emulsion fuel without water content. When the water content was removed, it showed lower fuel consumption than MDO. This is because the water in the fuel caused it to be converted to expansion energy by volume expansion. In addition, volume expansion of the water promoted fuel atomization, which caused rapid combustion of the fuel.
3.3. NOx and Black-Carbon Reduction Characteristic with Emulsified and Marine Diesel Oil

Figure 8. Comparison of specific fuel consumption of emulsified marine oil, with and without water.

Figure 9 shows the combustion consumption reduction rate for MDO fuel and emulsion fuel. In the case of emulsion fuel having a water content of 16%, fuel consumption was decreased by up to 3.5% compared to the fuel consumption of MDO. Furthermore, fuel consumption was decreased as the water content was increased in the emulsion fuel. Based on these results, it was found that the fuel atomization was promoted due to microexplosion and the moisture in the emulsion fuel. As a result, it is expected that the overall emissions will be reduced due to the reduction of the fast combustion and post combustion periods.

Figure 9. The reduction rate of specific fuel consumption of emulsified marine oil, with and without water.

3.3. NOx and Black-Carbon Reduction Characteristic with Emulsified and Marine Diesel Oil

Figure 10 shows the comparative analysis result of experimental and numerical analysis results for nitrogen oxide according to load variation. The numerical analysis and experimental results showed very similar results.
Figure 10. Comparison on the NOx emission with experimental and numerical results.

Figure 11 shows the characteristic results and reduction rate of NOx emission of the emulsion fuel according to MDO and water content. Nitrogen products were increased in the low load region, while nitrogen oxides were decreased up to 15% under 50% load conditions. In the low load region, although the moisture that accompanies the emulsion evaporates and lowers the ambient temperature, combustion is more active and dominant due to combustion acceleration caused by the micro explosion of fuel from the phase change of moisture. However, under 50% load condition, due to the evaporation of water in the emulsion, a higher water content than the low load condition, and latent heat of evaporation, combustion temperature in the combustion chamber was decreased. In addition, as the water content of the emulsion increases, the reduction of nitrogen oxides has been shown to increase.

Figure 11. Characteristics on the NOx emission with MDO and emulsified MDO contained water concentrations.

Figure 12 shows the particulate matter emission characteristics and the reduction rate of emulsion fuel according to MDO and water content. Except for the 10% load, all other loads showed a reduction
in BC. In the 10% region, particulate matters in the emulsion fuel were rather increased. This implies that the effect of the water content in the emulsion fuel was negligible at a low load condition. However, in other load regions, the particulate matter and the nitrogen oxides were reduced by lowering the combustion chamber temperature as well as promoting atomization of the fuel due to moisture content in the emulsion fuel. The decrease in BC when using emulsion fuels was due to the fact that the water contained in the fuel increased the chances of the atomized fuel to come into contact with the air, while promoting the atomization of the fuel due to the micro explosion of water due to the evaporation of water due to the phase change. Because of this shortening of post-combustion, BC decreased drastically when using EMDO rather than using MDO.

![Figure 12](image_url)

**Figure 12.** Characteristics on the BC emission with MDO and emulsified MDO containing water concentrations.

**4. Conclusions**

This study shows the results of reducing nitrogen oxides and particulate matters using MDO and water-in-fuel emulsified oil used in ships.

(1) Emulsion samples were obtained from the emulsified fuel supply system before the test, and compositions and fuel stability characteristics of fuels containing 10%, 13%, and 16% of water content and marine diesel oil (MDO), and additives were analyzed.

(2) Using emulsion fuel and MDO fuel, the maximum combustion pressure position was retarded in a high load region, while the minimum combustion pressure position was advanced in a low load region, compared to the MDO in a low load region. In addition, fuel consumption decreased when emulsion fuel was used.

(3) As the water content of emulsion fuel increased, the overall nitrogen oxides were reduced. Nitrogen oxides were reduced due to lower combustion temperature caused by the latent heat of evaporation from the phase change of water in fuel.

(4) As the water content of the emulsion fuel increased, the particulate matter showed a reduction efficiency of up to 60% or more. In this study, the consumption of emulsion fuel reduced combustion consumption, and nitrogen oxides and particulate matter showed up to 15% and 60% reduction. This is because the water content in the emulsion promotes atomization of fuel particles due to microexplosion...
and lowers combustion temperature due to latent heat of evaporation, thereby reducing particulate matter and nitrogen oxides.

**Author Contributions:** Conceptualization, I.C.; methodology, I.C.; investigation, C.L.; data curation, I.C.; writing—original draft preparation, C.L.; writing—review and editing, C.L.

**Acknowledgments:** This work was supported by a Research Grant of Pukyong National University (2018).

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

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