

Article

Nitrogen Oxides and Particulate Matter from Marine Diesel Oil (MDO), Emulsified MDO, and Dimethyl Ether Fuels in Auxiliary Marine Engines

Jinkyu Park ¹, Iksoo Choi ², Jungmo Oh ¹  and Changhee Lee ^{3,*} 

¹ Division of Marine Engineering, Mokpo National Maritime University, Mokpo 58628, Korea; pj2019@mmu.ac.kr (J.P.); jmoh@mmu.ac.kr (J.O.)

² STX Engine Ltd., Changwon-ci, Kyungsangnam-do 51574, Korea; nicsu@onestx.com

³ Department of Mechanical and Shipbuilding Convergence Engineering, Pukyong National University, Busan 48547, Korea

* Correspondence: leemech@pknu.ac.kr; Tel.: +82-51-629-7816

Received: 7 April 2020; Accepted: 28 April 2020; Published: 1 May 2020



Abstract: Exhaust gases from ships and automobiles have a significant impact on people and the environment. As a result, diesel engines used in land and marine vehicles are gradually being restricted, and low-carbon engines are under development. This study considers marine diesel oil (MDO) that is used in ships to meet the emission regulations required by the International Maritime Organization. This investigation explores the method and application technology for the reduction of nitrogen oxides (NO_x) and particulate matter using emulsified fuel and mass-produced dimethyl ether (DME) fuel, which are analyzed. When comparing emulsified fuel and DME fuel to MDO, which is a ship oil, NO_x are reduced by 20–45% and the particulate matter is reduced by 60–97%. When emulsified fuel containing moisture is used, the combustion chamber temperature is lowered due to the optimal expansion by moisture contained in the fuel. The particulate matter is also reduced. When DME fuel is used, it reduces the particulate matter by more than 97% in comparison with the existing MDO fuel and the emulsified fuel. The conditions are believed to be suitable for combustion and they can be satisfied by supplying oxygen during post-combustion.

Keywords: marine diesel oil; emulsified marine diesel oil; nitrogen oxides emission; particulate matter; dimethyl ether fuels

1. Introduction

Exhaust gases from ships and automobiles have a significant impact on people and the environment. As a result, diesel engines used in land and marine vehicles are gradually being restricted and low-carbon engines are currently being developed. In accordance with the regulations of the International Maritime Organization (IMO) [1], the emission control area is determined in accordance with international conventions for the prevention of pollution from ships. Emissions must be managed in emission control areas. Due to the limitations of exhaust gases, especially nitrogen oxides (NO_x) emissions, internal combustion engines are being applied to reduce NO_x and particulate matter (PM) in exhaust gases using the ‘optimal emulsifying fuel composition’. Therefore, it should be noted that estimation and forecasting of diesel engine emissions is very important in this context [2]. Moreover, predicting emissions from diesel engines in real time is not an easy task. With the development of powerful, accurate, and fast predictive algorithms, diesel engine exhaust can be controlled in real time.

Meanwhile, studies on NO_x reduction using emulsified fuels have been actively conducted. Lim et al. [3,4] showed a deterioration in the fuel efficiency at low loads when the test diesel engine was operated by dispersing water in light oil with a mixer using ultrasonic and shear force without using

additives, but at high loads. Favourable operating conditions, stabilization of fuel economy, and a high NO_x reduction rate were confirmed. However, by mixing water, light oil, and additives, and applying an emulsified fuel in oil-in-water, the fuel efficiency is improved by reducing NO_x, which dramatically reduces the particulate matter. For this reason, by mixing water particles in light oil, the combustion chamber temperature decreases due to micro-explosions caused by the phase change of water. In addition, the post combustion combusts rapidly due to atomization, thereby significantly reducing the particulate matter [5–11]. Specifically, heavy fuel oil (HFO), which is used as a ship fuel, has high density characteristics relative to on-shore fuels; hence, it is easy to emulsify, and has the feature of separating oil and water; thus, it is highly practical. Kawasaki Heavy Industries applied emulsion fuel to bulk carriers of 58,000 tons (MAN B&W 6S50MC-C, 8630 kW/116 rpm) and succeeded in continuous operations [12] for 2740 h. This suggests the possibility of using emulsion fuel for vessels. This emulsion fuel was proven to be effective in reducing the particulate matter, as well as NO_x. Murayama et al. [6] confirmed the reduction effect of 48% using emulsion fuel. However, since the method of using the emulsion fuel has a reduction rate of NO_x that does not meet the IMO regulation value, the disadvantage is that it is difficult to achieve the target value with this method alone.

For a long time, the search has been on to find a fuel for compression engines that is environmentally friendly and can be easily stored and transported. Dimethyl ether (DME, CH₃-O-CH₃) [11] is an alternative fuel for diesel engines that has a low auto ignition temperature. It also has good evaporative performance when sprayed into the combustion chamber, and it has a higher cetane number (> 55) than diesel fuel. In particular, DME is an oxygen-containing fuel that consists of 34.8 wt.% oxygen. As there is no direct coupling between carbon and carbon in the fuel characteristics, almost no particulate matter is emitted in the diesel engine [12–19]. Due to these advantages, it is possible to apply a large amount of exhaust gas recirculation (EGR) without much difficulty to the engine. This can greatly reduce NO_x and has many excellent characteristics as an alternative fuel for diesel engines [19–24].

Industrially mass-produced DME is a very promising alternative fuel for diesel engines [25–27]. DME has a simple molecular structure, C–O–C without a C–C bond. DME also has a very high cetane number (> 55), high oxygen content (34.8 mass%), and better atomization, combustion, and fuel economy than diesel [28,29]. DME is also known as a potentially very clean fuel that does not have much smoke, and can be burned without particulate matter emissions. In addition, a high EGR allows NO_x emissions to be controlled to meet increasingly stringent regulatory standards [30] for application to diesel engines. These properties include the bulk modulus, low calorific values, and viscosity. The bulk modulus and viscosity values of DME are much lower than diesel's bulk modulus and viscosity values. This leads to higher pressures, intense pressure fluctuations, and steam leaks in fuel delivery systems (e.g., high-pressure pumps, common rails, injectors). In order to solve this problem, it is not possible to use a fuel supply device for general diesel; thus, a fuel supply system dedicated to DME must be applied. [31,32]. A realistic alternative is biodiesel [33–36], which is an alternative oxygenated fuel for diesel engines. Biodiesel is gaining momentum due to its sustainability, good exhaust quality, and biodegradability [37–40]. In DME engines, a good lubricity and a high calorific biodiesel complement the properties of DME and eliminate the use of lubricating additives by mixing biodiesel.

Developing new combustion techniques to improve performance and reduce the emissions is a difficult and expensive option. Some notable works on homogeneous charge compression ignition as a potential combustion technology for DME combustion have shown promising results with a simultaneous reduction of NO_x and particulate matter emissions [29,41–43]. Other possible methods for achieving complete combustion and less emissions include a controlled fuel injection strategy [44–51], fuel injector configuration, injection pressures, and employing combustion after treatment processes such as EGR, oxidation catalysts, and particle filters [52,53]. In this review paper, the effect of injection strategies, fuel additives, and exhaust gas after treatment techniques on emissions are thoroughly examined in order to suggest the optimum methods for reducing emissions. In the end, a summary is drawn to show the direction in which research on DME as an alternative fuel should be focused to achieve the goals of reduced emission and better combustion.

Finally, comparative values of NO_x emissions from DME compression ignition engines and those from diesel fuel vary depending on the engine conditions and the fuel supply system. Some studies found that NO_x emissions are lower, while other studies have reported the opposite [54,55]. To lower NO_x emissions, some researchers reported that DME combustion results in lower NO_x emissions [56–58] than diesel combustion. The reasons for this include a lower heating value, the higher heat of vaporization, a shorter ignition delay, a reduced amount of fuel that is injected during the ignition delay period, and a decreased amount of fuel burned during the premixed burning phase. As a result, this can lead to a lower peak combustion temperature. In regard to higher NO_x emissions, it is possible that a higher amount of NO_x can be produced from DME than from diesel fuel for an early injection start. This is because the duration of the peak temperature would be longer in the initial combustion period due to the shorter ignition delay of DME. When injection retardation is optimized for each fuel, NO_x from DME is lower than that of diesel fuel [57].

In this study, the experimental data and numerical analysis results were compared and analyzed using the existing marine diesel engine’s experimental data and AVL BOOST (www.avl.com/boost). The numerical analysis was conducted on the characteristics of NO_x and particulate matter reduction in marine engines using emulsified fuel and DME fuel according to the content of fuel and water used in the marine engine. In general, a study was conducted on the exhaust characteristics of oil-in-water emulsion fuel through marine fuel, moisture, and additives. In addition, combustion and exhaust characteristics based on the excess air ratio according to the compression ratio change of the turbocharger were analyzed using emulsified fuel with a moisture content of 16%. In addition, the characteristics of NO_x and particulate matter emission from DME fuel and emulsion fuel similar to diesel fuel were compared and analyzed. This study analyzed the combustion and exhaust characteristics based on the hole diameter and the injection timing of the nozzle of a general marine diesel engine. This research was focused on combustion and exhaust reduction based on the optimal hole diameter and the injection timing.

2. Materials and Research Methods

2.1. Experimental Method

Regarding the engine used in this study, a 600-kW-class generator engine was constructed, as shown in Figure 1. The experimental apparatus includes Encoder, which can measure the number of revolutions of the engine on the crankshaft, and a pressure sensor (model 6056 A, Kistler, Winterthur, Switzerland) on cylinder 1 to measure the pressure in the combustion chamber, and measures the combustion pressure. In addition, to measure the flow rate of the incoming fuel, a flow meter, a load regulator, and a system capable of measuring NO_x and particulate matter were installed at the outlet of the exhaust outlet. Tables 1–3 show the engine specifications, exhaust gas measurement devices, and experimental conditions used in this study, respectively. Table 4 shows the experimental conditions of the study. The key properties of emulsified marine diesel oil (MDO), DME, and marine diesel fuel are shown in Table 4 [8,57,59]. In addition to the advantages above, it has a low carbon-to-hydrogen ratio (C:H), with the chemical formula CH₃–O–CH₃.

Table 1. Specifications for the test engine.

Items/Descriptions	Specifications
Engine type	Four-stroke turbo-charged direct injection 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 2. Exhaust gas instrument.

Items	Specification
Dynamometer	Load controller (in a marine ship)
Exhaust gas Analyzer	cold-dry method and uses NDIR modules
Smoke meter	Diesel opacimeter (OP 130D)

Table 3. Numerical conditions.

Fuel	Marine Diesel Oil
	Emulsified Marine Diesel Oil of 10%, 13%, and 16% Moisture Concentrations [8]
	DME Fuel
Engine speed (rpm)	900
Load (kW)	150, 300, 450, 600

Table 4. Properties of MDO, emulsified MDO (EMDO), and DME fuel.

Property (Unit/Condition)	Unit	DME [57,59]	EMDO_10% [8]	EMDO_13% [8]	EMDO_16% [8]	Diesel Fuel [57,59]
Chemical structure	-	CH ₃ -O- CH ₃	-	-	-	-
Molar mass	g/mol	46	-	-	-	170
Carbon content	mass%	52.2	79.1	77.6	76.1	86
Hydrogen content	mass%	13	13.1	12.9	12.0	14
Oxygen content	mass%	34.8	0	0	0	0
Carbon-to-hydrogen ratio	-	0.337	-	-	-	0.516
Critical temperature	K	400	-	-	-	708
Critical pressure	MPa	5.37	-	-	-	3.00
Critical density	kg/m ³	259	-	-	-	-
Liquid density	kg/m ³	667	872	878	882	831
Relative gas density (air = 1)	-	1.59	-	-	-	-
Cetane number	-	>55	-	-	-	40–50
Auto-ignition temperature	K	508	-	-	-	523
Stoichiometric air/fuel mass ratio	-	9.0	-	-	-	14.6
Boiling point at 1 atm	K	248.1	-	-	-	450–643
Enthalpy of vaporization	kJ/kg	467.13	-	-	-	300
Lower heating value	MJ/kg	27.6	36.8	34.6	33.4	42.5
Gaseous specific heat capacity	kJ/kg K	2.99	-	-	-	1.7
Ignition limits	vol% in air	3.4/18.6	-	-	-	0.6/6.5
Modulus of elasticity	N/m ²	6.37 × 10 ⁸	-	-	-	14.86 × 10 ⁸
Kinematic viscosity of liquid	cSt	<0.1	-	-	-	3
Surface tension (at 298 K)	N/m	0.012	-	-	-	0.027
Vapor pressure (at 298 K)	kPa	530	10	10	10	10
Moisture	Vol%	0	11	13.5	16.1	0

2.2. Numerical Analysis Method

The software adopted for the simulation was AVL BOOST®, version 2019.1(AVL List GmbH, Graz, Austria) which provides a graphical user interface (GUI) with icons representing the components of the internal combustion engine (ICE). For the engine in Figure 1, a simulation model was constructed

using icons as shown in Figure 2a, and once all necessary data was collected, the model was built in AVL BOOST™ software [60] and turbocharger (TC1) model was controlled on the air flow rate of the turbocharger, as shown in Figure 2b. Figure 2c shows the combustion chamber pressure and heat generation rate characteristics for the experimental and numerical results (Figure 2a). First, the experimental results and numerical values using MDO show similar results. Through the test results and numerical analysis results, the combustion and heat generation rates according to water content were compared after verification. The numerical results in Figure 2c show that the maximum combustion pressure increases with increasing water content. Furthermore, based on the heat generation rate characteristics, the numerical results show that the combustion pressure decreases as the water content increases, and combustion is actively performed [61].

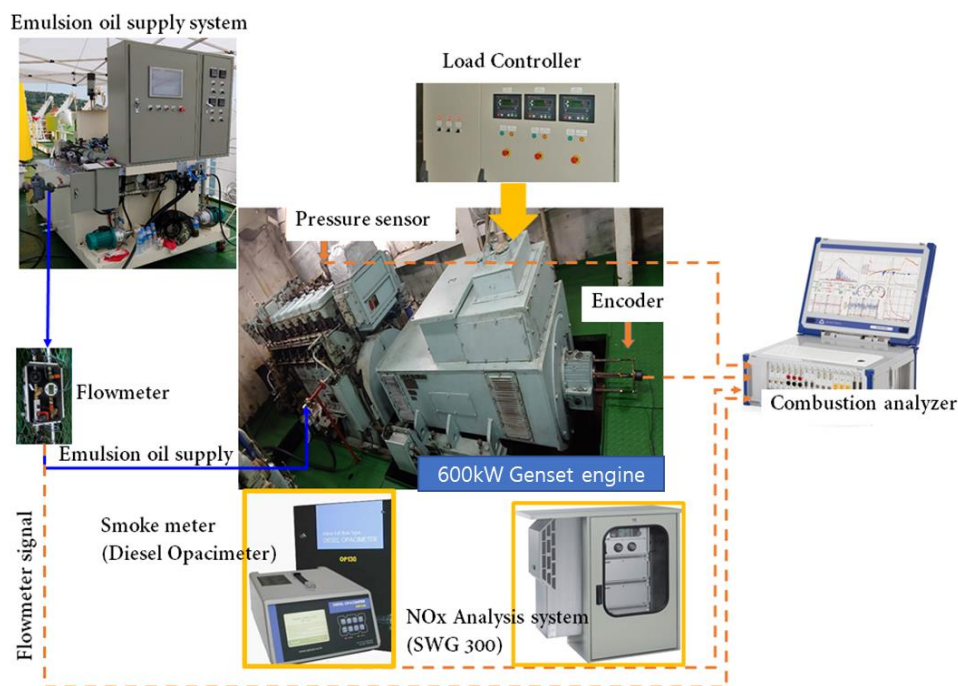
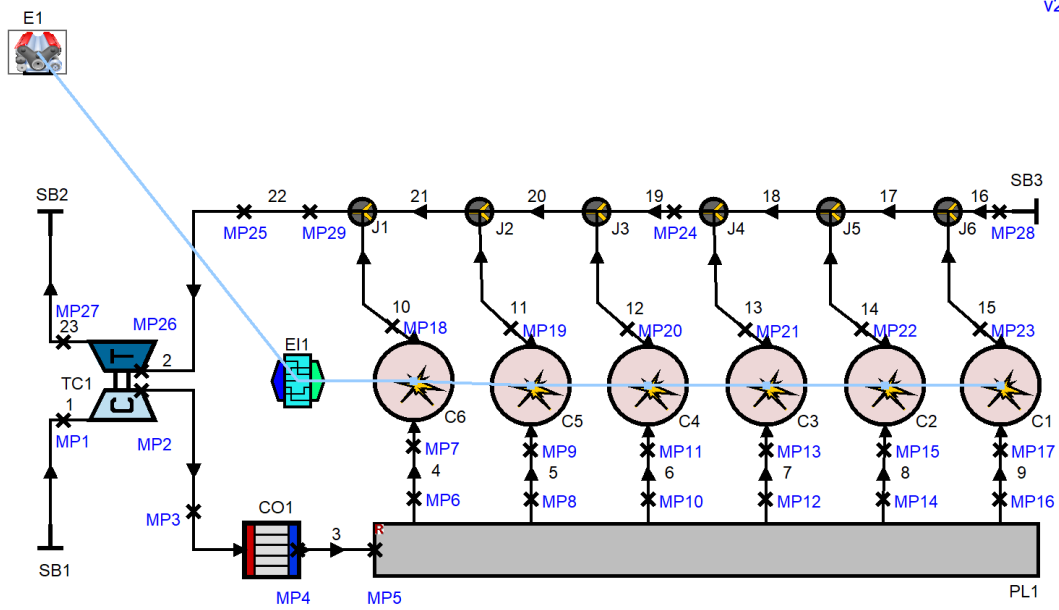


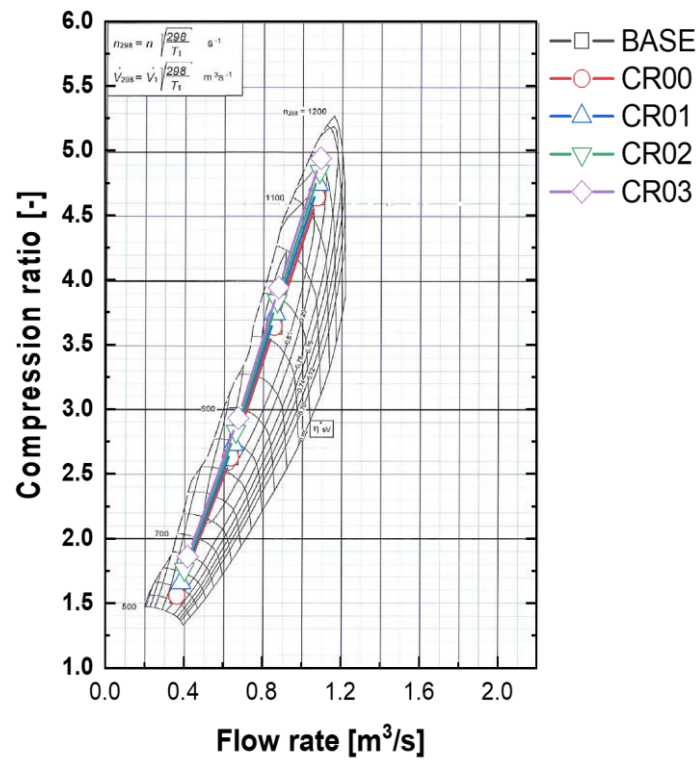
Figure 1. Schematic for a four-stroke marine engine, the data was from [61].

In the simulation model, initial and boundary conditions were established by modelling cylinders, turbochargers, valves or heat exchangers, and engine components. The modelled engine configuration considered reference cylinder 1 (C1), the main engine characteristics for the spatial distribution of the cylinders, namely, the explosion sequence C1-C2-C4-C6-C5-C3 and the firing angle of each cylinder. The model's C1 (AVL BOOST™) is associated with Element 1 Engine 1 (E1) and defines the engine type, operating speed, moment of inertia, and brake average effective pressure (BMEP) used. The combustion method adopts an experimental mixed control combustion (MCC) AVL combustion model that predicts the amount of heat released (ROHR) and NO_x emissions based on the amount of fuel in the cylinder and turbulent kinetic energy from injection.

v2019.1

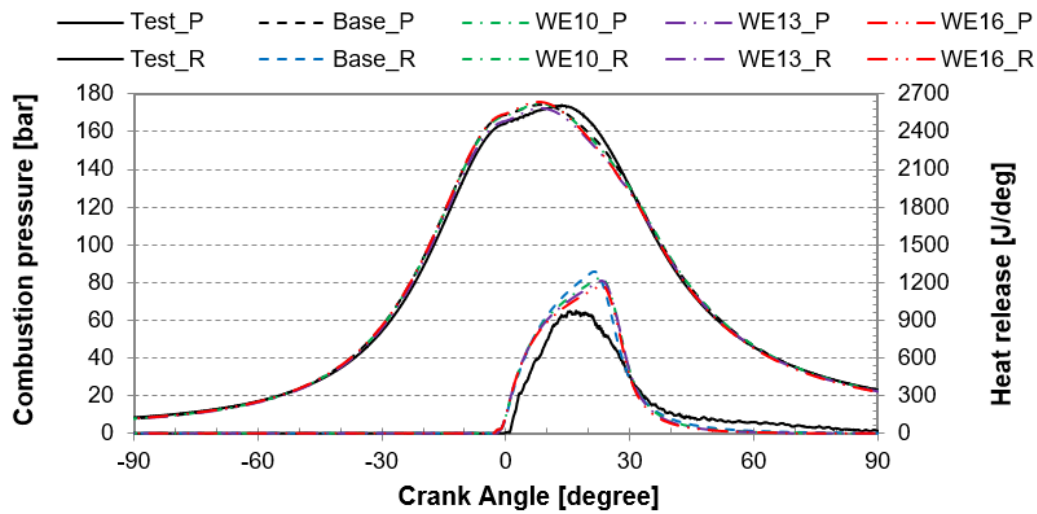


(a) AVL BOOST model



(b) Turbocharger experimental data in accordance with compression ratio

Figure 2. Cont.



(c) Verification of numerical and experimental results with engine of Figure 1 [61]

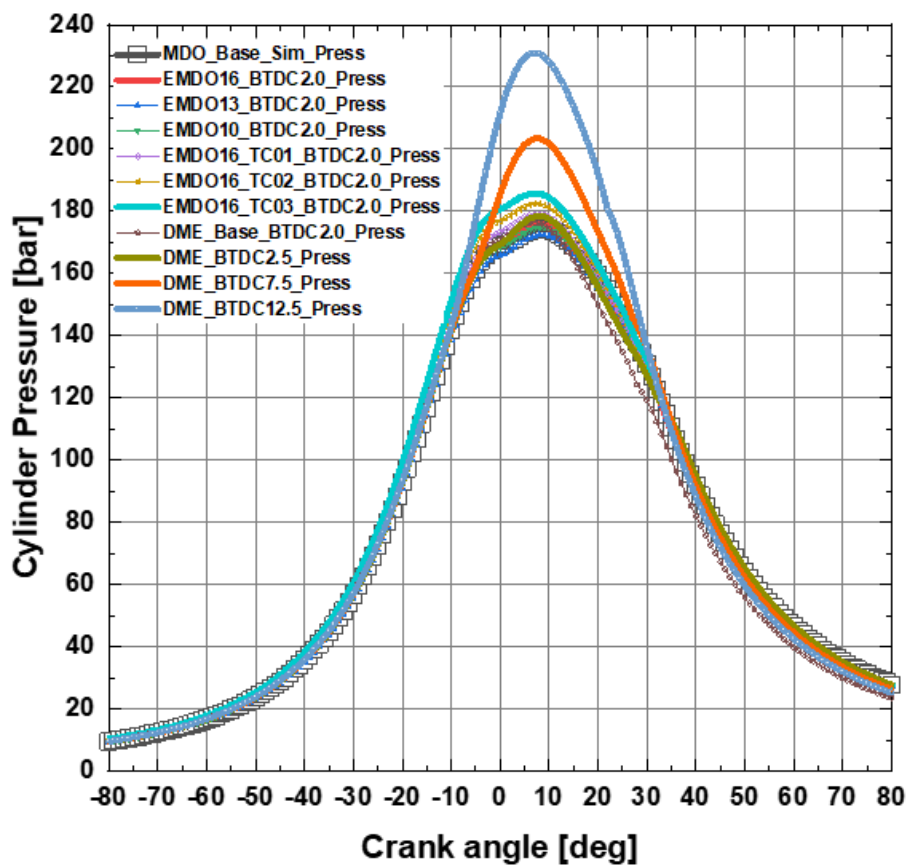
Figure 2. AVL BOOST™ model and turbocharger data for a four-stroke marine diesel engine. (Test: Experimental data, Base: Numerical data, P: combustion pressure, R: heat release, WE10: water emulsion including 10% of moisture concentration).

3. Results and Investigation

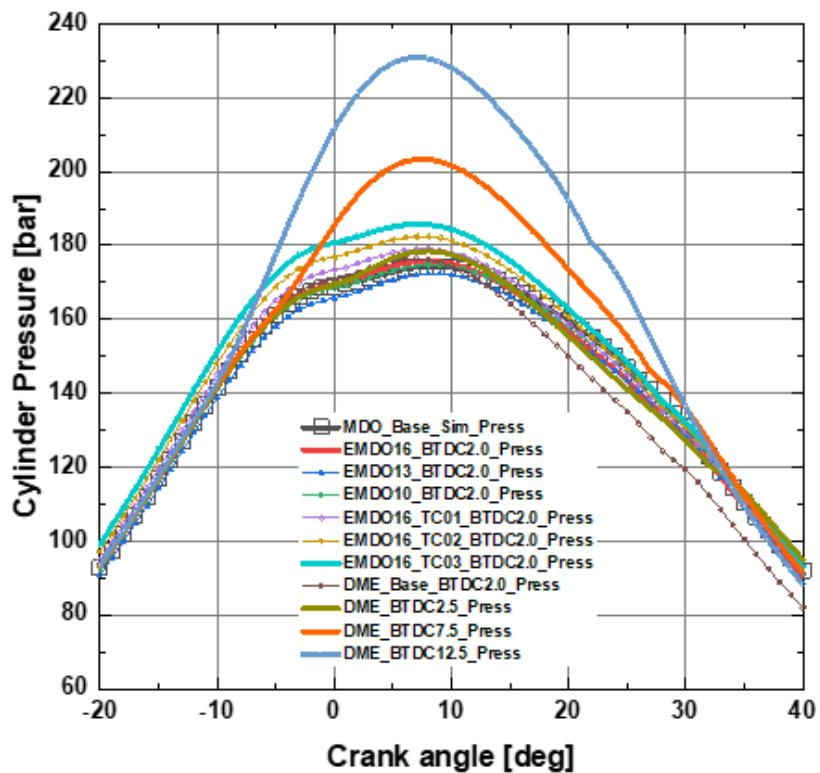
3.1. Combustion Characteristics in Accordance with MDO, EMDO, and DME Fuels

Figure 3 displays the results of the combustion pressure characteristics of the marine engine according to the injection timing change using MDO, emulsified MDO (EMDO), and DME fuels. Compared with the combustion pressure of MDO, the pressure ratio of EMDO and the turbocharger containing 16% water increases, and the combustion pressure increases when DME fuel is used. As the moisture content of the water increases, it is believed that the moisture contained in the EMDO fuel increases the combustion pressure due to volume expansion because of the water’s phase change. For the case of DME fuel, the injection timing shows similar combustion characteristics for 2.0 CA BTDC; however, the combustion pressure tends to increase significantly as the injection timing advances.

Figure 4 illustrates the ship engine’s rate of heat release according to the injection timing change using MDO, EMDO, and DME fuels. After considering the heat generation rate results while using MDO fuel, there is a rapid heat generation rate and a longer post-combustion property compared with EMDO and DME fuels, which causes particulate matter generation. In addition, NO_x generation and post-combustion increase as the combustion chamber temperature increases due to rapid combustion. When EMDO contains moisture, it somewhat slows the combustion characteristics and shortens the post-combustion characteristics compared with the basic MDO. For this reason, NO_x and particulate matter are expected to decrease. In addition, DME fuel contains 30% or more oxygen. This shows the heat generation rate at the same injection time in comparison with the existing MDO. In addition, it shows a very gentle heat generation rate and the post combustion is rapidly shortened. Therefore, it is believed that NO_x and particulate matter will be reduced very rapidly. Based on the characteristics of combustion pressure and the heat generation rate using various fuels, it is possible to analyze the emissions of NO_x and particulate matter.



(a) Whole database graph



(b) Subgraph

Figure 3. Combustion pressure history of the cylinder in accordance with MDO, EMDO, and DME fuels for 100% engine loads.

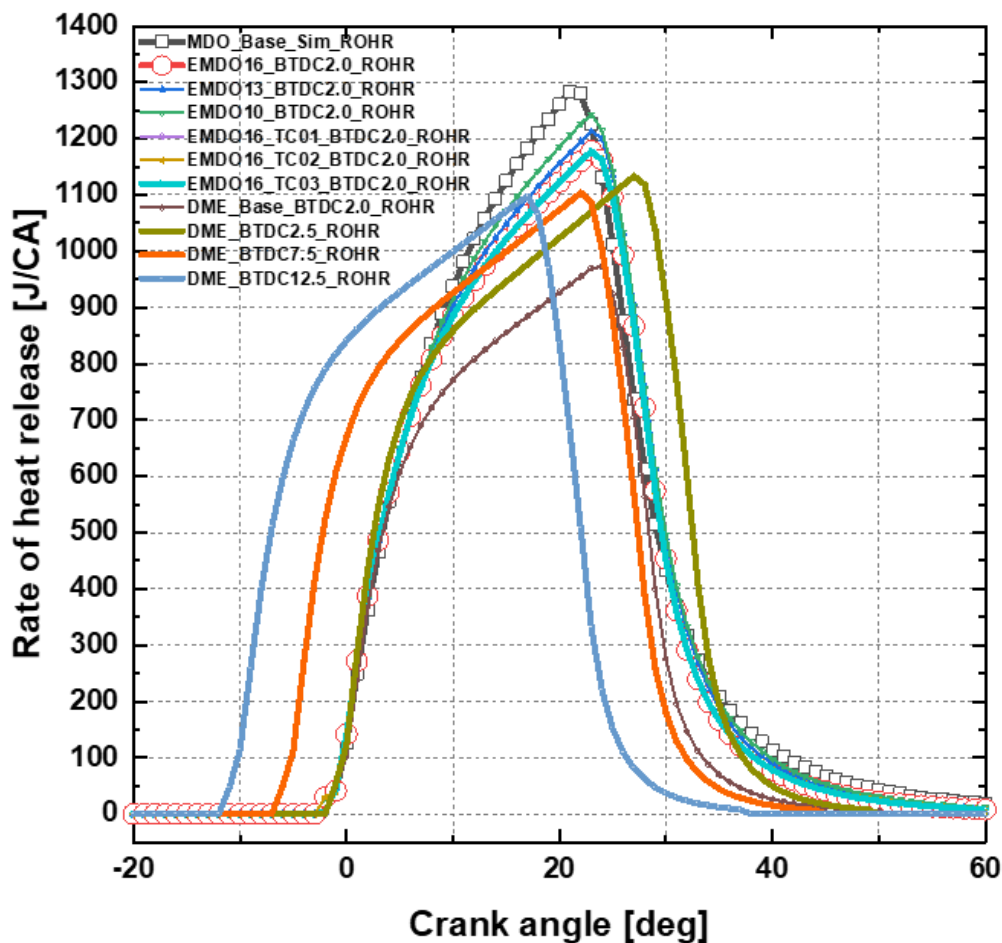


Figure 4. Rate of heat release in accordance with MDO, EMDO, and DME fuels for 100% engine loads.

3.2. Location Characteristics on Peak Combustion Pressure in Accordance with EMDO, MDO, and DME Fuels

Figure 5 depicts the combustion characteristics according to the location where the highest combustion pressure occurs for the various fuels, injection timing, and turbocharger pressure ratio. Using the results obtained from Figures 3 and 4, the characteristics of combustion were analyzed through the generation characteristics of the highest combustion pressure. First, when comparing the characteristic curve of the highest combustion pressure obtained using MDO fuel, most of the EMDO and DME fuels show the location of the highest combustion pressure that is perceived. This causes the tendency of the highest combustion pressure to advance through the rapid combustion of MDO fuel. As mentioned earlier, it is expected that the NO_x will increase due to the increase in the combustion chamber temperature due to rapid combustion. In the case of DME fuel, the position of the highest combustion pressure is perceived in the low load region and the high load region in comparison to the MDO fuel. When the injection timing is 12.5CA BTDC, the location of the highest combustion pressure is perceived. This phenomenon is considered to occur due to the small volume elastic modulus and a longer fuel injector period because the density of fuel is less than 30% compared to the MDO through the composition of the fuel mentioned in Table 3. When the pressure ratio of the EMDO and the turbocharger is changed, the highest combustion pressure is perceived as the moisture content in the fuel increases and the pressure ratio of the turbocharger increases. These phenomena also show that the combustion chamber temperature is lowered due to atomization of the fuel and micro-explosions during the phase change due to moisture. In addition, post-combustion is rapidly exhibited due to atomization. It is believed that NO_x and particulate matter can be reduced at the same time through the control of the combustion state. As mentioned earlier, the fuel's DME, which is an oxygen fuel, is a

phenomenon in which the density and volumetric modulus of the fuel are small, since the position of the highest combustion pressure is perceived even though the injection timing is advanced.

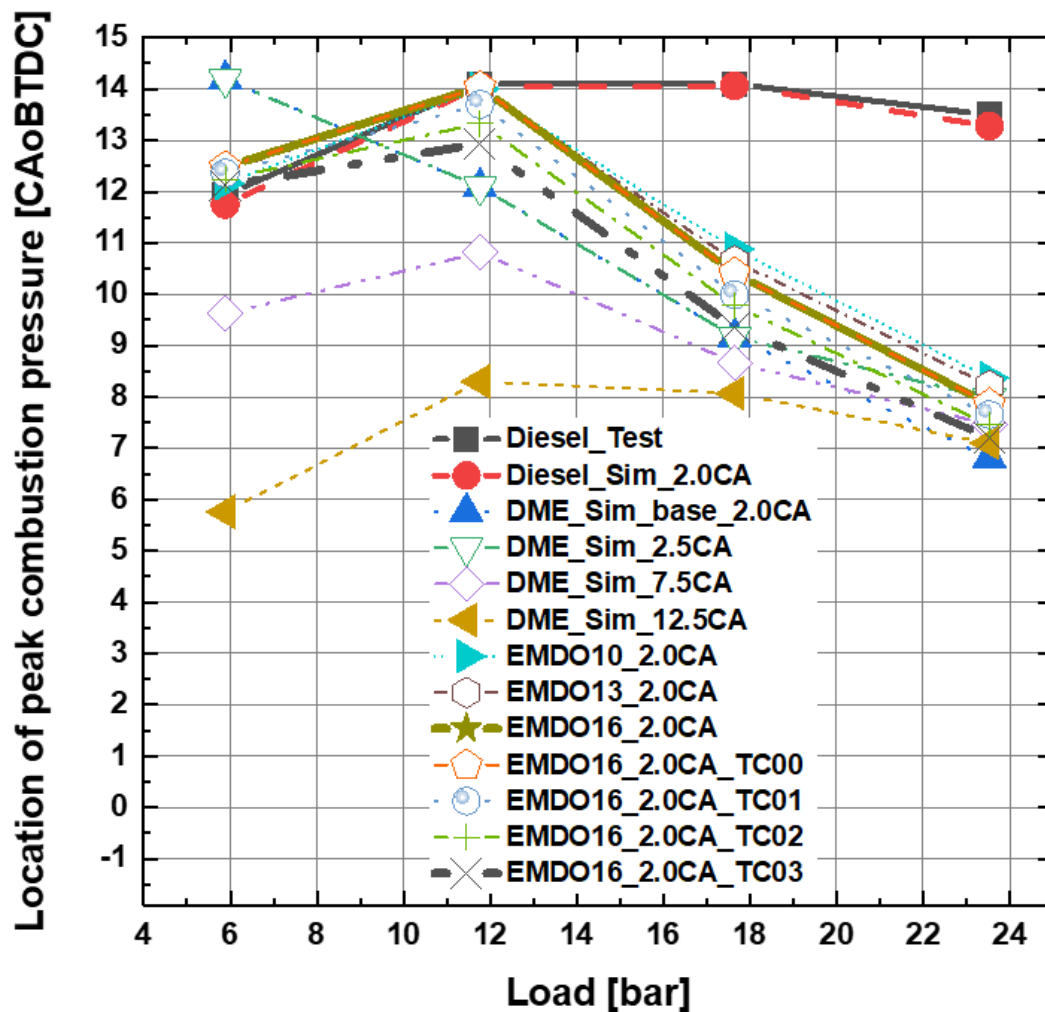


Figure 5. Location of the peak combustion pressure in a cylinder chamber in accordance with MDO, EMDO, and DME fuels.

3.3. NO_x Reduction with EMDO, MDO, and DME Fuels

Figure 6 shows the results of nitrogen tetrachloride for emulsified fuel according to the injection timing change, turbocharger compression ratio, and the moisture content for MDO, EMDO, and DME fuels. First, when considering the emulsifying fuel characteristics based on the moisture content, the overall NO_x emissions are reduced in comparison to MDO fuel. The reason for this is that the moisture contained in the emulsified fuel is lowered in the combustion chamber due to the volume expansion and the latent heat effect of evaporation due to the phase change according to the temperature. It is hypothesized that the combustion was active due to the promotion of atomization due to the micro-explosion of water and fuel. In the case of emulsified fuel with a moisture content of 16%, the pressure of the turbocharger was adjusted to increase the amount of intake air. Along with the micro-explosion, sufficient air was injected to promote the combustion of emulsified fuel. This is considered to be a factor that can be controlled for NO_x emission by controlling the compression ratio of the emulsified fuel and the turbocharger. In the case of DME, which contains oxygen, it emits more NO_x than conventional MDO, especially at a low load. This can generate a large amount of NO_x due to an increase in the pressure of the high combustion chamber. In addition, a plethora of NO_x can be produced by increasing the temperature of the combustion chamber due to the injection timing.

In order to eliminate this cause, under the same conditions as the injection timing of the MDO, NO_x were reduced to a very low level compared to the combustion conditions of other emulsified fuels. It is believed that the cause of this is that fuel containing 30% oxygen and the density of the fuel are low; hence, rapid combustion is avoided. To reduce the amount of NO_x, it is considered to be a very suitable fuel for reducing NO_x and the particulate matter by adjusting the compression ratio of the emulsion fuel and the turbocharger. This can also be achieved by controlling the injection period by increasing the injection timing of the DME fuel and the effective cross-sectional area of the nozzle hole.

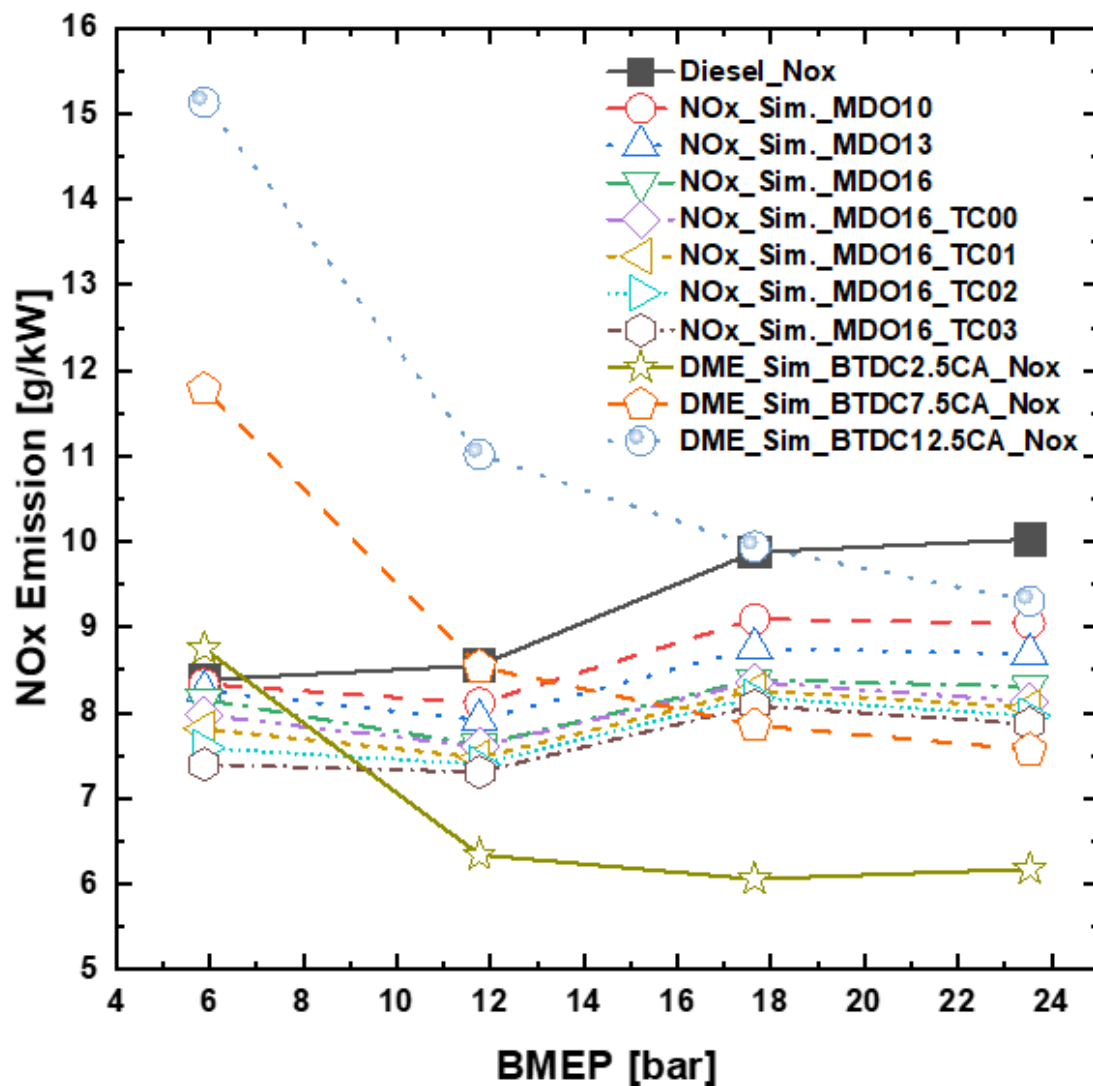


Figure 6. NO_x emissions according to MDO, EMDO, and DME fuels in terms of injection timing, turbocharger compression ratio, and moisture concentration.

Figure 7 shows the results of reducing nitrogen tetrafluoride for emulsified fuel according to the injection timing change, the turbocharger compression ratio, and the moisture content for MDO, EMDO, and DME fuels. From these results, the NO_x reduction characteristics of emulsified fuel and the emulsified fuel with a moisture content of 16% according to the moisture content show that the NO_x are reduced by up to 20% in comparison to the MDO fuel. NO_x are reduced due to the increase in the moisture content and the increase in the compression ratio of the turbocharger. This is due to the atomization of the fuel that is caused by micro-explosions in the fuel, which is attributed to the volume expansion of the moisture. In addition, the volume expansion is caused by the phase change of the moisture. However, in the case of DME fuel, the reduction of NO_x can change rapidly with the

injection timing. When the injection timing relies on the injection timing of the existing MDO fuel, there is a reduction of up to 40%. From these results, the result of adjusting the injection timing and increasing the area of the pore diameter of the fuel nozzle is displayed in Figure 8. As a result, if the nozzle hole diameter is 0.396 mm, the nozzle diameter is suitable for NO_x reduction. It is considered reasonable to determine these properties by comparing their correlation with the particulate matter.

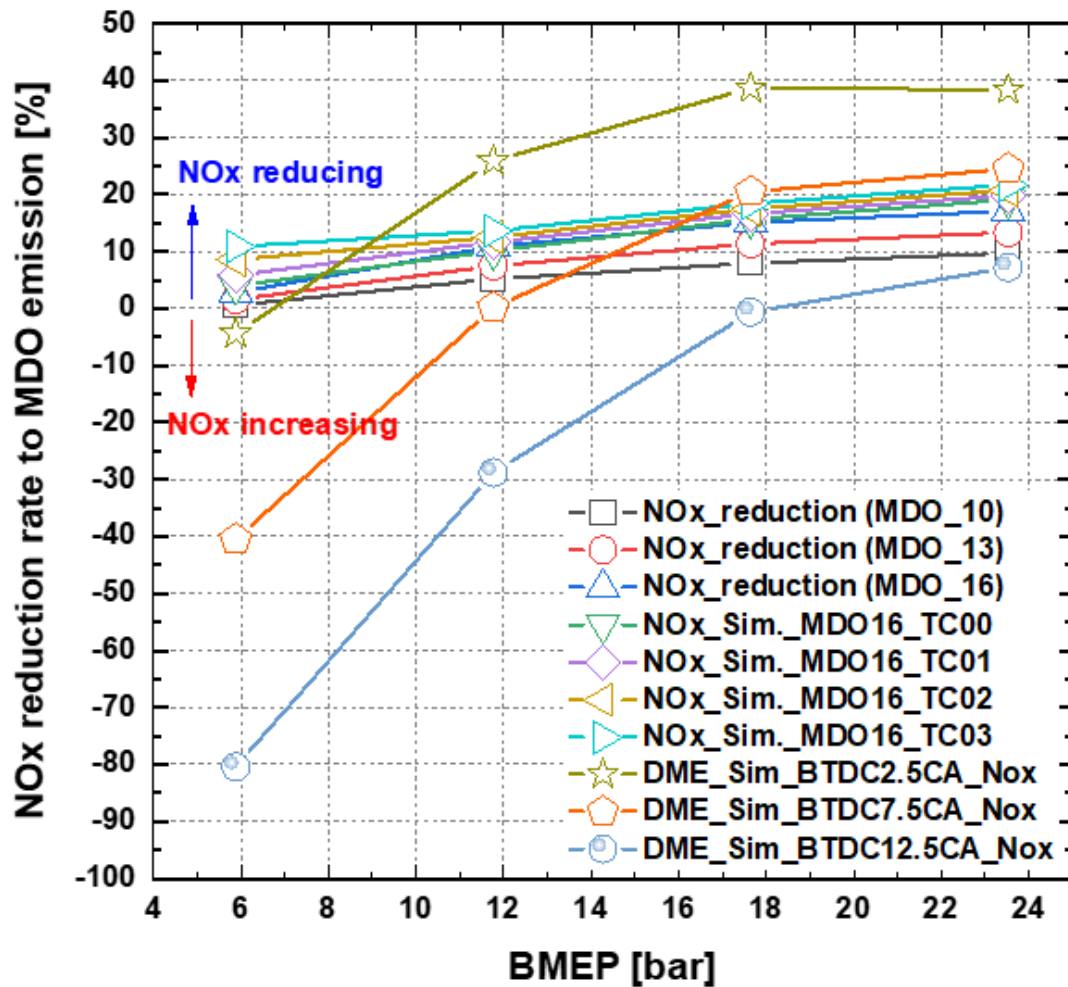


Figure 7. NO_x reduction rate according to the MDO, EMDO, and DME fuels for the conditions of injection timing, turbocharger compression ratio, and moisture concentration.

Figure 9 presents the results of the emission characteristics of the emulsified fuels and the DME fuels dependent on the DME and the moisture content. Overall, the results show a decrease when using the existing MDO fuel, emulsified fuel, and DME fuel. This is because the production of particulate matter was suppressed due to the rapid combustion of post-combustion, which can be predicted from the heat generation rate curve. Figure 10 demonstrates the results of Figure 9 in terms of showing the reduction of particulate matter based on MDO fuel. When 16% of the moisture is contained and the compression ratio of the turbocharger is increased, the analysis reveals that the reduction rate of the particulate matter is reduced to 70%. As a result, the increase in the excess air ratio due to the increase in the compression ratio of the turbocharger affects the reduction of NO_x; however, the result is somewhat slower for the reduction of particulate matter. When DME fuel is used, it reduces the particulate matter by more than 97% by comparing the results of using the existing MDO fuel and the emulsified fuel. The reason for this is believed to be that the conditions, which are suitable for combustion, are satisfied by supplying the oxygen required for post-combustion.

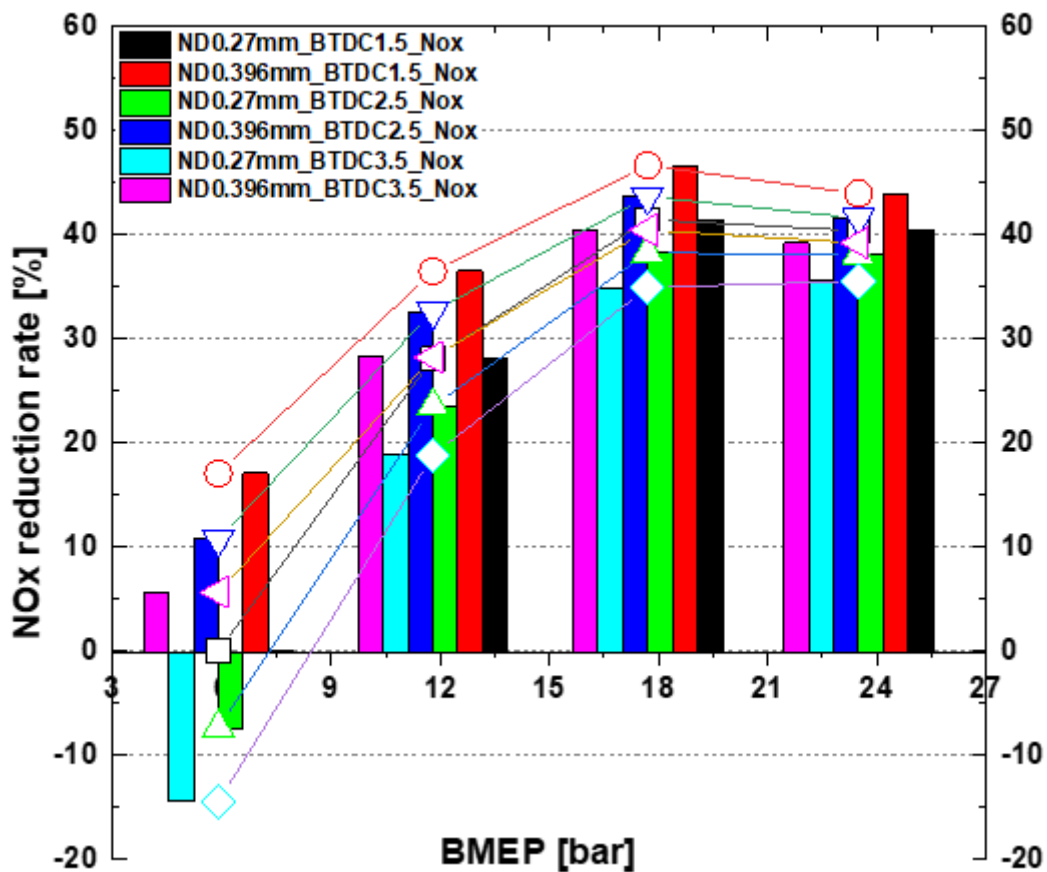


Figure 8. NO_x reduction rate according to injection timing and the ratio of the nozzle hole diameter with DME fuels.

Figure 11 illustrates the results of the reduction ratio of the particulate matter according to the ratio of the pore size of the nozzle and the injection timing using DME fuel. In comparison with the results that were obtained in Figure 8, as the pore diameter increases, the tendency for the particulate matter to increase is demonstrated. In addition, the trade-off relationship of the particulate matter reduction with respect to the injection timing is also perceived. When the pore diameter is 0.27 mm, it has no significant effect on the characteristics of the particulate matter discharge, depending on the injection timing. However, when the pore diameter is 0.396 mm, the emission of the particulate matter increases by more than 0.27 mm. As there is a particulate matter discharge based on the pore diameter and the injection timing, there is a trade-off relationship.

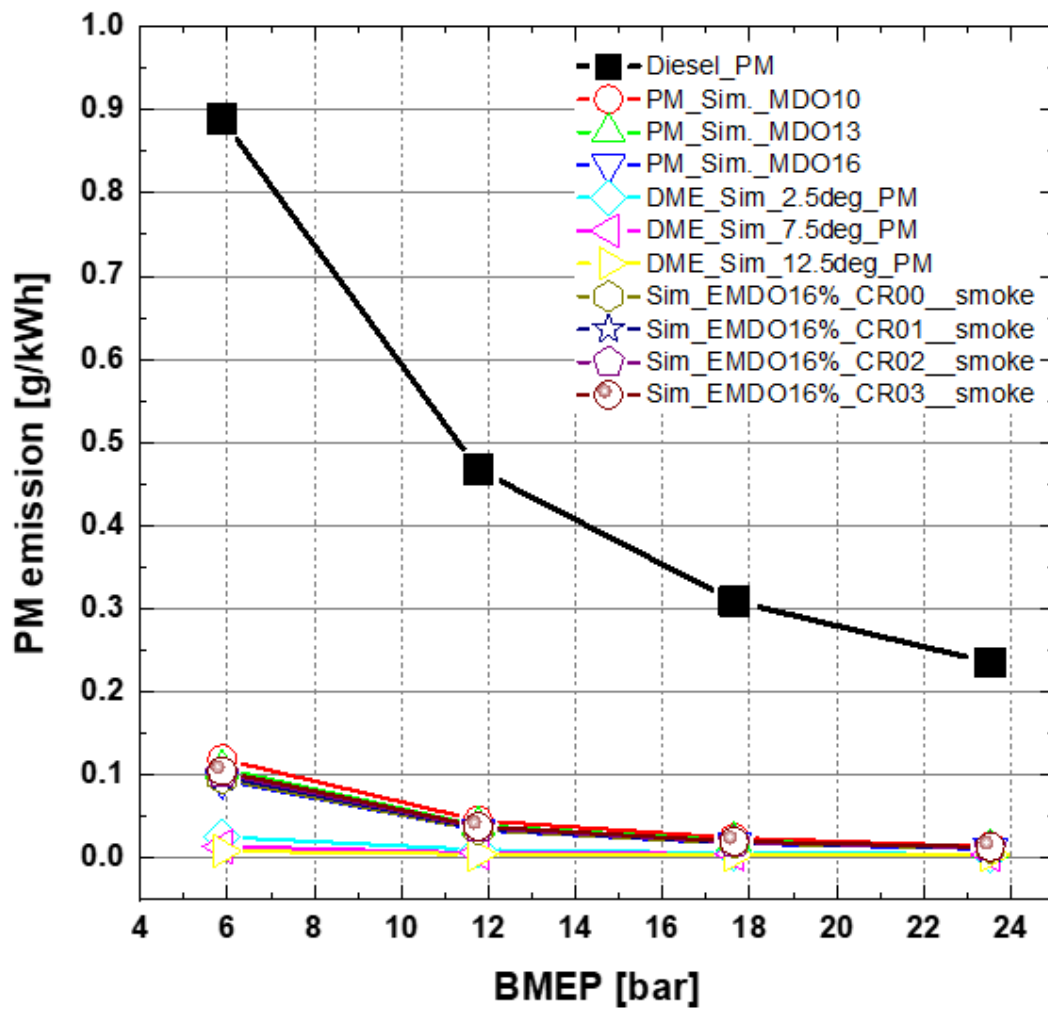


Figure 9. Particulate matter emissions according to MDO, EMDO, and DME fuels due to injection timing, turbocharger compression ratio, and moisture concentration.

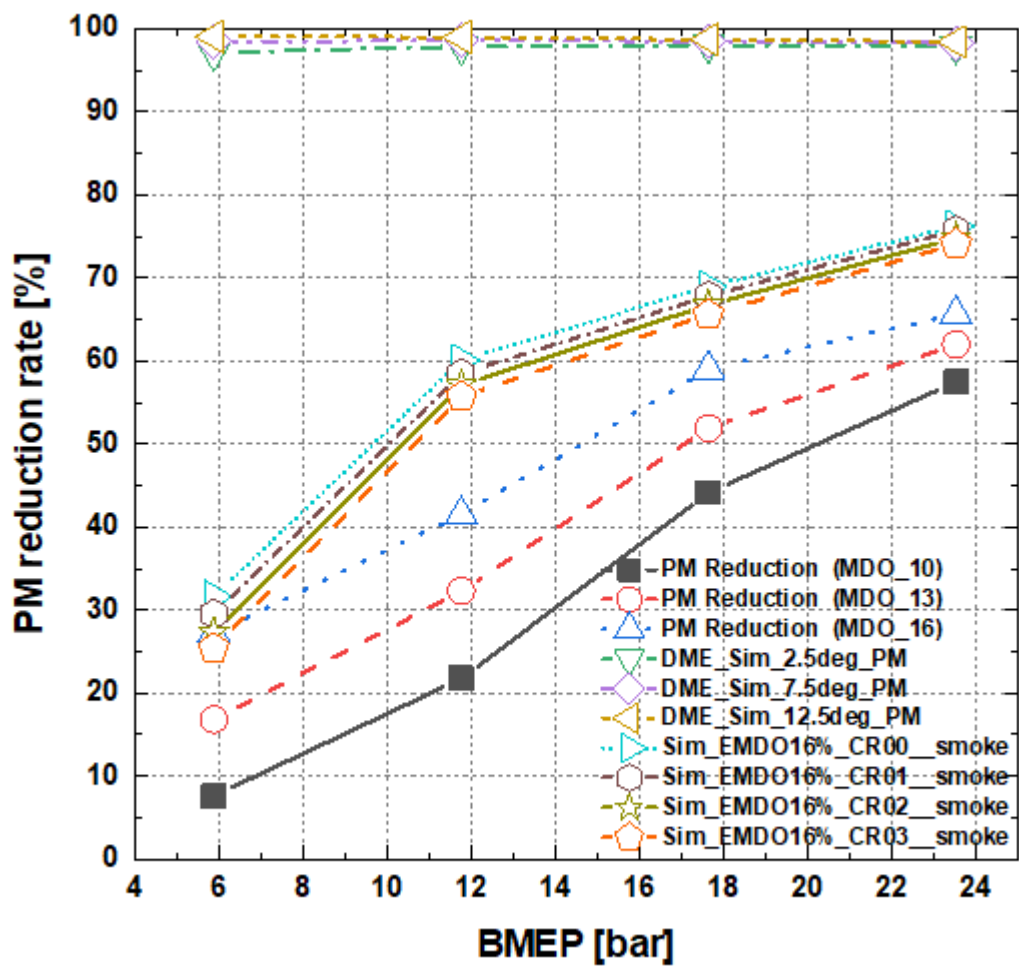


Figure 10. Particulate matter reduction rate according to MDO, EMDO, and DME fuels due to injection timing, turbocharger compression ratio, and moisture concentration.

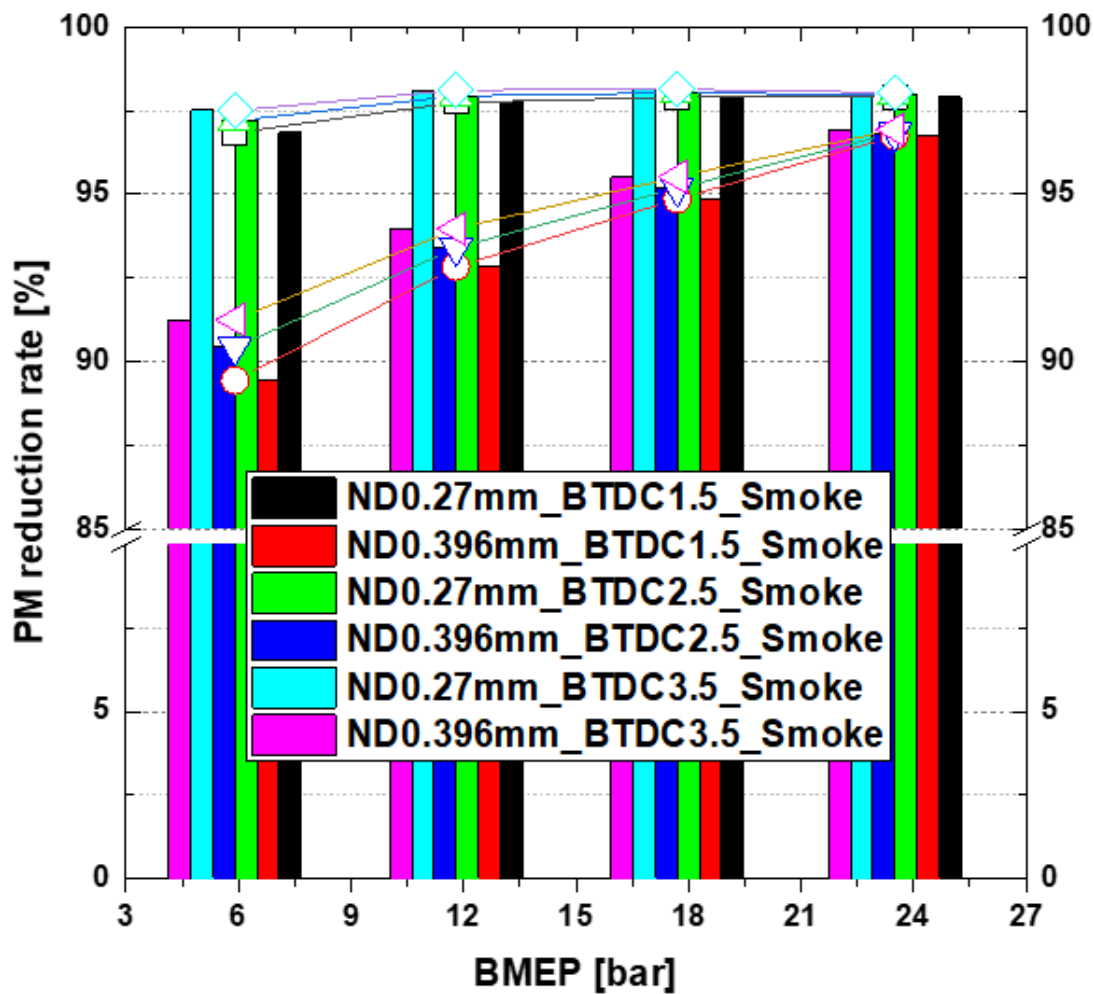


Figure 11. Particulate matter reduction rate according to injection timing and the ratio of the nozzle hole diameter with DME fuels.

4. Conclusions

In this study, NO_x and particulate matter were simulated with MDO, EMDO, and DME within a 16% moisture concentration in accordance with the change in the turbocharger compression ratio and the DME fuels by the AVL BOOST simulation program. We first obtained the experimental data by using the MDO fuel with a 600-kW marine auxiliary engine and then analyzed three types of fuel specifications based on the combustion and emission characteristics of marine diesel fuels. This study revealed the following findings:

- (1) Based on the results of the heat generation rate in accordance with the change in the injection timing using MDO, EMDO, and DME fuels, the MDO fuel shows a rapid heat generation rate and a longer post-combustion property in comparison with EMDO and DME fuels.
- (2) For the case of emulsified fuel with a moisture content of 16%, the pressure of the turbocharger is adjusted to increase the amount of intake air. In addition to the micro-explosions, sufficient air is injected to promote the combustion of emulsified fuel. This is considered a factor that can be controlled for NO_x emission by controlling the compression ratio of the emulsified fuel and the turbocharger.
- (3) By increasing the water content of the emulsified fuel, NO_x are reduced. The NO_x are reduced due to the lower combustion temperature caused by the latent heat of evaporation from the phase change of water in the fuel.

- (4) By increasing the water content of the emulsified fuel, the particulate matter has a reduction efficiency of up to 60% or more. When DME fuel is used, it reduces the particulate matter by more than 97% when comparing the results of using the existing MDO fuel and the emulsified fuel. The conditions that are suitable for combustion are believed to be satisfied because of the supplied oxygen that is required for post-combustion.

Author Contributions: Conceptualization, J.P.; methodology, I.C.; investigation, J.O.; data curation, J.O.; writing—original draft preparation, C.L.; writing—review and editing, C.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

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

References

1. IMO. *Annex VI of MARPOL 73/78 Regulations for the Prevention of Air Pollution from Ships and NOx Technical Code*; International Maritime Organization: London, UK, 1998.
2. Marine Environment Protection Committee. Proposal to Designate an Emission Control Area for Nitrogen Oxides, Sulphur Oxides and Particulate Matter. Available online: <http://www.epa.gov/nonroad/marine/ci/mepc-59-eca-proposal-es.pdf> (accessed on 7 December 2010).
3. Lim, J.K.; Cho, S.G.; Hwang, S.J.; Yoo, D.H. Effect on characteristics of exhaust emissions by using emulsified fuel in diesel engine. *J. Korean Soc. Mar. Eng.* **2007**, *31*, 44–50. (In Korean)
4. Lim, J.K.; Cho, S.G.; Hwang, S.J.; Yoo, D.H. Effects of emulsified fuel on combustion characteristics in a diesel engine. *J. Korean Soc. Power Sys. Eng.* **2007**, *11*, 51–55. (In Korean)
5. Bertola, A.; Li, R.; Boulouchos, K. Influence of water-diesel fuel emulsions and EGR on combustion and exhaust emissions of heavy-duty diesel engines equipped with common-rail injection system. *SAE Tech. Pap. Ser.* **2003**. [[CrossRef](#)]
6. Guo, Z.; Wang, S.; Wang, X. Stability mechanism investigation of emulsion fuels from biomass pyrolysis oil and diesel. *Energy* **2014**, *66*, 250–255. [[CrossRef](#)]
7. Chauhan, B.S.; Kumar, N.; Cho, H.M.; Lim, H.C. A study on the performance and emission of a diesel engine fueled with Karanja biodiesel and its blends. *Energy* **2013**, *56*, 1–7. [[CrossRef](#)]
8. Oh, J.; Im, M.; Oh, S.; Lee, C. Comparison of NO_x and smoke characteristics of water-in-oil emulsion and marine diesel oil in 400-kW marine generator engine. *Energies* **2019**, *12*, 228. [[CrossRef](#)]
9. 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](#)]
10. Tsuji, Y.; Tanaka, I. Simulation technology for large marine diesel engine in dynamic response. *Report Mitsui Ship.* **2011**, *204*, 1–6. (In Japanese)
11. Ying, W.; Genbao, L.; Wei, Z.; Longbao, Z. Study on the application of DME/diesel blends in a diesel engine. *Fuel Process. Technol.* **2008**, *89*, 1272–1280. [[CrossRef](#)]
12. Lee, S.; Oh, S.; Choi, Y. Performance and emission characteristics of an SI engine operated with DME blended LPG fuel. *Fuel* **2009**, *88*, 1009–1015. [[CrossRef](#)]
13. Park, S. Optimization of combustion chamber geometry and engine conditioned for compression ignition engines fueled with dimethyl ether. *Fuel* **2012**, *97*, 61–71. [[CrossRef](#)]
14. Yeom, K.; Bae, C. Knock characteristics in liquefied petroleum gas (LPG) = dimethyl ether (DME) and gasoline–DME homogeneous charge compression ignition engines. *Energy Fuels* **2009**, *23*, 1956–1964. [[CrossRef](#)]
15. Park, S. Numerical study on optimal operating conditions of homogeneous charge compression ignition engines. *Energy Fuels* **2009**, *23*, 3909–3918. [[CrossRef](#)]
16. Zhou, L.B.; Wang, H.W.; Jiang, D.M.; Huang, Z. Study of Performance and Combustion Characteristics of a DME Fuelled Light-Duty Direct Injection Diesel Engine. In Proceedings of the SAE International, Warrendale, PA, USA, 25 October 1999.
17. Fleisch, T.; McCarthy, C.; Basu, A. A new clean diesel technology: Demonstration of ULEV emissions on a Navistar diesel engine fuelled with dimethyl ether. *J. Fuel. Lubr.* **1995**, *104*, 42–53.

18. Clausen, L.R.; Elmegaard, B.; Houbak, N. *Design of Novel DME/Methanol Synthesis Plants Based on Gasification of Biomass*; DCAMM Special Report, No. S123; Technical University of Denmark (DTU): Lyngby, Denmark, 2011.
19. Ying, W.; Li, H.; Jie, Z.; Longbao, Z. Study of HCCI-DI combustion and emissions in a DME engine. *Fuel* **2009**, *88*, 2255–2261. [[CrossRef](#)]
20. Xinling, L.; Zhen, H. Emission reduction potential of using gas-to-liquid and dimethyl ether fuels on a turbocharged diesel engine. *Sci. Total Environ.* **2009**, *407*, 2234–2244. [[CrossRef](#)]
21. Junjun, Z.; Xinqi, Q.; Zhen, W.; Bin, G.; Zhen, H. Experimental investigation of low-temperature combustion (LTC) in an engine fuelled with dimethyl ether (DME). *Energy Fuels* **2009**, *23*, 170–174. [[CrossRef](#)]
22. Jang, J.; Bae, C. Effects of valve events on the engine efficiency in a homogeneous charge compression ignition engine fuelled by dimethyl ether. *Fuel* **2009**, *88*, 1228–1234. [[CrossRef](#)]
23. AVL. AVL Global Emission Legislation Report 2011. Available online: <https://www.avl.com/web/guest/avl-focus-2011> (accessed on 13 February 2019).
24. Loganathan, S.; Martin, M.L.J.; Nagalingam, B.; Prabhu, L. Heat release rate and performance simulation of DME fuelled diesel engine using oxygenate correction factor and load correction factor in double Wiebe function. *Energy* **2018**, *150*, 77–91. [[CrossRef](#)]
25. Benajes, J.; Novella, R.; Pastor, J.M. Computational optimization of a combustion system for a stoichiometric DME fuelled compression ignition engine. *Fuel* **2018**, *223*, 20–31. [[CrossRef](#)]
26. Lamani, V.T.; Yadav, A.K.; Narayanappa, K.G. Influence of low-temperature combustion and dimethyl ether-diesel blends on performance, combustion, and emission characteristics of common rail diesel engine: A CFD study. *Environ. Sci. Pollut. Res.* **2017**, *24*, 15500–15509. [[CrossRef](#)] [[PubMed](#)]
27. Peng, G.; Cao, E.; Tan, Q.; Wei, L. Effect of alternative fuels on the combustion characteristics and emission products from diesel engines: A review. *Renew Sustain. Energy Rev.* **2017**, *71*, 523–534.
28. Park, W.; Park, S.; Reitz, R.D.; Kurtz, E. The effect of oxygenated fuel properties on diesel spray combustion and soot formation. *Combust. Flame* **2017**, *180*, 276–283. [[CrossRef](#)]
29. Arcoumanis, C.; Bae, C.; Crookes, R.; Kinoshita, E. The potential of di-methyl ether (DME) as an alternative fuel for compression-ignition engines: A review. *Fuel* **2008**, *87*, 1014–1030. [[CrossRef](#)]
30. Cipolat, D. The Effect of Fuel Characteristics on the Fuel Injection Process in a CI Engine Fuelled on Diesel and DME. Available online: <https://www.sae.org/publications/technical-papers/content/2007-24-0119/> (accessed on 15 April 2020).
31. Cipolat, D.; Bhana, N. Fuelling of a compression ignition engine on ethanol with DME as ignition promoter: Effect of injector configuration. *Fuel Process. Technol.* **2009**, *90*, 1107–1113. [[CrossRef](#)]
32. Selvan, V.A.M.; Anand, R.B.; Udayakumar, M. Combustion characteristics of diesohol using biodiesel as an additive in a direct injection compression ignition engine under various compression ratios. *Energy Fuels* **2009**, *23*, 5413–5422. [[CrossRef](#)]
33. Hao, C.; He, J.; Hua, H. Investigation on combustion and emission performance of a common rail diesel engine fueled with diesel/biodiesel/PODE blends. *Appl. Therm. Eng.* **2018**, *31*, 43–55.
34. Iannuzzi, S.E.; Barro, C.; Boulouchos, K.; Burger, J. POMDME-diesel blends: Evaluation of performance and exhaust emissions in a single cylinder heavy-duty diesel engine. *Fuel* **2017**, *203*, 57–67. [[CrossRef](#)]
35. Bhide, S.; Morris, D.; Leroux, J.; Wain, K.; Pertez, J.M.; Boehman, A.L. Characterization of the viscosity of blends of dimethyl ether with various fuels and additives. *Energy Fuels* **2003**, *17*, 1126–1132. [[CrossRef](#)]
36. Atadashi, I.M.; Aroua, M.K.; Aziz, A.A. High quality biodiesel and its diesel engine application: A review. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1999–2008. [[CrossRef](#)]
37. Rashedul, H.K.; Masjuki, H.H.; Kalam, M.A.; Ashraful, A.M.; Ashrafur, S.M.; Shahir, S.A. The effect of additives on properties, performance and emission of biodiesel fuelled compression ignition engine. *Energy Convers. Manag.* **2014**, *88*, 348–364. [[CrossRef](#)]
38. Pullen, J.; Saeed, K. Factors affecting biodiesel engine performance and exhaust emissions Part II: Experimental study. *Energy* **2014**, *2*, 17–34. [[CrossRef](#)]
39. An, P.; Sun, W.; Li, G.; Tan, M.; Lai, C.; Chen, S. Characteristics of particle size distributions about emissions in a common-rail diesel engine with biodiesel blends. *Proced. Environ. Sci.* **2011**, *11*, 1371–1378.
40. Chapman, E.M.; Boehman, A.L. Pilot ignited premixed combustion of dimethyl ether in a turbodiesel engine. *Fuel Process. Technol.* **2009**, *89*, 1262–1271. [[CrossRef](#)]

41. Curran, H.J.; Fischer, S.L.; Dryer, F.L. The reaction kinetics of dimethyl ether. II: Low-temperature oxidation in flow reactors. *Int. J. Chem. Kinet.* **2000**, *32*, 741–759.
42. Wang, Y.; Zhou, L.B.; Yang, Z.J.; Dong, H.Y. Study on combustion and emission characteristic of a vehicle engine fuelled with DME. *Proc. Inst. Mech. Eng. Part D* **2005**, *219*, 263–269.
43. Youn, I.M.; Park, S.H.; Roh, H.G.; Lee, C.S. Investigation on the fuel spray and emission reduction characteristics for dimethyl ether (DME) fuelled multi-cylinder diesel engine with common-rail injection system. *Fuel Process. Technol.* **2011**, *92*, 1280–1287. [[CrossRef](#)]
44. Kim, H.J.; Park, S.H.; Lee, K.S.; Lee, C.S. A study of spray strategies on improvement of engine performance and emissions reduction characteristics in a DME fuelled diesel engine. *Energy* **2011**, *36*, 1802–1813. [[CrossRef](#)]
45. Cocco, D.; Tola, V.; Cau, G. Performance evaluation of chemically recuperated gas turbine (CRGT) power plants fuelled by di-methyl-ether (DME). *Energy* **2005**, *31*, 1446–1458. [[CrossRef](#)]
46. Yoon, S.H.; Cha, J.P.; Lee, C.S. An investigation of the effects of spray angle and injection strategy on dimethyl ether (DME) combustion and exhaust emission characteristics in a common-rail diesel engine. *Fuel Process. Technol.* **2010**, *91*, 1364–1372. [[CrossRef](#)]
47. Park, S.H.; Kim, H.J.; Lee, C.S. Effects of dimethyl-ether (DME) spray behavior in the cylinder on the combustion and exhaust emissions characteristics of a high-speed diesel engine. *Fuel Process. Technol.* **2010**, *91*, 504–513. [[CrossRef](#)]
48. Ying, W.; Li, H.; Longbao, Z.; Wei, L. Effects of DME pilot quantity on the performance of a DME PCCI–DI engine. *Energy Convers. Manag.* **2010**, *51*, 648–654. [[CrossRef](#)]
49. Kim, M.Y.; Yoon, S.H.; Ryu, B.W.; Lee, C.S. Combustion and emission characteristics of DME as an alternative fuel for compression ignition engines with a high-pressure injection system. *Fuel* **2008**, *87*, 2779–2786. [[CrossRef](#)]
50. Kim, H.J.; Lee, K.S.; Lee, C.S. A study on the reduction of exhaust emissions through HCCI combustion by using a narrow spray angle and advanced injection timing in a DME engine. *Fuel Process. Technol.* **2011**, *9*, 1756–1763. [[CrossRef](#)]
51. Park, S.; Choi, B.; Oh, B.S. A combined system of dimethyl ether (DME) steam reforming and lean NO_x trap catalysts to improve NO_x reduction in DME engines. *Int. J. Hydrogen Energy* **2011**, *36*, 6422–6432. [[CrossRef](#)]
52. Ying, W.; Longbao, Z. Experimental study on exhaust emissions from a multi-cylinder DME engine operating with EGR and oxidation catalyst. *Appl. Therm. Eng.* **2008**, *28*, 1589–1595. [[CrossRef](#)]
53. Dimethylether. Decreasing Emissions Caused by Seagoing Vessels. Available online: www.maritimesymposium-rotterdam.nl/uploads/Route/Dimethylether.pdf (accessed on 31 March 2020).
54. Zhang, H.F.; Seo, K.; Zhao, H. Combustion and emission analysis of the direct DME injection enabled and controlled auto-ignition gasoline combustion engine operation. *Fuel* **2013**, *107*, 800–814. [[CrossRef](#)]
55. Fleisch, T.H.; Meurer, C. DME, the diesel fuel for the 21st century? In Proceedings of the Conference Program at “International Congress: Engine and Environment”, Graz, Austria, 24–25 August 1995.
56. Ishida, M.; Jung, S.; Ueki, H.; Sakaguchi, D. Combustion of premixed DME and natural gas in a HCCI engine. *Combust. Engines* **2005**, *121*, 20–29.
57. Kapus, P.; Ofner, H. Development of fuel injection equipment and combustion system for DI diesels operated on di-methyl ether. *J. Fuel. Lubr.* **1995**, *104*, 54–69.
58. DjebaïLi, N.; Paillard, C. Burning velocities of dimethyl ether and air. *Combust. Flame* **2001**, *125*, 1329–1340.
59. Sorenson, S.C.; Glensvig, M.; Abata, D. Di-methyl ether in diesel fuel injection systems. *Trans. J. Fuel Lubr.* **1998**, *107*, 438–449.
60. AVL BOOST Theory Reference. v2019 R1. Available online: <https://www.avl.com/-/avl-boost-2019-r1>. (accessed on 6 November 2019).
61. Choi, I.; Lee, C. Numerical study on nitrogen oxide and black carbon reduction of marine diesel engines using emulsified marine diesel oil. *Sustainability* **2019**, *11*, 6347. [[CrossRef](#)]

