



## Full Length Article

# Performance and emission characteristics of additives-enhanced heavy fuel oil in large two-stroke marine diesel engine



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## ABSTRACT

The International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC) has gradually strengthened the laws regulating ship exhaust emissions. The majority of ships designed for international voyages and powered by large two-stroke marine diesel engines use heavy fuel oil (HFO), which has the advantage of a low price compared to other types of fuel. However, HFO generates large amounts of harmful exhaust emissions during combustion in a marine diesel engine. In addition, as fuel costs account for a large portion of the expenditure budgets of the shipping companies that operate and manage such ships, fuel cost reduction is of considerable interest to such companies. In this study, two fuel additives, oil-soluble Ca-based and oil-soluble Fe-based organometallic compounds, which can improve the performance of diesel engines, were injected into HFO at fixed concentrations (1/4000 and 1/6000 of the total fuel, respectively), in attempts to reduce fuel consumption and exhaust emissions. For enhanced experimental accuracy and reproducibility, a large two-stroke diesel engine installed in a land-based power plant was used as the test subject. Evaluative tests were conducted for three engine loads (50%, 75%, and 100%). The engine performance (i.e., the fuel consumption rate, maximum combustion pressure, and exhaust gas temperature) and the exhaust emissions (NO<sub>x</sub>, particulate matter (PM)) were analyzed before and after the fuel additive insertion.

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## 1. Introduction

More than 90% of international trade is now conducted via shipping [1]. The increase in the volume of world seaborne trade has led to an increase in the number of active ships. Vessels travelling internationally must adhere to the rules and regulations established by the IMO (International Maritime Organization) MEPC (Marine Environment Protection Committee) [2–7], which has gradually been strengthening the laws regulating NO<sub>x</sub> emissions [2,3]. Fig. 1 shows the current NO<sub>x</sub> emission regulations for marine diesel engines imposed by the IMO. Because IMO Tier III regulations will be applied to new ships sailing in the North American Emission Control Area (a 200 nautical mile wide area around the coast of North America) from 2016 on, both shipping and marine diesel-engine manufacturing companies worldwide are showing considerable interest in NO<sub>x</sub> reduction strategies [4–7]. The majority of ships intended for international voyages and powered by large two-stroke marine diesel engines use heavy fuel oil (HFO).

HFO is a black, liquid fuel; in fact, it is the lowest-grade of fuel oil [8]. HFO is less expensive than other types of fuels, but because its viscosity is the highest of any fuel oils, it cannot be used in an engine unless it is heated above 140 °C. Furthermore, HFO generates a large amount of harmful exhaust emissions during combustion [8]. Ryu et al. [9–11] attempted to reduce the viscosity of HFO through mixing with dimethyl ether, which has low viscosity. Using a mixture of dimethyl ether and HFO, these researchers succeeded in reducing the viscosity of HFO so that it could be used in marine diesel engines without heating and they confirmed that engine performance could be improved in this manner. Many researchers have been investigating and demonstrating techniques for reducing NO<sub>x</sub> emissions for some time. The primary NO<sub>x</sub> reduction techniques can be roughly divided into two categories: pre- and post-processing methods. The exhaust post-processing methods include selective catalytic reduction (SCR) [12–15] and exhaust gas recirculation (EGR) techniques [17,18]. The pre-processing methods include water-injection techniques [14], water-emulsified fuel methods [16,17], and the use of fuel additives [19–22]. The cited reports are samples of various studies with confirmed results that have been conducted on this topic. SCR

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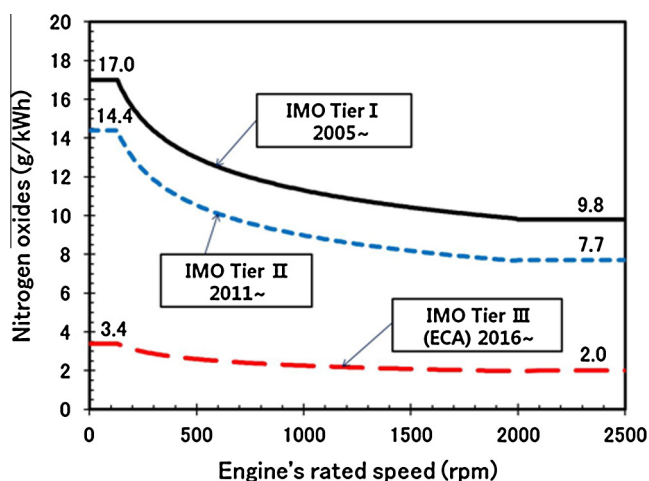


Fig. 1. IMO regulations for NOx emissions from marine diesel engines. The dates of introduction of the various tiers are indicated.

techniques reduce NOx by allowing exhaust gas and a reducing agent (i.e., ammonia) to pass through a catalyst layer simultaneously and allowing the NOx to react with the reducing agent to resolve itself into nitrogen and water vapor through deoxidation. EGR techniques reduce the amount of NOx generated by supplying exhaust gas to an engine intake to decrease the combustion temperature. Water-injection technique reduces the amount of NOx generated by spraying water to decrease the combustion temperature. Techniques based on water-emulsion fuel reduces NOx using emulsion fuel mixing fuel and water.

Of the many fuel-consumption reduction strategies available, this study examined the mixing of additives with marine HFO to attempt to reduce both fuel consumption and emissions specifically, NOx, and particulate matter (PM). Two additives were considered: oil-soluble Ca- and Fe-based organometallic compounds, identified as A1 and B1, respectively. To improve the accuracy and reproducibility of the study, the experiment was conducted on a large two-stroke diesel engine installed at a land-based plant, and A1 and B1 were added to fuel at 1/4000 and 1/6000 ratios, respectively. These ratios are those recommended by the manufacturer. Rengui Guan et al. [23] conducted a study that investigated the effects of Fe- and Ca-based additives on NO emission. Also, Ryu et al. [24] examined the engine performance by using Ca-based additive only in a 2-stroke large diesel engine. The experiment was conducted for three engine loads (50%, 75%, and 100%), and both the engine performance (fuel consumption rate, maximum combustion pressure (P-max), and exhaust gas temperature) and toxic exhaust emissions (NOx, PM) were measured before and after the additive injection to facilitate a comparative analysis of the effects of the additives.

## 2. Experimental apparatus and method

### 2.1. Fuel oils

In this study, two fuel additives were added to HFO that was used to fuel a large two-stroke diesel engine. Table 1 shows the properties of the HFO and the fuel oils A1 and B1 used in this study, where A1 and B1 correspond to A1 at 1L/4000L (0.025 vol%) concentration and B1 at 1L/6000L (0.017 vol%) concentration, respectively, mixed with neat HFO. Note that the viscosities of A1 and B1 are lower than that of HFO. Furthermore, A1 is rich in oxygen. The properties of the three fuel oils were analyzed at a specialized fuel analysis laboratory, the Ulsan Testing Center of Intertek Kim-

Table 1  
Properties of HFO and fuel oils A1 and B1, consisting of HFO and additives.

Item	HFO	A1	B1
Density at 15 °C, g/mL	0.9384	0.9378	0.9415
Ash, mass%	0.042	0.030	0.048
S, mass%	0.254	0.273	0.29
Viscosity at 100 °C, mm <sup>2</sup> /s	24.27	23.39	17.86
Water by distillation, vol%	0.10	0.20	0.30
N, mass%	0.33	0.32	0.35
Gross calorific value, MJ/kg	44.17	44.15	43.95
Net calorific value, MJ/kg	41.62	41.59	41.54
C, mass%	86.68	86.56	87.39
H, mass%	12.04	12.07	11.37
O, mass%	0.65	0.75	0.55

sco., Ltd., in the Republic of Korea. A dosing pump (AX1-12 model, CMG Techwin) with a 110-mL/min capacity, which facilitated automatic fixed-quantity injections, was installed near the control tank as the additive injection equipment, and a supply pipe was connected so that the fuel was injected into the top of the control tank.

### 2.2. Engine test

The experiment was conducted on an actual large two-stroke diesel engine installed at a land-based plant. Table 2 lists the specifications of the engine used in this study, and Fig. 2 is a photograph of the engine showing its size. The target equipment for the performance and exhaust experiment was a 40-MW-class diesel engine generator. Data were acquired using an absolute manometer and a hygrometer, which were installed to a side of engine inlet filter. And, we planned to maintain the test for one hour in order to minimize this effect. However, due to a system problem, test for 50% load was measured and recorded for 30 min. Load was held constant within  $\pm 3\%$  controlled by a load limiter, and generator output voltage was maintained at the constant rated value. The fuel consumption rate was measured through an on-site mass flowmeter (IP67/NEMA/TYPE4X, Endress Hauser) installed near the fuel supply line. For the fuel-consumption calculation, the factors influencing the performance were determined using the calibration curve and calculation method suggested by the flowmeter manufacturer. The engine P-max was measured using an engine indicator type 50 of leutert (Germany) and materials filed by the manufacturer were utilized for various factors and application curves that are necessary to calculate performance. And, the engine exhaust gas temperature was measured on engine exhaust gas pipe using Rueger (Switzerland). Each value was obtained by measuring the exhaust gas temperature at all 12 engine cylinders and then calculating the average

Table 2  
Test engine specifications.

Item	Description
Engine type	MAN B&W 12K80MC-S, low-speed two-stroke diesel engine
Bore × stroke	800 × 2300 mm <sup>2</sup>
Combustion type	Direct injection type
No. of cylinders	12
MCR output	41,320 kW
MCR rpm	109.1 rpm
Mean effective pressure	16.4 kgf/cm <sup>2</sup>
Max. piston speed	14.14 m/s
Mean piston speed	8.36 m/s
Weight	1413 ton
Number of turbo chargers	2
Turbo charger rpm	11,000 rpm
Firing order	1-5-12-7-2-6-10-8-3-4-11-9-1



Fig. 2. Photograph of test engine. A land-based test engine located at a power plant was used.

value. The NO<sub>x</sub> concentration was measured using a Greenline MK2 gas analyzer (EUROTRON) and analyzed using electrochemical methods. Once a 5-min period had elapsed after each sample was taken, i.e., when the readings had stabilized, a set of three measurements was taken at 10-min intervals. The average of these values was used as the measured result. For the PM measurement, an AST-MC sampling system (ASTEK) was used, which allowed samples to be obtained using isokinetic sampling methods. The working principle of this calculation method is that dust is collected in a thimble filter (25 × 90 mm) placed in the filter holder of the apparatus, which sucks in sample gas at the same rate as the flow rate, so that the emission gas outflow is undisturbed. Silica-fiber filter paper, which can maintain a constant temperature, was dried sufficiently for 1–3 h to remove any moisture for

the PM mass concentration calculation. The PM mass concentration is defined as the mass of the PM contained in 1 Sm<sup>3</sup> of dry exhaust gas in the standard state (0 °C, 760 mmHg). Fig. 3 is a schematic diagram of the experimental apparatus for the engine used in this study.

### 3. Results and discussion

#### 3.1. Fuel consumption rate

The fuel consumption rate results are shown in Table 3 and Fig. 4. When A1 was added to the HFO to produce A1, the rate of fuel consumption declined by approximately 2.2%, 0.7%, and 0.8% for the 50%, 75%, and 100% engine loads, respectively. For added B1 in the B1 configuration, the rate declined by 1.21% and 0.13% for the 50% and 100% engine loads, respectively. However, the rate of fuel consumption increased by 0.04% for B1 at an engine load of 75%. Therefore, it was confirmed that the addition of the examined fuel additives to HFO improved fuel efficiency for almost every load setting. In particular, it was determined that the improvements in the rate of fuel consumption following the addition of A1 and B1 were most significant at a 50% engine load. We are of the view that this improved performance is due to the combustion-promoting effects of the additives. Fuel additives served as fuel dispersing agents that diffuses the sludge in HFO. Because this sludge is drained when HFO is purified using a purifier, it cannot be used. However, the amount of usable fuel could be increased by dispersing the sludge in HFO. In addition, a decrease in the amount of fuel consumption is related to an increase in P-max. When P-max increases, a rack of a mechanical governor that controls fuel quantity moves in the direction of fuel consumption reduction, thereby confirming a decrease in fuel consumption. Additionally, fuel expenses account for most of the budget required to operate ships. Large diesel engines are used in ships. The power of the engine used in this study was 41,320 kW. As high engine power is needed

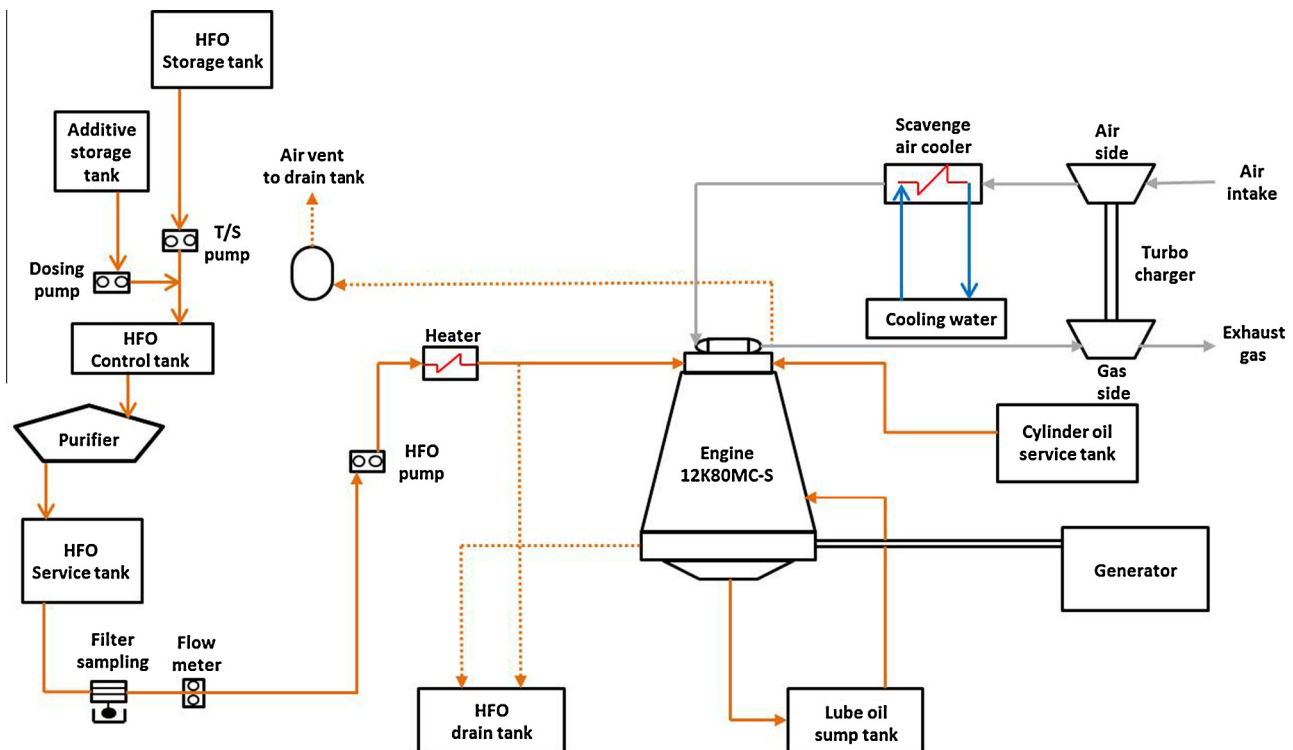
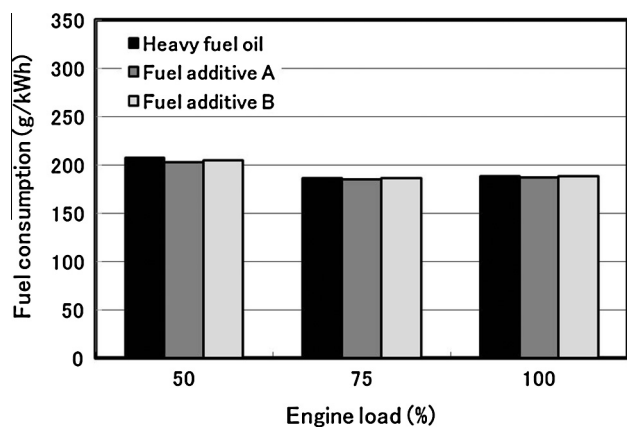


Fig. 3. Schematic diagram of experimental apparatus.

**Table 3**  
Fuel consumption rates for HFO, A1, and B1 under various engine loads.

Load (%)	Fuel consumption for HFO (g/kW h)	Fuel consumption for A1 (g/kW h)	Deviation	Ratio (%)
50	207.43	202.83	−4.6	−2.22
75	186.40	185.10	−1.3	−0.70
100	188.42	186.91	−1.51	−0.80
Load (%)	Fuel consumption for HFO (g/kW h)	Fuel consumption for B1 (g/kW h)	Deviation	Ratio (%)
50	207.43	204.92	−2.51	−1.21
75	186.40	186.48	0.08	0.04
100	188.42	188.17	−0.25	−0.13



**Fig. 4.** Fuel consumption rate as a function of engine load. Reductions were obtained for almost all cases in which A1 and B1 were used.

to operate ships, the level of fuel consumption is also high. It is estimated that reductions in fuel consumption as small as 1% can have significant effects in reducing the operating costs of ships.

### 3.2. Maximum combustion pressure

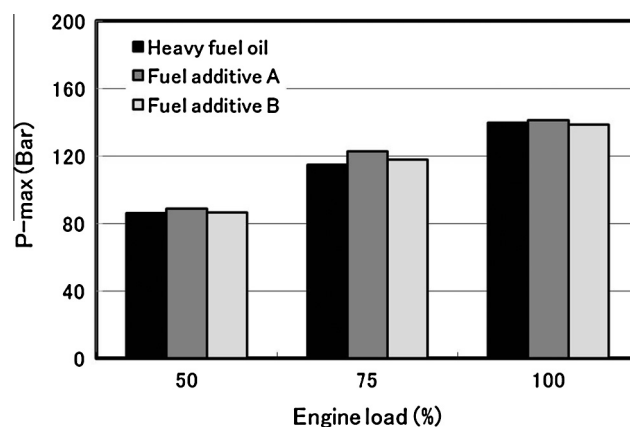
The P-max values of the engine for the various engine loads and for each of the examined fuels were examined, and the results are shown in Table 4 and Fig. 5. Each value was obtained by measuring the pressures at all 12 engine cylinders and then calculating the average value. A slight decrease in P-max occurred in the case of B1 at 100% engine load; thus, it was confirmed that the addition of either of the two additives to the HFO increased P-max for almost every load setting. In particular, the rate of increase was highest at the commonly used engine load of 75%. Furthermore, the rate of increase was higher for A1 than B1. This may be due to the effects of the greater oxygen content in A1, as shown in Table 1, as oxygen enhances combustibility by actively promoting combustion within the engine.

### 3.3. Exhaust gas temperature

The exhaust gas temperature after combustion for each engine load and the various fuels is shown in Table 5 and Fig. 6. Each value

**Table 4**  
P-max for HFO, A1, and B1, for various engine loads.

Load (%)	P-max for HFO (Bar)	P-max for A1 (Bar)	Deviation	Ratio (%)
50	86.25	88.83	2.58	2.99
75	114.83	122.91	8.08	7.04
100	139.83	141.08	1.25	0.89
Load (%)	P-max for HFO (Bar)	P-max for B1 (Bar)	Deviation	Ratio (%)
50	86.25	86.33	0.08	0.09
75	114.83	117.92	3.09	2.69
100	139.83	138.66	−1.17	−0.84



**Fig. 5.** P-max as a function of engine load. Increases in P-max were obtained for almost all cases in which A1 and B1 were used.

was obtained by measuring the exhaust gas temperature at all 12 engine cylinders and then calculating the average value. It was confirmed that the addition of the additives to the HFO decreased the exhaust gas temperature for every engine load setting. The highest rate of decrease was obtained for the low load setting of 50%, for both additives. We concluded that these results are due to the dispersant included in the additives, which uniformly dispersed the asphaltene and sludge within the HFO. This, in turn, ensured stable combustion within the engine.

### 3.4. NOx emissions

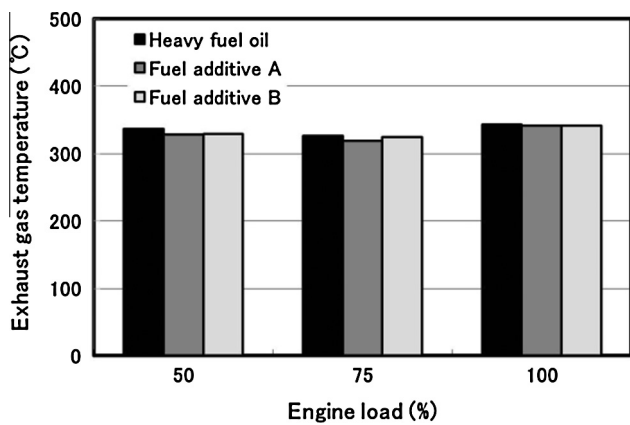
The NOx emissions measurement results are shown in Table 6 and Fig. 7. It was found that the NOx emissions decreased by 23.02%, 32.61%, and 26.39% for engine loads of 50%, 75%, and 100%, respectively, when A was added. The NOx emissions decreased by 16.52%, 17.29%, and 19.74% for the 50%, 75%, and 100% engine loads, respectively, when B was added. Therefore, a decrease in NOx emissions was confirmed at every load setting when the two fuel additives were added to the HFO. It is thought that this improvement is related to the increase in P-max and the decrease in the exhaust gas temperature discussed above. The explosion pressure increased suddenly due to rapid combustion in the combustion chamber as a result of oxygen contained in A1 fuel, and the temperature of the exhaust gas decreased as the auto-ignition temperature was reduced by the low-temperature explosion. Thus, the explosion at the low temperature led to a decrease in the amount of NOx generated.

Note that the decrease in the rate of NOx emissions was greater for A1 than for B1.

The NOx emissions produced by large two-stroke diesel engines within vessels can be largely divided into fuel NOx, which occurs when the N component within the engine fuel is oxidized during the combustion process, and thermal NOx, which is generated

**Table 5**  
Exhaust gas temperatures for HFO, A1, and B1, for various engine loads.

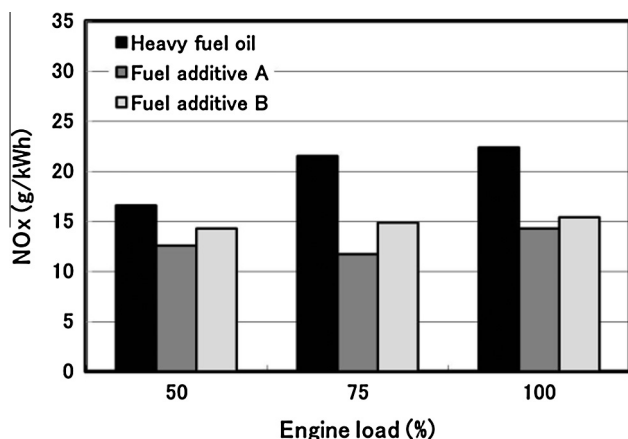
Load (%)	Exhaust gas temperature for HFO (°C)	Exhaust gas temperature for A1 (°C)	Deviation	Ratio (%)
50	337.08	328.08	-9.00	-2.67
75	326.42	318.83	-7.59	-2.33
100	343.08	341.17	-1.91	-0.56
Load (%)	Exhaust gas temperature for HFO (°C)	Exhaust gas temperature for B1 (°C)	Deviation	Ratio (%)
50	337.08	328.92	-8.16	-2.42
75	326.42	324.92	-1.50	-0.46
100	343.08	341.92	-1.16	-0.34



**Fig. 6.** Exhaust gas temperature as a function of engine load. Reductions in temperature were obtained when A1 and B1 were used.

**Table 6**  
NOx emissions for HFO, A1, and B1, at various engine loads.

Load (%)	NOx emissions for HFO (g/kW h)	NOx emissions for A1 (g/kW h)	Deviation	Ratio (%)
50	16.6	12.6	-4.0	-24.10
75	21.5	11.7	-9.8	-45.58
100	22.4	14.3	-8.1	-36.16
Load (%)	NOx emissions for HFO (g/kW h)	NOx emissions for B1 (g/kW h)	Deviation	Ratio (%)
50	16.6	14.3	-2.3	-13.86
75	21.5	14.9	-6.6	-30.70
100	22.4	15.4	-7.0	-31.25



**Fig. 7.** NOx emissions as a function of engine load. The reductions in the emissions due to the use of A1 and B1 can be clearly seen.

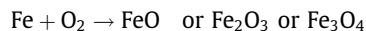
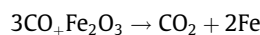
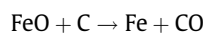
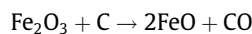
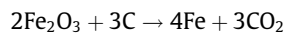
when the N component within the air that is injected for combustion is oxidized during the high-temperature combustion process. The majority of NO is generated during or immediately after the

combustion process. The NO production reaction occurs as follows [25]:

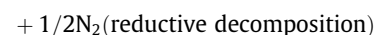
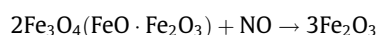
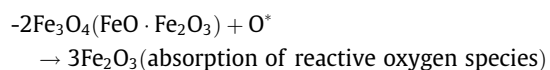
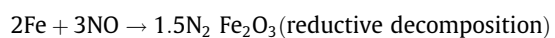
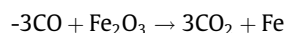


Fe-nanofluids are divided into three types of Fe oxides:  $\text{Fe}(\text{OH})_2$ ,  $\text{Fe}(\text{OH})_3$ ,  $\text{Fe}_3\text{O}_4$ , which can be expressed as  $\text{FeO} \cdot n\text{H}_2\text{O}$ ,  $\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$ , and  $\text{FeO} \cdot \text{Fe}_2\text{O}_3$ . Each of them constitutes formulas of FeO,  $\text{Fe}_3\text{O}_4$ , and  $\text{Fe}_2\text{O}_3$ . Therefore, they coexist as Fe, FeO,  $\text{Fe}_3\text{O}_4$ ,  $\text{Fe}_2\text{O}_3$ , and other types of Fe oxides in a high-temperature engine combustion chamber. Such Fe oxides facilitate an oxidation reaction with C as an oxidation catalyst in a high-temperature engine combustion chamber. In other words, it is believed that PM is reduced as the oxidation reaction is facilitated with unburned carbon or soot particles, which are created during combustion [26,27].

The PM reduction reaction of Fe-nanofluids in a high-temperature engine combustion chamber is expressed in the following reaction equations [26,27].



NOx reduction technology based on nanocatalyst fuel additives allows for the mixing and combusting of a small amount of the fuel additives that contain the nanoparticles, or ions of Fe compounds, with fuel oil and the reduction in NOx production. Whereas it is not yet clear how the reaction mechanism works and NOx is reduced by these substances, this could be roughly explained as stated below [26,27]:



The NOx reduction reaction caused by Fe-based fuel additives could be interpreted as a reductive decomposition reaction of NOx set off by Fe and a reaction where the absorption of reactive oxygen species curbs NOx production [26,27].

The reduction effect observed in the findings of this study is thought to be primarily related to thermal NOx in that combustion enhancement by oxygen supplied in the combustion chamber reduced the amount of air supplied as well as thermal NOx.

### 3.5. Particulate matter (PM) emission

The PM emission results are shown in Table 7 and Fig. 8. Following the addition of A, the PM emission rates declined by 57.41%, 59.43%, and 59.67%, respectively, for engine loads of 50%, 75%, and 100%, respectively. Following the addition of B, the PM emission rates declined by 38.85%, 39.98%, and 40.88%, respectively, for engine loads of 50%, 75%, and 100%, respectively. The measured PM emissions constitute a remarkable decline in response to the addition of A and B to the HFO, compared to the values for HFO alone. In addition, higher PM reduction rates were obtained for A1 than B1.

PM could be reduced by facilitating combustion and completely combusting unburned carbon and other substances. Our analysis showed that a reaction to facilitate combustion was larger with oil-soluble metal organics and oil-soluble organometallic compounds than it was with organic dispersants. Metal components in organometallic compounds act as active material in a reaction that facilitates combustion, and the Ca and Fe additives that were used in this study are known to trigger a huge reaction that facilitates combustion.

According to a paper by Howard and Kausch [28], the mechanism for a reduction in PM caused by adding Ca and Fe additives to HFO could be explained as follows: (1) organometallic compounds that contain Ca create hydroxyl radicals in flame gases, and (2) the hydroxyl radicals react with soot or soot precursors in the gases at high temperature and reduce PM (hydroxyl radicals production mechanism). Furthermore, organic compounds con-

taining Fe in transition metals work as oxidation catalysts, facilitating oxidation reactions with carbon. As such, it could be deduced that the amount of unburned carbon created during combustion is substantially reduced (oxidative mechanism) [26,27].

## 4. Conclusions

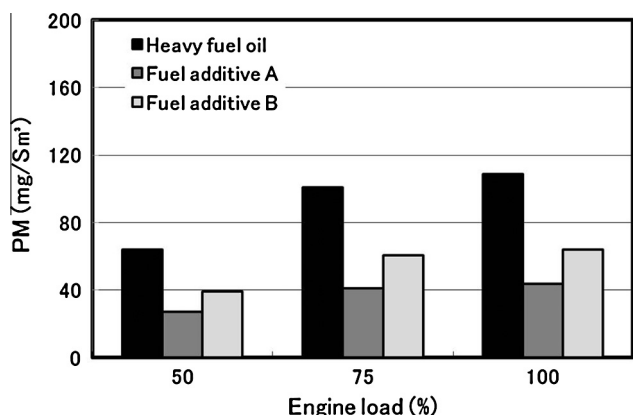
This study examined the effects of the inclusion of oil-soluble Ca- and Fe-based organometallic compounds (denoted A1 and B1, respectively) as additives in HFO on large two-stroke marine diesel-engine performance. To determine the effects of A1 and B1, the engine performance (i.e., fuel consumption, P-max, and exhaust gas temperature) and the exhaust emission rates for NOx and PM before and after the inclusion of the additives at different engine loads (50%, 75%, and 100%) were compared. The results of this study are as follows:

1. It was determined that adding A1 and B1 at a low engine load of 50% reduced fuel consumption by 2.22% and 1.21%, respectively. Excluding the case of added B1 at a 75% engine load, the inclusion of the additives reduced the rate of fuel consumption at every examined engine load. Furthermore, A1 more effectively reduced the rate of fuel consumption than B1, and the fuel efficiency is improved for every load setting using this additive. In addition, the fuel consumption rate was more significantly reduced at low loads. We are of the view that this improved performance is due to the combustion-promoting effects of the additives.
2. The greatest increases in the rate of P-max caused by the addition of A1 and B1 were found to 7.03% and 2.69%, respectively, which were obtained for an engine load of 75%. A1 decrease was obtained for the case of added B1 at 100% load; thus, it was confirmed that the input of the examined additives increased the P-max at almost every load setting. The results suggest that this enhancement is due to the improved and actively promoted combustibility facilitated by A1 and B1.
3. The measured exhaust gas temperature results indicate that the most significant declines in temperature caused by the input of A1 and B1 were 2.67% and 2.42%, respectively, which occurred for a low engine load of 50%. It was thus confirmed that the addition of A1 and B1 to HFO resulted in a lower exhaust gas temperature at every load setting. We conclude that this was due to the effects of A1 and B1 on the engine combustion, as these additives facilitated stable combustion within the engine.
4. Significant reduction in NOx emissions was confirmed for every load setting. The results indicated a 23.02–32.61% decrease for added A1, and a 16.52–19.74% reduction for B1. These results are thought to be related to the observed increase in P-max and the decrease in the exhaust gas temperature. The reduction rate was greater for added A1 than for added B1.
5. Considerable reductions in PM emissions were obtained for all load settings: 57.41–59.67% for added A1 and 38.85–40.88% for added B1.

To enhance the accuracy and reproducibility of the results of this study, the experiments were conducted on a large two-stroke diesel engine installed at a land-based power plant, which was less affected by marine conditions, i.e., heavy weather, waves, and wind, than a ship engine would be. This study has confirmed that the input of either of two different additives, i.e., oil-soluble Ca- and Fe-based organometallic compounds, to marine HFO improves engine performance and reduces exhaust emissions in the case of large HFO-fueled high-power two-stroke diesel engines. Therefore, we conclude that reductions in fuel consumption and exhaust emissions (i.e., NOx and PM) can be achieved through

**Table 7**  
PM emissions for HFO, A1, and B1 at various engine loads.

Load (%)	PM emissions for HFO (mg/m <sup>3</sup> )	PM emissions for A1 (mg/m <sup>3</sup> )	Deviation	Ratio (%)
50	64.1	27.3	-36.8	-57.41
75	100.8	40.9	-59.9	-59.43
100	108.6	43.8	-64.8	-59.67
Load (%)	PM emissions for HFO (mg/m <sup>3</sup> )	PM emissions for B1 (mg/m <sup>3</sup> )	Deviation	Ratio (%)
50	64.1	39.2	-24.9	-38.85
75	100.8	60.5	-40.3	-39.98
100	108.6	64.2	-44.4	-40.88



**Fig. 8.** Particulate matter (PM) emissions as a function of engine load. Significant reductions were obtained using A1 and B1 compared to HFO alone.

the inclusion of additives during operation of a large two-stroke diesel engine fueled by marine HFO.

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