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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 (NOx, particulate matter (PM)) were analyzed before and after the fuel additive insertion.

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 NOx emissions [2,3]. Fig. 1 shows the current NOx 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 NOx 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 NOx emissions for some time. The primary NOx 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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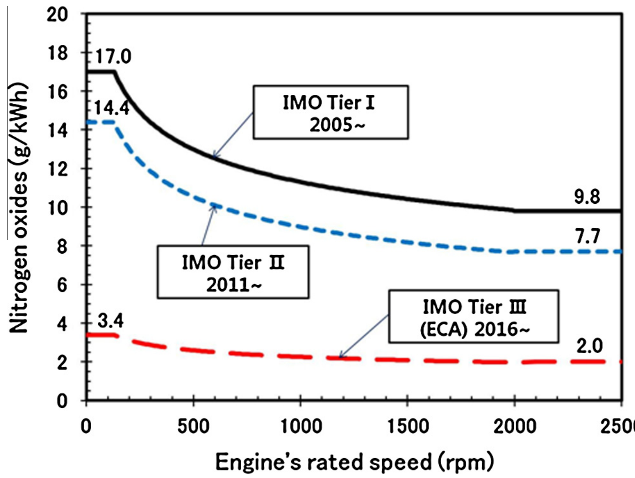

Fig. 1. IMO regulations for NOx emissions from marine diesel engines. The dates of introduction of the various tiers are indicated.

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 reduces 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^2/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 ±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^2
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^2
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