

Article

Characterization of Particle and Gaseous Emissions from Marine Diesel Engines with Different Fuels and Impact of After-Treatment Technology

Jinxi Zhou, Song Zhou and Yuanqing Zhu *

College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China; jinxizhou@hrbeu.edu.cn (J.Z.); zhousong617@sina.com (S.Z.)

* Correspondence: zhuyuanqing617@sina.com

Received: 4 June 2017; Accepted: 27 July 2017; Published: 31 July 2017

Abstract: The International Maritime Organization (IMO) Marine Environment Protection Committee (MEPC) and some countries have gradually strengthened the laws regulating ship exhaust emissions. The aim of this paper is to estimate the impact of an after-treatment technology exhaust gas cleaning (EGC) system on marine diesel engine emissions and the cost advantage compared to using low-sulfur fuel oil. The emission characteristics of SO₂ and particulate matter (PM) produced from high sulfur oil and low sulfur oil in a low-speed two-stroke marine diesel engine were also presented. The removal efficiency of SO₂ has been tested and the PM removal efficiency was also predicted in this study. When using high sulfur oil, the emission factor of SO₂ and PM were from 8.73 g/kWh to 11.6 g/kWh and 2.0 g/kWh to 2.7 g/kWh, respectively. These values are significantly higher than the emission values from using low sulfur oil. The fuel sulfur content (FSC) was the key factor affecting the emission factors of SO₂ and PM. The fuel change could reduce the mass emission factor of PM, which is above 90% for the total particle emission with the two fuels. When using the EGC system, the desulfurization efficiencies were above 99%. The pH values at a 25, 39, 53, and 67% load were also stabilized to be around 7.5, 7.6, 7.7, and 8, respectively. The EGC system can also capture part of the primary PM and secondary PM formed from SO₂. The EGC system was more effective for PM of the size larger than 1 μm. Thus, according to this study, the usage of low sulfur oil and EGC will also substantially decrease the emission of currently unregulated hazardous chemical species in the exhaust gas of ships in addition to satisfying future emissions regulations of ship. Furthermore, the EGC system also had a significant cost advantage compared to using low-sulfur fuel oil.

Keywords: marine diesel engine; SO₂; PM; EGC; low sulfur oil

1. Introduction

Maritime transport accounts for a large proportion of the transportation industry. However, the resulting gaseous and particle emissions from ships pose a threat to public health and the environment [1,2]. The emissions of ships considerably contribute to the levels of ambient air pollutants [3–5]. This is especially the case with the recent usage of low-grade heavy fuel oil (HFO), which has the advantage of low price compared to other types of fuel. HFO includes some sulfur and is mainly used to power ships that have low-speed diesel engines installed. The SO₂ and particulate matter (PM) are mainly derived from HFO combustion due to the high fuel sulfur content (FSC) [6,7]. The sulfate and bound water were the main chemical species contributing to the mass of PM [8]. In addition to substantial SO₂ and PM emissions, high amounts of NO_x and polycyclic aromatic hydrocarbons (PAHs) are generated, which also have hazardous effects on health [9,10]. The quality and type of fuel can affect the emissions of harmful substances [11]. The NO_x-reduction method involves selective catalytic reduction (SCR) technology, which is a widely recognized technology

applied in ships. The PAHs are usually attached to the surface of PM, such as elemental carbon (EC), organic carbon (OC), and sulfate [12,13]. The PAHs, OC, and EC are usually affected by engine loads [14]. PM emissions are largely dependent on the operating conditions of engines as well as fuel type [15,16]. According to some opinions, optimizing the combustion conditions of engines and changing the fuel type can solve the emission problem in ships [17]. It was assumed that a reduction in the fuel sulfur content (FSC) will considerably reduce the emissions of particulate matter (PM). The difference between the high sulfur oil and low sulfur oil for PM emissions was minimal, with the amount of coarse PM and of particles emitted remaining unchanged.

The International Maritime Organization Marine Environment Protection (IMO MEPC) and other countries have stated that sulfur emission regulations and PM from ship emissions will likely exceed that of regulations in the future [18,19]. Many regions have also set sulfur emission-controlled areas (SECAs), such as in the Caribbean of United States, Baltic Sea, North Sea, North America, Hong Kong, and the eastern coastal areas of China. Among these areas, the emission-controlled areas (ECA) of the Caribbean of United States and North Sea also have strict requirements for NO_x and PM emissions. The sulfur content has to be 3.5% (m/m) in non-ECA before 2020 and 0.5% (m/m) after 2020. In ECAs, the content has to still be 0.1% (m/m) according to the regulations of the IMO [20,21]. To solve the sulfur and PM emission problems in ships, using low-sulfur fuel oil (or LNG and other cleaning fuels) [22,23] or installing exhaust gas cleaning (EGC) systems have been suggested. Compared to using only HFO, the two methods—using low-sulfur fuel and installing a scrubber—can add the total cost of shipping. The price of the low-sulfur fuel is much higher than HFO with additional modification costs for the fuel conversion system. The EGC systems include the initial investment in the system, maintenance cost, and employee wages. The EGC technologies can significantly reduce the emission of PM [24]. The diesel filter would not be suitable for the low-power, low-speed marine diesel engine due to back pressure [25]. The EGC technologies include closed-loop, open-loop, and hybrid systems [26]. The open-loop system uses seawater to remove SO₂ in the exhaust gas based on natural alkaline of seawater and waste water. After scrubbing, this water is discharged into the sea. However, it can cause secondary pollution and contribute to the greenhouse effect due to the release of carbon dioxide. Furthermore, it has high energy consumption [27–29]. The closed-loop system uses fresh water or seawater as the carrier in addition to sodium hydroxide as the absorbent to remove SO₂ in exhaust gas. It has the advantages of high desulfurization efficiency, low energy consumption, and no CO₂ emissions. The closed-loop system is the most suitable technology for the exhaust gas desulfurization technology of ships [30–32].

This study presents the impact of the after-treatment technology exhaust gas cleaning (EGC) system on marine diesel engine emissions and the advantages in terms of cost compared to using low-sulfur fuel oil. The emission factors of various pollutants from low-speed two-stroke marine diesel engines were also investigated. Using the EGC system and using low sulfur oil also complies with the new FSC limit in ECAs or non-ECAs before and after 2020. The aim of this study was to investigate and predict the removal efficiency of SO₂ and PM for the EGC system. The economic comparison of using the EGC system and low-sulfur oil was also a major research goal.

2. Material and Methods

2.1. Engine and Test Cycle

The study engine in this real test was a two-stroke, slow-speed marine diesel engine. The engine ran at 6160 kW and 99 rpm. During the study, loads were assigned with the main engine (ME) running at 25, 39, 53, and 67%. The test cycle is shown in Table 1.

Table 1. Engine operating conditions.

Load (%)	Power (kW)	Speed (rpm)
25	1525	62.4
39	2382	72.4
53	3244	80.4
67	4105	86.8

2.2. Fuel Properties

The study engine was run with high sulfur oil (3.36 wt % of S) and low-sulfur oil <0.1 wt % of S). The sulfurous organic material was added into the diesel oil to adjust the sulfur fuel content according to the content of HFO. The selected properties are in Table 2.

Table 2. Selected properties of the different types of fuel.

Product Property	High-Sulfur Oil	Low-Sulfur Oil
Density at 15 °C (kg/m ³)	889.5	872
Sulfur (m/m)	3.36	<0.1
Carbon, wt %	89.4	87.2
Hydrogen, wt %	13.2	12.8
Nitrogen, wt %	<0.2	<0.2
Oxygen, wt %	<0.4	<0.4
Net calorific value (MJ/kg)	43.5	42.3

2.3. EGC System Description

This EGC system was designed in accordance with a maximum power of 4200 kW, while the body material of this tower was stainless steel. It was 2.2 m in diameter and 6 m high. The ratio of liquid to gas was 2 L/m³, while the ratio of sodium to sulfur was about 0.8–0.9 when operating. The scrubber included a two-spray layer and demister structure. The required desulfurization efficiency was greater than 97.15%, which corresponds with the 0.1% fuel sulfur content limit. It consisted of a tower shell, spray system, mist eliminator, external steel structure, and so on. All parts of the scrubber were made of corrosion-resistant stainless steel. It could withstand SO₂ and ultrafine particle corrosion in addition to meeting the requirement of anti-corrosion. The EGC system included the required temperature, pressure measuring points, and so on. The operation mode of the EGC system was a closed-loop cycle.

Alkali was fed to the scrubbing water pipes to maintain the pH value and ensured desulfurization efficiency. Generally, 50% NaOH was used for the supplementary alkali. As the low condensation point of 20% NaOH solution is −30 °C, 20% NaOH solution was also chosen as supplementary alkali in some situations.

The EGC system included a scrubber system and wastewater treatment system. The desulfurization byproduct included sulfite, sulfate, hydrosulfite, polycyclic aromatic hydrocarbon (PAH), and sludge. There was an oxidizing fan in the wastewater treatment system, which was used to make sulfite into sulfate. The wastewater treatment system also included a buffer tank, coagulant, monitoring system, and separator. The requirements of IMO included the pH value, turbidity, and PAH concentration. The nitrate will be detected by the inspection department of the ship at the scene.

2.4. Measurement and Analysis

The analyzed exhaust gas from the engine was sampled from the pipes before and after the scrubber. The principle diagram showing a schematic of the engine test system can be found in Figure 1.

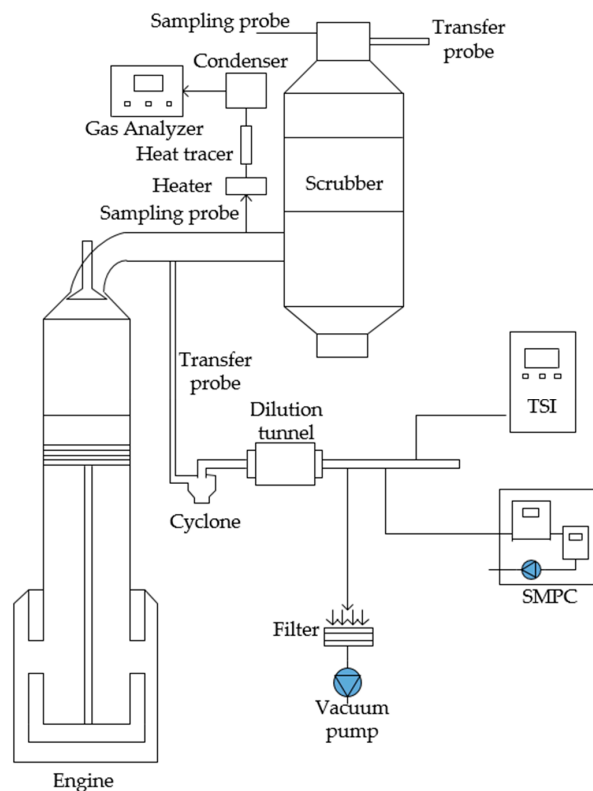


Figure 1. Principle diagram schematic of engine test system.

Figure 2 is a photograph of the experimental setup for a scrubber in a marine diesel engine.



Figure 2. Photograph of the experimental setup for the scrubber in a marine diesel engine.

2.4.1. Gas Measurement

SO_2 , NO_x , O_2 , CO_2 , and CO were measured by exhaust gas analyzers (PG-350, Horiba, Japan). The analyzers were equipped with chemiluminescence detection (CLD), non-dispersive infrared sensor (NDIR), and zirconia sensor. NO_x was measured by CLD with fluid modulation. SO_2 and CO were analyzed by NDIR with fluid modulation. CO_2 was measured by NDIR with light source modulation. O_2 was measured by a zirconia oxygen analyzer. The measurement was to be carried out at each mode point after the engine was stabilized. When stabilized for at least 5 min, the output of the analyzer was

to be recorded on a strip chart recorder or a data acquisition system. The duration for every mode was 30 min and the recording period was not to be less than 10 min. For data acquisition systems of PG-350, the sampling frequency was 12 per minute.

2.4.2. PM Measurement

The sampling for PM analyzers and filter collections was taken from the pipe after dilution. The cyclone can remove particulate matter of a large diameter. The dilution ratio ranged from 500 to 800. PM filter samples were collected on a quartz filter with diameter of 47 mm (Zefluor, Pall, NY, USA). The quartz filters need to be heated in the muffle furnace at 500 °C for 4h to remove carbon impurities before sampling. Before and after collection, the filters were conditioned for 24 h in an environmentally-controlled space (ratio of humidity (RH) = 40%, T = 25 °C). The particles on the were measured using microbalance (XS105, Mettler-Toledo, Columbus, OH, USA). The NanoScan SMPS (Model 3910, 10 to 420 nm, TSI, USA) and Engine Exhaust Particle Sizers (Model 3330, 0.3–10 µm, TSI, Shoreview, MN, USA) were used to measure the particle size distribution.

3. Results and Discussions

3.1. Emission Characterization of Major Pollutants

The major pollutants from the exhaust gas of diesel engine were SO₂, NO_x, CO₂, CO, and PM. The results of emission factors for SO₂, NO_x, CO₂, CO, and PM in terms of g/kWh are presented in Table 3. In this study, the emission factors of SO₂ were significantly higher with high sulfur oil. The SO₂ emission factors before a scrubber with loads are presented in Figure 3.

Table 3. Emission factors of different gases for the main engine.

Load	SO ₂	NO _x	CO ₂	CO	PM
%	g/kWh	g/kWh	g/kWh	g/kWh	g/kWh
HSO	-	-	-	-	-
25	8.73	10.87	467.2	0.875	2.022
39	11.60	11.83	622.8	0.545	2.726
53	10.40	10.16	569.6	0.490	2.231
67	10.52	9.809	576.1	0.490	2.584
LSO	-	-	-	-	-
25	0.23	9.82	423.3	0.926	0.107
39	0.36	10.93	562.7	0.643	0.085
53	0.34	9.06	502.6	0.5	0.092
67	0.29	9.13	528.4	0.5	0.109

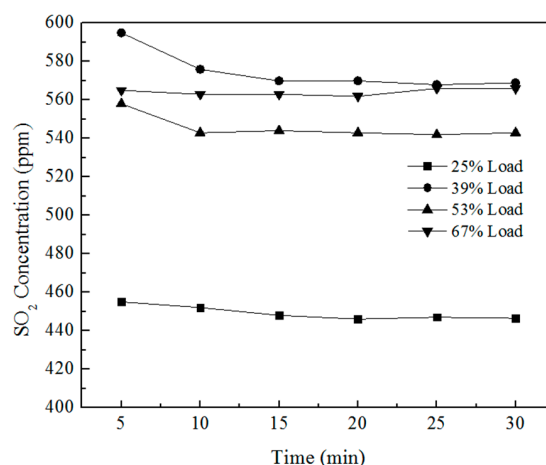


Figure 3. SO₂ concentration with main engine loads.

The minimum value of the SO_2 emission factor was 8.75 g/kWh at a 25% load, while the maximum value of the SO_2 emission factor was 11.60 g/kWh at 39% load with high sulfur oil. The results were associated with the engine combustion conditions and specific fuel oil consumption (SFOC). The value of SO_2 emission factor was 0.23–0.36 g/kWh for low sulfur oil. The SO_2 emission in exhaust gas was from the burning of sulfur in fuel oil. For the engine, the fuel-injection quantity increased as the load increased, before the quantity of SO_2 increased. The concentration of SO_2 was also influenced by air inflow. In this test, the maximum concentration value of SO_2 at 39% load was higher than 53% and 67% loads. This is due to the air inflow being less with the 39% load for this engine. The fuel change resulted in a 97% reduction in SO_2 emissions. According to this study, when the engine switched its fuel from a HFO to a low-sulfur marine diesel oil (MDO, <0.1 wt % of S), it can comply with the new FSC limit of 0.1% (m/m). With high sulfur oil, the PM emission factors were 2.022, 2.726, 2.231, and 2.584 g/kWh for the 25, 36, 53, and 67% loads, respectively. These values obtained were much larger than those obtained using low sulfur oil.

The typical particle size distribution in the exhaust gas is presented in Figures 4 and 5. Figure 4 shows the size distributions of PM mass, while Figure 5 depicts the size distribution of the PM amounts from an engine with two fuels at the load of 67%. For the curve of the high sulfur oil, there are three clear peaks with one large peak at around 5 μm , one peak at around 0.5 μm , and the last at 0.1–0.2 μm . For the curve of the low sulfur oil, there are also three peaks with one large peak at around 0.5 μm , one peak at around 0.45 μm , and the last between 2–3 μm . The change in fuel reduced the PM mass by around 90% for the total PM mass emission with the two fuels. The main reason for the reduced PM with the fuel change was the reduction in emissions of PM by 0.1–10 μm and the domination of coarse particles in the mass of PM. This also mainly corresponded with FSC in fuels. The amount of PM was dominated by nanoparticles and the fuel change had little impact on nanoparticles or the nucleation mode. The effect of fuel change on the amount of PM is presented in Figure 5, with an almost identical size distribution of the PM amounts, aside from the position of the peaks. For two fuel oils, the peaks were around 0.055 and 0.095 μm , respectively. The amount of PM was mainly in the accumulation mode and nucleation mode.

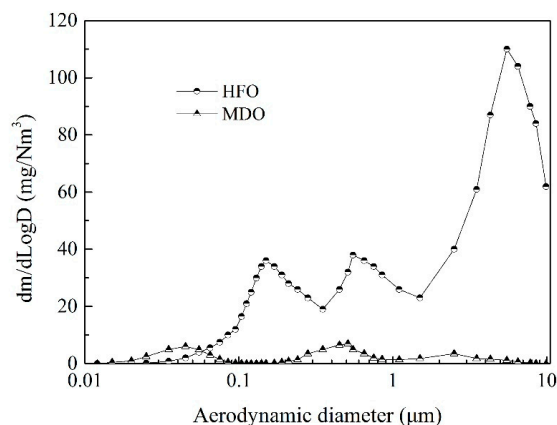


Figure 4. Particle mass size distribution in the exhaust gas from the engine.

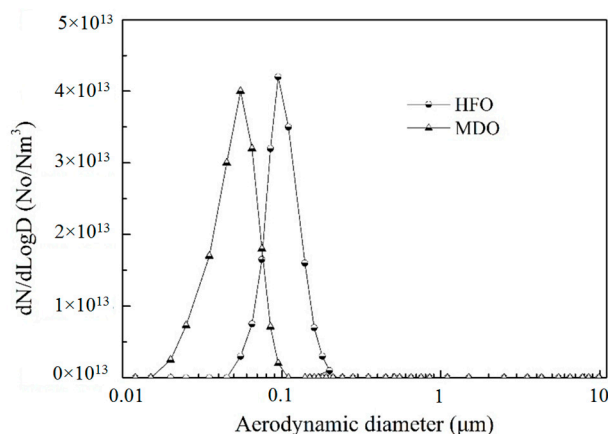


Figure 5. Particle amount size distribution in the exhaust gas from the engine.

3.2. Removal Efficiency of Gaseous Pollutants

Figure 6 shows the efficiency of reducing SO_2 at different loads by using high sulfur oil. It shows that the efficiency of reducing SO_2 decreased with an increase in load by up to 99%. The required desulfurization efficiency was related to the area and the fuel used, which was found to be 97.15% from the data in this test. This is sufficient for cleaning the exhaust gas from a 3.5% (m/m) sulfur fuel to meet the requirements of the IMO. The EGC system was an equivalent way to meet the 0.1% (m/m) sulfur fuel requirements.

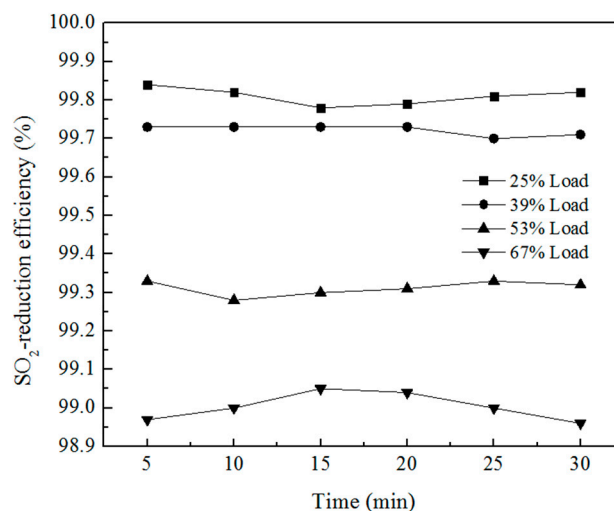


Figure 6. Efficiency in reducing SO_2 with different engine loads.

In this test, the CO_2 concentrations before and after the scrubber only slightly changed at all loads. As Figure 7 shows, SO_2 (ppm)/ CO_2 (%v/v) was at the range of 0.2–1.4, with the ratio being far lower than the required limit 4.3 of 0.1% (m/m) sulfur fuel.

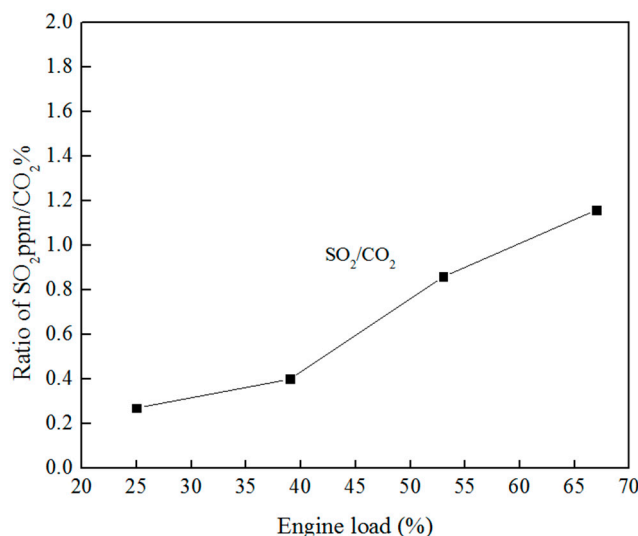


Figure 7. SO₂ (ppm)/CO₂ (%v/v) with different engine loads.

Figure 8 shows the NaOH flow and pH value with different engine loads. In this test, when the EGC system and engine were stabilized, the maximum SO₂ removal efficiency was maintained and the pH values at 25, 39, 53, and 67% loads were also stabilized to remain at about 7.5, 7.6, 7.7, and 8 pH respectively. The pH value was controlled by NaOH flow, which was maintained by a closed-loop control by a programmable logic controller (PLC). The pH meters, NaOH flow pumps and PLC program allow for accurate control of the pH value.

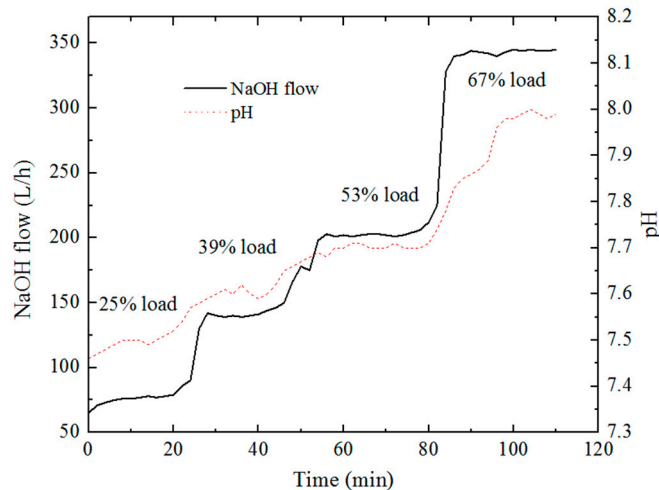


Figure 8. NaOH flow and pH value with different engine loads.

3.3. Removal Efficiency of Particulate Matter

The predicted removal efficiency as a function of the particle size at different loads was shown in Figure 9, while the removal efficiency of PM is presented in Figure 10. The EGC system was more effective for PM with a size of more than 1 μm . The highest efficiency for the total PM mass was at the 53% load, which was found to be around 54%. The lowest efficiency was about 43%. The removal efficiency for PM₁₀ had no obvious difference at all loads, while the average value of the removal efficiency was 36%. However, the removal efficiencies for PM_{2.5} were lower by 5% at all loads. However, the PM in the accumulation mode was not reduced and the number of PM did not decrease.

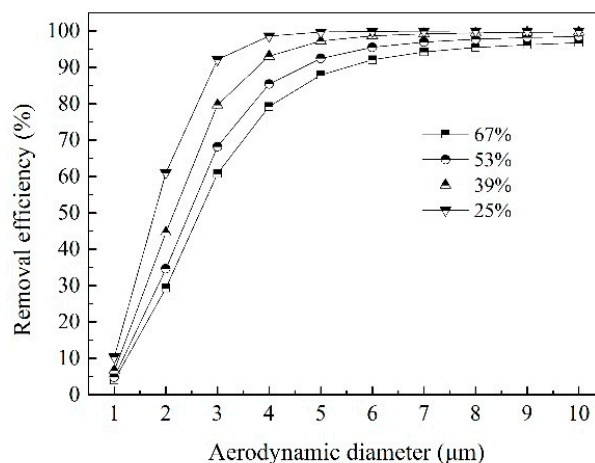


Figure 9. Removal efficiency as a function of particle size at different loads.

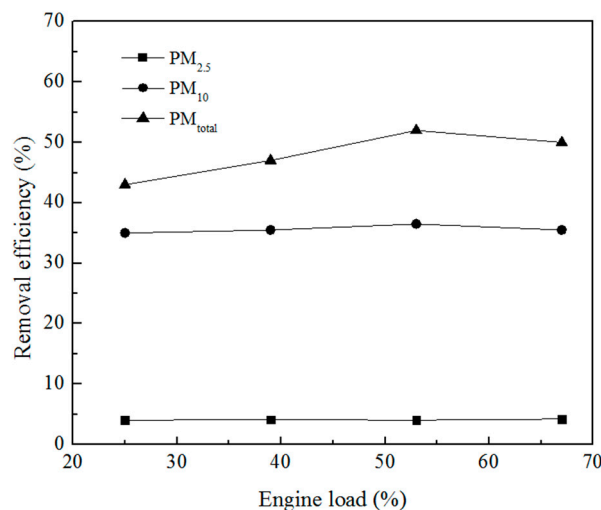


Figure 10. Particulate matter (PM) removal efficiencies with different engine loads.

4. Economic Study

The sulfur content is 3.5% (m/m) in non-ECA before 2020 and 0.5% (m/m) after 2020. In ECA, the content remains at 0.1% (m/m) according to the regulations of IMO. Therefore, one of the two methods using low-sulfur fuel and installing a scrubber must be selected. The following shows the consumption and economic analysis of the EGC system. Furthermore, a comparison between using low-sulfur fuel oil and a scrubber was also made. The calculated data for a closed-loop EGC system on a 6S35MC MAN B&W marine diesel engine (CSSC Marine Power CO., LTD, Zhenjiang, China) is provided in the rest of this section.

The initial investment of the EGC system mainly includes the system equipment cost, production and processing cost, ship modification cost, maintenance cost, and employee wages. When using low-sulfur fuel oil, the initial investment includes equipment and modification cost of the fuel conversion system and maintenance cost. For the scrubber, the installation cost was 10% of the equipment procurement cost, while the maintenance costs were 4% of the equipment procurement cost. Employee expenses were based on the international average wage level. According to the initial investment of this EGC system, the equipment procurement cost was \$1,500,000, while the total initial investment was \$2,400,000. Along with the advancement in the scrubber industrialization, the initial cost will be reduced. The initial investment of the EGC system was higher than using low-sulfur fuel oil, with the initial cost difference between installing a scrubber and using low-sulfur fuel oil

being \$2,000,000. All prices of consumables—such as fuel, chemical production, and other costs—were analyzed according to the prices in 2016. The initial cost of this scrubber is equivalent to the cost of around a 5 MW two-stroke engine, although one of the two methods must be used to meet the emission regulations of IMO and the initial costs will not have large fluctuations with an increase in engine power. The economic data was from the test and emission project guide of MAN Diesel & Turbo. The NaOH consumption from this test and fuel oil consumption was due to SFOC and the engine power. Furthermore, the initial investment and running costs of the EGC system were calculated according to the requirements of IMO and other references.

The engine load and sailing time in ECAs and non-ECAs can affect the total consumption. The absolute consumption according to the load profile is shown in Table 4.

Table 4. Absolute consumption according to the load profile.

Engine Load % MCR	25%	50%	75%	100%	Total
Load Profile, Time	15%	15%	50%	20%	
Fuel oil (kg/h)	30	57	279	150	516
NaOH (L/h)	3	7	30	17	57
Electric power (kWh)	1	2	10	5	18

The yearly consumptions and running costs of installing the scrubber and using low-sulfur fuel oil were analyzed according to the emission regulations after the year of 2020 in Tables 5 and 6. The sulfur content of fuel is required to be at 0.5% (m/m) in non-ECAs and 0.1% (m/m) in ECAs. The ship sailing time was presumed to be 2000 hours in ECAs with a running scrubber and 4000 hours in non-ECAs without a scrubber.

Table 5. Yearly running cost in USD (United States dollar) using high sulfur fuel and scrubber.

SOx Scrubber	Consumption	Price	Total Cost Thousand \$/Year
Fuel 3.5% S	3102 (ton/year)	170 \$/ton	527
Electric power	105 (MWh/year)	200 \$/MW	21
NaOH	354 (m ³ /year)	200 \$/m ³	71
Total	-	-	619

Table 6. Yearly running cost in USD (United States dollar) using low-sulfur fuel without scrubber.

No Scrubber	Consumption	Price	Total Cost Thousand \$/Year
ECA Fuel, 0.1% S	1034 (ton/year)	400 \$/ton	414
Non-ECA Fuel 0.5% S	2068 (ton/year)	300 \$/ton	621
Total	-	-	1,035

When HFO and a scrubber were used in the ships, the yearly running cost of the EGC system was \$619,000/year and the results are presented in Table 5. Table 6 shows the yearly running cost in USD of using low-sulfur fuel without a scrubber. The yearly running cost of using low-sulfur fuel was \$1,035,000/year. The results show that compared to using low-sulfur fuel oil, using a scrubber could reduce the yearly running cost of ships and the saving cost is a key factor influencing the cost payback period of installing a scrubber. The difference of \$416,000/year was a result of the high price of low-sulfur fuel oil and the value was also defined as the yearly saving cost from using a scrubber.

The yearly running cost of a scrubber was related to the sailing time of ship in ECAs, with the total sailing time supposed to be 6000 h annually. The relationship between yearly saving cost and sailing time in ECAs for using a scrubber is presented in Figure 11, while the relationship between cost payback period and yearly saving cost is presented in Figure 12. The yearly saving cost is the

difference in value of the yearly running costs between using low-sulfur fuel oil and using a scrubber. Under the regulations, the saving in cost increases and the cost payback shortens with an increase in sailing time in ECAs. Therefore, compared to using low-sulfur fuel oil, installing a scrubber was more advantageous and the advantages will be more evident after 2020. The increase in the emissions control area and sailing time in ECAs will also intensify the advantages of the EGC system.

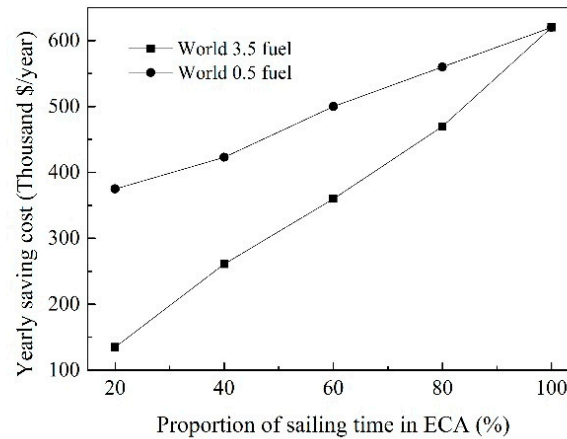


Figure 11. Relationship between yearly saving cost and sailing time in ECA with a scrubber.

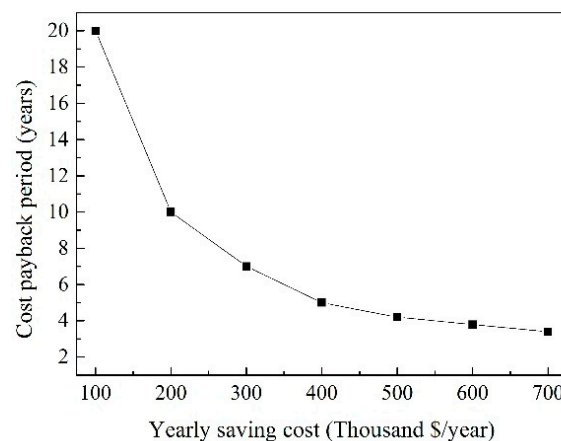


Figure 12. Relationship between cost payback period and yearly saving cost with a scrubber.

The large price difference between HFO and low-sulfur fuel oil would lead to a shortened payback period for larger power engines. The engine power could affect the difference in the value of the yearly running cost from using a scrubber and using low-sulfur fuel oil. The results are shown in Figure 13, with the difference being the yearly saving cost of using a scrubber. The relationship between engine power and cost payback period with a scrubber is presented in Figure 14. As shown in Figures 13 and 14, the savings in increased cost and cost payback period sharply shortens with an increase in engine power. In particular, when engine power rose from 4 MW to 12 MW, the cost payback period was shortened from five years to two years. The above results fully demonstrate the cost advantage of scrubber installation for ships.

Although the fuel price has declined in recent years, the supply of low-sulfur fuel oil is limited in the long-term because of the limitation of fuel oil refining capacity. The development of the shipping industry would inevitably lead to an increase in fuel price, with the running cost of ships also increasing. The cost advantage of scrubber installation would become more prominent. Therefore, the EGC system was more suitable for an engine with higher power as the initial cost will not change considerably with an increase in engine power. Due to the stringent emission regulations of the IMO, one of the two

methods must be selected and used to meet the emission requirements. Using LNG (Liquefied Natural Gas) is an alternative, but it also has several disadvantages, such as cost of modifications, refueling problems, and sailing endurance. Therefore, the EGC system is recommended.

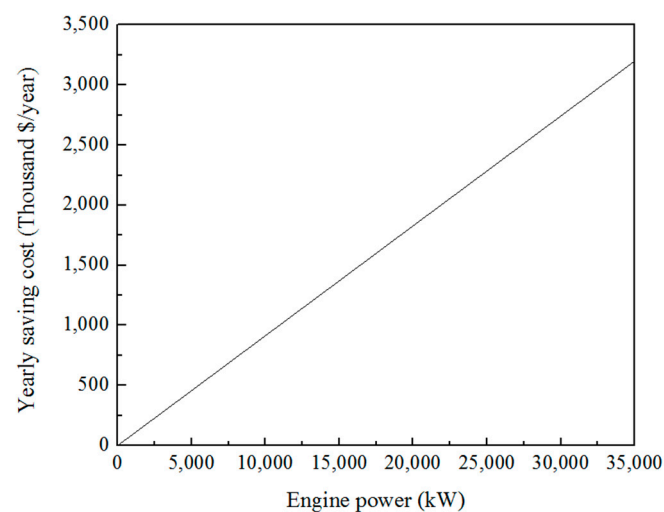


Figure 13. Relationship between yearly saving cost and engine power with a scrubber installed.

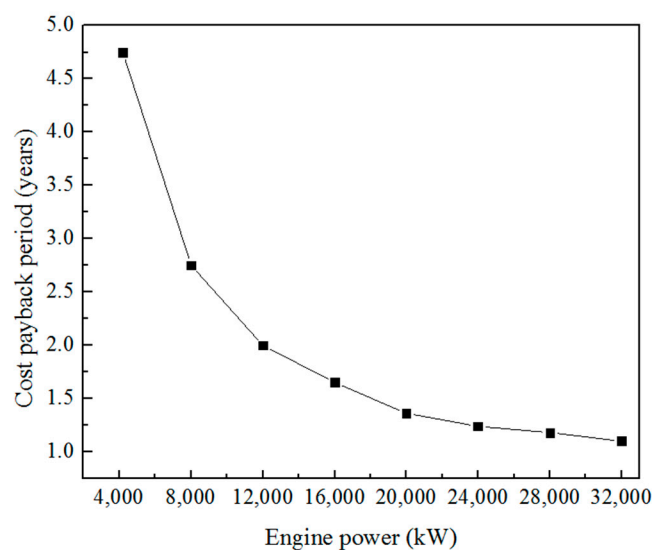


Figure 14. Relationship between engine power and cost payback period with a scrubber installed.

5. Conclusions

In this study, the particle and gaseous emissions from marine diesel engines with different fuels and after-treatment technology were studied. The exhaust emission factors of PM, SO₂, NO_x, CO, and CO₂ between high sulfur oil and low sulfur oil were compared on a two-stroke marine diesel engine. The effect of the EGC system on exhaust emissions and the economic comparison between using HFO with an EGC system and using low sulfur oil were also studied. The results of this paper are as follows:

- a. It was determined that the emission factors of SO₂ were 8.73–11.6 g/kWh with high sulfur oil and 0.23–0.36 g/kWh with low sulfur oil at all loads. It can comply with the new FSC limitation of 0.1% (m/m) of IMO. The PM emission factors were 2.022–2.726 g/kWh with high sulfur oil and 0.085–0.109 g/kWh with low sulfur oil at all loads.

- b. The fuel change could reduce the PM mass above 90% for the total particle emissions with the two fuels. The main reason for the reduced PM with the fuel change was the decrease in emissions of PM mass between 0.1 and 10 μm as well as particles in the coarse particle mode. This also mainly corresponded with FSC in fuels. The amount of PM had no change and was dominated by nanoparticles, although the peaks were not the same.
- c. The efficiency of the reduction of SO_2 decreased with an increase in load by up to 99%. The EGC system is an equivalent way to meet the 0.1% (m/m) sulfur fuel requirements. Due to some sediment from the scrubbing liquid being carried by the exhaust gas, the removal efficiency measured by total PM mass was not very high. The PM of the accumulation mode and amount of PM did not decrease.
- d. The EGC system with high sulfur oil also had an obvious cost advantage compared to using low sulfur oil, with the EGC system being more suitable for an engine with higher power. The advantages will be more evident after 2020. In conclusion, the EGC system has the prominent advantage of satisfying the emission regulations of the IMO and other international organizations.

Acknowledgments: We gratefully acknowledge the financial support of the National Natural Science Foundation of China (No. 51379050 and No. 51509050).

Author Contributions: Jinxi Zhou and Song Zhou conceived and designed the experiments; Jinxi Zhou performed the experiments; Jinxi Zhou and Yuanqing Zhu analyzed the data; Yuanqing Zhu contributed experiment device and data analysis tools; Jinxi Zhou wrote the paper.

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

References

- Blasco, J.; Duran-Grados, V.; Hampel, M.; Moreno-Gutierrez, J. Towards an integrated environmental risk assessment of emissions from ships' propulsion systems. *Environ. Int.* **2014**, *66*, 44–47. [[CrossRef](#)] [[PubMed](#)]
- Corbett, J.J.; Winebrake, J.J.; Green, E.H.; Kasibhatla, P.; Eyring, V.; Lauer, A. Mortality from ship emissions: A global assessment. *Environ. Sci. Technol.* **2007**, *41*, 8512–8518. [[CrossRef](#)] [[PubMed](#)]
- Lu, G.; Brook, J.R.; Alfarra, M.R.; Anlauf, K.; Leaitch, W.R.; Sharma, S.; Wang, D.; Worsnop, D.R.; Phinney, L. Identification and characterization of inland ship plumes over Vancouver, BC. *Atmos. Environ.* **2006**, *40*, 2767–2782. [[CrossRef](#)]
- Becagli, S.; Sferlazzo, D.M.; Pace, G.; di Sarra, A.; Bommarito, C.; Calzolari, G.; Ghedini, C.; Lucarelli, F.; Meloni, D.; Monteleone, F.; et al. Evidence for heavy fuel oil combustion aerosols from chemical analyses at the island of Lampedusa: A possible large role of ships emissions in the Mediterranean. *Atmos. Chem. Phys.* **2012**, *12*, 3479–3492. [[CrossRef](#)]
- Yau, P.S.; Lee, S.C.; Cheng, Y.; Huang, Y.; Lai, S.C.; Xu, X.H. Contribution of ship emissions to the fine particulate in the community near an international port in Hong Kong. *Atmos. Res.* **2013**, *124*, 61–72. [[CrossRef](#)]
- Johansson, L.; Jalkanen, J.P.; Kalli, J.; Kukkonen, J. The evolution of shipping emissions and the costs of regulation changes in the northern EU area. *Atmos. Chem. Phys.* **2013**, *13*, 11375–11389. [[CrossRef](#)]
- Capaldo, K.; Corbett, J.J.; Kasibhatla, P.; Fischbeck, P.; Pandis, S.N. Effects of ship emissions on sulphur cycling and radiative climate forcing over the ocean. *Nature* **1999**, *400*, 743–746.
- Lack, D.A.; Corbett, J.J.; Onasch, T.; Lerner, B.; Massoli, P.; Quinn, P.K.; Bates, T.S.; Covert, D.S.; Coffman, D.; Sierau, B.; et al. Particulate emissions from commercial shipping: Chemical, physical, and optical properties. *J. Geophys. Res.* **2009**, *114*. [[CrossRef](#)]
- Petzold, A.; Weingartner, E.; Hasselbach, J.; Lauer, P.; Kurok, C.; Fleischer, F. Physical properties, chemical composition, and cloud forming potential of particulate emissions from a marine diesel engine at various load conditions. *Environ. Sci. Technol.* **2010**, *44*, 3800–3805. [[CrossRef](#)] [[PubMed](#)]
- Agrawal, H.; Welch, W.A.; Henningsen, S.; Miller, J.W.; Cocker, D.R. Emissions from main propulsion engine on container ship at sea. *J. Geophys. Res.* **2010**, *115*. [[CrossRef](#)]

11. Kaivosoja, T.; Jalava, P.I.; Lamberg, H.; Virén, A.; Tapanainen, M.; Torvela, T.; Tapper, U.; Sippula, O.; Tissari, J.; Hillamo, R.; et al. Comparison of emissions and toxicological properties of fine particles from wood and oil boilers in small (20–25 kW) and medium (5–10 MW) scale. *Atmos. Environ.* **2013**, *77*, 193–201. [[CrossRef](#)]
12. Agrawal, H.; Welch, W.A.; Miller, J.W.; Cocker, D.R. Emission measurements from a crude oil tanker at sea. *Environ. Sci. Technol.* **2008**, *42*, 7098–7103. [[CrossRef](#)] [[PubMed](#)]
13. Healy, R.M.; O' Connor, I.P.; Hellebust, S.; Allanic, A.; Sodeau, J.R.; Wenger, J.C. Characterisation of single particles from in-port ship emissions. *Atmos. Environ.* **2009**, *43*, 6408–6414. [[CrossRef](#)]
14. Viana, M.; Amato, F.; Alastuey, A.; Querol, X.; Moreno, T.; Garcia, S.; et al. Chemical tracers of particulate emissions from commercial shipping. *Environ. Sci. Technol.* **2009**, *43*, 7472–7477. [[CrossRef](#)] [[PubMed](#)]
15. Sarvi, A.; Fogelholm, C.J.; Zevenhoven, R. Emission from large-scale medium-speed diesel engine: Influence of fuel type and operating mode. *Fuel Process Technol.* **2008**, *89*, 520–527. [[CrossRef](#)]
16. Sippula, O.; Stengel, B.; Sklorz, M.; Streibel, T.; Rabe, R.; Orasche, J.; Lintemann, J.; Michalke, B.; Abbaszade, G.; Radischat, C.; et al. Particle emissions from a marine engine: Chemical composition and aromatic emission profiles under various operating conditions. *Environ. Sci. Technol.* **2014**, *48*, 11721–11729. [[CrossRef](#)] [[PubMed](#)]
17. Moldanova, J.; Fridell, E.; Winnes, H.; Holmin-Fridell, S.; Boman, J.; Jedynska, A.; Tishkova, V.; Demirdjian, B.; Joulie, S.; Bladt, H.; et al. Physical and chemical characterisation of PM emissions from two ships operating in European Emission Control Areas. *Atmos. Meas. Tech.* **2013**, *6*, 3577–3596. [[CrossRef](#)]
18. Eyring, V.; Isaksen, I.S.A.; Berntsen, T.; Collins, W.J.; Corbett, J.J.; Endresen, O.; Grainger, R.G.; Moldanova, J.; Schlager, H.; Stevenson, D.S. Transport impacts on atmosphere and climate: Shipping. *Atmos. Environ.* **2010**, *44*, 4735–4771. [[CrossRef](#)]
19. Svensen, T.E. *Shipping 2020*; Executive Summary, DNV: Oslo, Norway, June 2012.
20. Marine Environmental Protection Committee. *2015 Guidelines for Exhaust Gas Cleaning Systems*; IMO: London, UK, 2015.
21. China Classification Society. *2011 Guidelines for Testing and Survey of Exhaust Gas Cleaning System*; CCS: Beijing, China, 2011.
22. Browning, L.; Hartley, S.; Bandemehr, A.; Gathright, K.; Miller, W. Demonstration of fuel switching on oceangoing vessels in the Gulf of Mexico. *J. Air Waste Manag. Assoc.* **2012**, *62*, 1093–1101. [[CrossRef](#)] [[PubMed](#)]
23. Winnes, H.; Fridell, E. Particle Emissions from ships: Dependence on fuel type. *J. Air Waste Manag. Assoc.* **2009**, *59*, 1391–1398. [[CrossRef](#)] [[PubMed](#)]
24. Di, N.F.; Carotenuto, C. Particulate matter in marine diesel engines exhausts: Emissions and control strategies. *Transp. Res. Part D* **2015**, *40*, 166–191.
25. Myung, C.K.; Juwon, J.; Jin, D. Nanoparticle Filtration Characteristics of Advanced Metal Foam Media for a Spark Ignition Direct Injection Engine in Steady Engine Operating Conditions and Vehicle Test Modes. *Energies* **2015**, *8*, 1865–1881. [[CrossRef](#)]
26. Zhou, S.; Li, Z. The Technology status of marine engine exhaust gas scrubber and its development trend. *Diesel Engine* **2014**, *5*, 1–6.
27. Anders, A.; Stefan, M. Use of seawater scrubbing for SO₂ removal from marine engine exhaust gas. *Energy Fuels* **2007**, *21*, 3271–3279.
28. Caiazzo, G.; Nardo, A.D.; Giuseppe, L.; Scala, F. Seawater scrubbing desulfurization: A model for SO₂ absorption in fall-down droplets. *Environ. Prog. Sust. Energy* **2012**, *31*, 277–287. [[CrossRef](#)]
29. Caiazzo, G.; Langella, G.; Miccio, F.; Fabrizio, S. An experimental investigation on seawater SO₂ scrubbing for marine application. *Environ. Prog. Sust. Energy* **2013**, *32*, 1179–1186. [[CrossRef](#)]
30. Sustainable Maritime Solutions Ltd. *EGCSA Handbook 2012*; Sustainable Maritime Solutions Ltd.: Wraysbury, UK, 2012; pp. 36–37.
31. Ship Operations Cooperative Program. *Exhaust Gas Cleaning System Selection Guide*; Ship Operations Cooperative Program: Panama City, Panama, 2011.
32. Alejandro, H.M. Study of Exhaust Gas Cleaning Systems for Vessels to Fulfill IMO III in 2016. Master's Thesis, Fachhochschule Kiel University of Applied Sciences, Kiel, Germany, 2011.

