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A review on regulations, current status, effects and reduction strategies of emissions for marine diesel engines

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ABSTRACT:

Marine diesel engines, which provide main power source for ships, mainly contribute to air pollution in ports and coastal areas. Thus there is an increasing demand on tightening the emission standards for marine diesel engines, which necessitates the research on various emission reduction strategies. This review covers emission regulations and emission factors (EFs), environmental effects and available emission reduction solutions for marine diesel engines. Not only the establishment of the emission control areas (ECAs) in the regulations but also many experiments show high concerns about the sulfur limits in fuels, sulfur oxides (SOx) and nitrogen oxides (NOx) emissions. Research results reveal that NOx emissions from marine diesel engines account for 50% of total NOx in harbors and coastal regions. Sulfur content in fuel oil is an important parameter index that determines the development direction of emission control technologies. Despites some issues, biodiesel, methanol and liquefied nature gas (LNG) play their important roles in reducing

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Abbreviations: EFs, emission factors; ECAs, emission control areas; SOx, sulfur oxides; NOx, nitrogen oxides; LNG, liquefied nature gas; FWE, fuel-water emulsion; EGR, exhaust gas recirculation; PM, particulate matter; SCR, selective catalytic reduction; HFO, heavy fuel oil; GHG, greenhouse gas; SO_2, sulfur dioxide; CO_2, carbon dioxide; IMO, International Maritime Organization; MARPOL, Marine Agreement Regarding Oil Pollution Of Liability; CO, Carbon monoxide; EU, European Union; US, United States; HC, hydrocarbon; CH_4, methane; PN, particle number; DPF, diesel particulate filter; SECAs, SOx emission control areas; EPA, Environment Protection Agency; NO_2, nitrogen dioxide; NRMM, non-road mobile machinery; DF, dual fuel; NO, nitric oxide; $PM_{2.5}$, fine particles; O_3, Ozone; VOCs, volatile organic compounds; MDO, marine diesel oil; IAH, intake air humidification; DWI, direct water injection; W/F, water to fuel; LP-SCR, low pressure selective catalytic reduction; HP-SCR, high pressure selective catalytic reduction; DOC, diesel oxidation catalyst; CRT, continuously regenerating trap; ESP, electrostatic precipitator; EHD ESP, electrohydrodynamically electrostatic precipitator; CCRT, catalyzed continuously regenerating trap; EGCS, exhaust gas cleaning system; NTP, non-thermal plasma

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emissions as well as in replacing fossil energy, being promising fuels for marine diesel engines. Fuel-water emulsion (FWE) and exhaust gas recirculation (EGR) are effective treatment option for NOx emissions control. Common rail fuel injection is an effective fuel injection strategy to achieve simultaneous reductions in particulate matter (PM) and NOx. Selective catalytic reduction (SCR) and wet scrubbing are the most mature and effective exhaust aftertreatment methods for marine diesel engines, which show 90% De-NOx efficiency and 95% De-SOx efficiency. It can be concluded that the integrated multi-pollutant treatment for ship emissions holds great promise.

Keywords: Marine diesel engines; Emissions; Alternative fuel; Exhaust gas aftertreatment

1. Introduction

Marine transportation has the advantages of large carrying capacity, high safety and low operating cost compared to other transportations. However, in spite of these advantages, massive NOx, PM and SOx emissions emitted from marine diesel engines cause serious environmental pollutions in ports and coastal areas [1-3]. Due to the characteristics of high mobility, large area and long duration of ship activities, the impact on the environment and human health is intensified [4]. Additionally, compared to automotive fuels, the quality of marine fuels is poor, which contributes to escalated emissions. For example, heavy fuel oil (HFO) for propulsion of the ocean-going ships, is the lowest-grade of oil [5], and can produce high exhaust emissions [6]. Marine diesel engines emit approximately 20 million tonnes of NOx, 10 million tonnes of SOx and 1 million tonnes of PM every year [7]. Moreover, there is growing concern about greenhouse gas (GHG) emissions from ship engines [8, 9]. NOx, sulfur dioxide (SO_2), and carbon dioxide (CO_2) emitted by ships account for 15%, 4-9%, and 2.7% of global anthropogenic pollution, respectively [10]. With the growth of shipping industry and business activities, more gaseous and particle emissions from maritime transportation will be discharged in the forthcoming years.

To address this issue, the International Maritime Organization (IMO) has implemented the Regulations for the Prevention of Air Pollution from Ships (MARPOL 73/78 Annex VI). Governments have also introduced regional ship emission standards. In recent years, the European Union (EU) and the United States (US) have updated their respective inland river ship emission standards, and China has also promulgated the national standard for ship engine emission control for the first time. The controlled emissions include not only NOx, PM, SOx, carbon monoxide (CO), hydrocarbon (HC) and methane (CH_4), but also particle number (PN)[10].

On the other hand, there is an increasing demand for energy because of the increase of shipping activities. The annual crude oil used in marine diesel engines is approximately 60 million barrels [12]. Hence, considering the non-renewability of fossil fuels, it has become essential to seek alternate fuels to meet the demand of shipping market. At present, the main alternate fuels commercially available for marine diesel engines include biodiesel, natural gas and methanol. Among them, biodiesel has several advantages such as renewability, compatibility of existing engines, low toxicity and environmentally friendly [13-15]. Biodiesel can be directly used for ship propulsion without modifying the engine structure. Use of biodiesel is capable of decreasing PM emission, but NOx emission may increase [16,17]. Anyway, biodiesel is considered as a most promising and attractive alternative [5,18]. Methanol is a technically feasible option for reducing ship emissions and there does not exist major problems in the supply chain [19]. Similar to methanol, natural gas can reduce both NOx emission and PM emission [20,21]. It is also easy to see that lower sulfur content is a common feature of these clean fuels. In fact, the application of these alternative fuels in marine diesel engines contributes to alleviating energy shortage as well as emissions.

In order to deal with increasingly stringent emission regulations, three strategies for emission reductions are available for marine diesel engines: fuel technologies, in-cylinder purification and exhaust gas aftertreatment[22]. In fuel technologies, the clean fuels in different proportions are delivered to intake ports or cylinders for combustion and if necessary, some additives are added to fuels [23-25]. As for in-cylinder purification, combustion optimization, addition of water and EGR are adopted. Exhaust gas aftertreatment can effectively reduce emissions whereas there is almost no penalty in the engine power and fuel economy. Among them, SCR is used to decrease NOx emission and Diesel particulate filter (DPF) is used to remove PM emission. In addition, a scrubber installed on a large ship as an aftertreatment device, can effectively remove SOx emissions [26-28].

The above emission control technologies are not used in isolation. The choices depend on many factors, such as the emission levels of old diesel engines and newly produced diesel engines, emission regulations, classification of engine use, costs and environmental effects. Nevertheless the combination and integration of multiple emission reduction technologies provide promising strategies to meet stricter emission regulations. This has great significance for global and regional pollutant prevention and control, and has remarkable social and ecological environmental benefits. In this paper, the emission factors, environmental effects and control technologies for marine diesel engines are reviewed and presented. The purpose of this paper is to provide some information related to air pollution from marine diesel engines and emission reduction strategies for researchers, engineers and ship owners.

2. Emissions from marine diesel engines

In this section, firstly, the current emission regulations for marine diesel engines are listed. Then, the results of emission levels of marine diesel engines and the effects on environmental pollution are presented. Besides, regulations and emissions levels of ship diesel engines and road diesel engines are briefly compared.

2.1. Emission regulations

Shipping transportation is considered to be a crucial source to global environmental pollution. Therefore, it is necessary to regulate and implement international maritime emission standards. In the MARPOL, the limits for NOx emissions are presented graphically in Fig.1. The NOx emission limits apply to both used and new marine diesel engines. The Tier I and Tier II limits are global, but the Tier III standards only apply to NOx ECAs. Additionally, the sulphur content in fuels must be limited because it can greatly increase SOx and PM emissions. The sulphur content limit of marine fuels in SOx emission control areas (SECAs) decreased from 1.5% to 1% and to 0.1% in 2015, and the maximum value globally declined from 4.5% to 3.5% and to 0.5% in 2020[29].

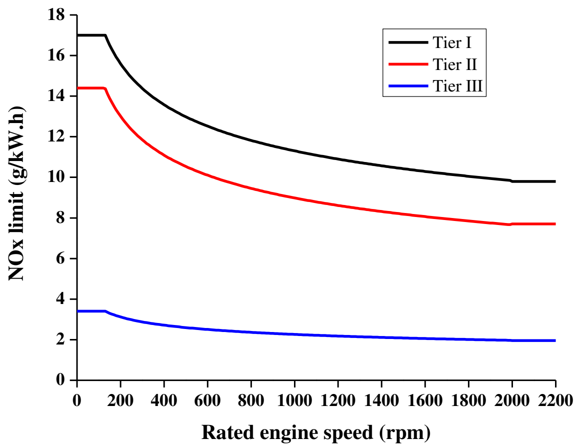


Fig.1. MARPOL Annex VI NOx emission limits after 2000 (Tier I), after 2011 (Tier II) and after 2016 (Tier III) [29].

Apart from IMO conventions, other maritime organisations, such as the US Environment Protection Agency (EPA), the EU and Ministry of Environmental Protection of China, have also set maritime regulations on the reduction of exhaust emissions.

In the EPA's regulation, ship engines are divided into three categories according to displacement per cylinder. Category 1 and Category 2 marine diesel engines are used as the propulsion power in many kinds of vessels at and around ports. Category 3 includes large diesel engines for ocean-going ships. Tables 1-3 show the allowed limits of exhaust emissions according to EPA Tier 3-4 for Categories 1 and 2 engines. New category 3 engines are needed to meet Tier 1-3 NOx emission standards.

Table 1. EPA Tier 3 standards for marine diesel category 1 commercial engines and diesel recreational engines[30].

Power (P) kW	Displacement (D) dm^3 per cylinder	NOx+HC g/kWh	PM g/kWh	Date
P<19	D<0.9	7.5(7.5) [a]	0.40(0.40) [a]	2009
19≤P<75	D<0.9	7.5(7.5) [a]	0.30(0.30) [a]	2009
		4.7(4.7) [a]	0.30(0.30) [a]	2014
75≤P<3700	D<0.9	5.4(5.8) [a]	0.14(0.15) [a]	2012
	0.9≤D<1.2	5.4(5.8) [a]	0.12(0.14) [a]	2013
	1.2≤D<2.5	5.6(5.8) [a]	0.11(0.12) [a]	2014
	2.5≤D<3.5	5.6(5.8) [a]	0.11(0.12) [a]	2013
	3.5≤D<7	5.6(5.8) [a]	0.11(0.11) [a]	2012

[a] The numbers in parentheses apply to high power density (>35 kW/dm^3) engines and diesel recreational engines.

Table 2. EPA Tier 3 standards for marine diesel category 2 engines [29].

Power (P) kW	Displacement (D) dm^3 per cylinder	NOx+HC g/kWh	PM g/kWh	Date
P<3700	7≤D<15	6.2	0.14	2013
	15≤D<20	7.0	0.27	2014
	20≤D<25	9.8	0.27	2014
	25≤D<30	11.0	0.27	2014

Table 3. EPA Tier 4 standards for marine diesel category 1/2 engines[29].

Power (P) kW	NOx g/kWh	HC g/kWh	PM g/kWh	Date
P≥3700	1.8	0.19	0.12	2014
	1.8	0.19	0.06	2016
2000≤P<3700	1.8	0.19	0.04	2014
1400≤P<2000	1.8	0.19	0.04	2016
600≤P<1400	1.8	0.19	0.04	2017

By contrast, except CO limit of 21.1 g/kWh, US EPA & California Emission Standards for heavy-duty onroad CI engines effective in 2015 are more stringent, with HC, NOx and PM emission limits of 0.19, 0.03 and 0.014 g/kWh respectively [31].

EU emission standards for off-road or non-road mobile machinery (NRMM) have evolved from Stage II to V. The new emission standard State V, the tightest in the world, comes into effect in January 2018-January 2020 for different engine types. Compared with Stage III A standards, EU Stage V regulations adopted stricter emission limits for engines used in inland waterway vessels, shown in Table 4. It is worth noting that the Stage V regulation differing from other marine regulations adopted PN emission limit for engines in inland waterway vessels.

Table 4. EU stage V emission standards for engines in inland waterway vessels [32].

Power (P)	CO	HC	NOx	PM	PN	Date
kW	g/kWh				1/kWh	
$19 \leq P < 75$	5.00	4.70 [a]		0.30	-	2019
	5.00	5.40 [a]		0.14	-	2019
$75 \leq P < 3700$	3.50	1.00	2.10	0.10	-	2019
	3.50	0.19	1.80	0.015	1×10^{12}	2020

[a] HC+NOx

In EU VI emission standards for heavy-duty onroad diesel engines, the limit of CO, HC, NOx, PM and PN is 1.5, 0.13, 0.40, 0.01 g/kWh and 8.0×10^{11} 1/kWh respectively [33]. Obviously, emission standards for marine engines are much more relaxed than those for onroad heavy-duty diesel engines used in trucks and buses.

To cut down pollutant emissions from marine engines, China has formulated and adopted some regulatory initiatives, such as China I/II Standards, IMO Annex VI Standards and domestic Emission Control Areas. China I/II Standards are shown in Tables 5 and 6. China I/II Standards apply to propulsion and auxiliary engines installed in inland and coastal vessels. Chinese oceangoing vessels and foreign vessels operating within Chinese waters are subject to the IMO

Annex VI. Starting from September 1, 2018, all diesel engines installed on-board Chinese-flagged ships and imported ships applying for domestic trade in the domestic ECAs are required to conform to the Annex VI Tier II NOx emission limits. From March 1, 2020, a carriage ban for fuel oils containing more than 0.5% sulfur will be enforced for all ships without an exhaust gas cleaning system (scrubber) [34]. A 0.1% sulfur limit will also apply to ships entering inland waterways and Hainan Island [34].

Table 5. China I emission standards for marine engines [34].

Power (P)	Displacement (D)	CO	NOx+HC	CH_4 [a]	PM	Date
kW	dm^3 per cylinder	g/kWh				
P≥37	D<0.9	5.0	7.5	1.5	0.40	2018
	0.9≤D<1.2	5.0	7.2	1.5	0.30	
	1.2≤D<5	5.0	7.2	1.5	0.20	
	5≤D<15	5.0	7.8	1.5	0.27	
P<3300	15≤D<20	5.0	8.7	1.6	0.50	
P≥3300		5.0	9.8	1.8	0.50	
	20≤D<25	5.0	9.8	1.8	0.50	
	25≤D<30	5.0	11.0	2.0	0.50	

[a] Applicable to NG (including dual fuel, DF) engines only.

Table 6. China II emission standards for marine engines[34].

Power (P)	Displacement (D)	CO	NOx+HC	CH_4 [a]	PM	Date
kW	dm^3 per cylinder	g/kWh				
P≥37	D<0.9	5.0	5.8	1.0	0.30	2021
	0.9≤D<1.2	5.0	5.8	1.0	0.14	
	1.2≤D<5	5.0	5.8	1.0	0.12	
P<2000	5≤D<15	5.0	6.2	1.2	0.14	
2000≤P<3700		5.0	7.8	1.5	0.14	
P≥3700		5.0	7.8	1.5	0.27	
P<2000	15≤D<20	5.0	7.0	1.5	0.34	
2000≤P<3300		5.0	8.7	1.6	0.50	
P≥3300		5.0	9.8	1.8	0.50	
P<2000	20≤D<25	5.0	9.8	1.8	0.27	
P≥2000		5.0	9.8	1.8	0.50	
P<2000	25≤D<30	5.0	11.0	2.0	0.27	
P≥2000		5.0	11.0	2.0	0.50	

[a] Applicable to NG (including dual fuel) engines only

In comparison to marine engines, China VI emission standards for on-road heavy-duty engines are much stricter, and adopted the same limits of CO, HC, NOx, PM and PN as the EU VI emission standards [35]. Besides, China VI emission standards for heavy-duty engines also set the NH_3 limit of 10 ppm [35].

It can be seen that the European Union, the United States and China standards cover the four basic pollutants CO, HC, NOx and PM. It is worth noting that the EU NRMM Stage V also specifically proposed PN control. Compared to China Stage II, both NRMM Stage V and EPA Tier 4 have further tightened the HC, NOx and PM limits. In addition, China Stage I and Stage II separately proposed CH_4 emission limits with a range of 1.0-2.0g / kWh. In comparison, the current Chinese standards have the most stringent restrictions on CH_4 emissions from inland watercraft.

2.2. Ship EFs

EFs have been used to compile inventories of air pollutants and quantify the influences of emissions on regional air quality and human health. For ships, there are usually two kinds of emission factors: fuel-based and power-based. Ship EFs are determined by measuring the emissions from engine exhaust pipes or from gaseous plumes of ship emissions in real world. EFs of gaseous and particulate pollutants from ships for various purposes have been studied by many researchers.

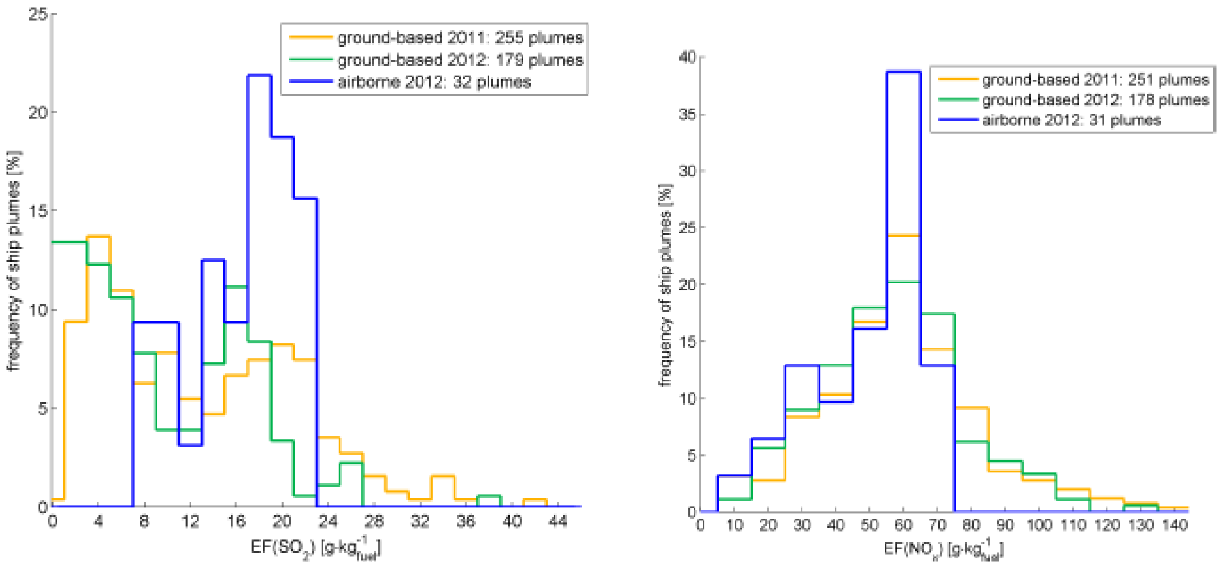
Because engine emission sampling methods on board in real world are the same as those on the engine bench in the lab, on-board ship EFs are close to bench test engine EFs under the same engine operation conditions. Cooper [36] measured emissions from 22 auxiliary engines with the maximum power of 720 to 2675 kW on board six ships at berth and found that the EFs for NOx, HC and CO varied considerably between the different engine models and loads. Schrooten et al. [37] estimated EFs for the main engines and auxiliaries according to ship type and size class. The NOx

EFs for the main engines from Spain are shown in Table 7. These results are helpful to air quality assessments in coastal areas. Zhang et al. [38] reported that NOx and PM EFs of 25.8g/kWh and 2.09 g/kWh respectively for the two low-engine-power vessels were higher than that for the high-engine-power vessels. A similar situation was also observed that fishing boats at low loads always had higher EFs for CO, PM and NO_2 [39]. It is worth noting that the unit of EFs is very important and it is the g/kWh (or specific emissions) that shows the trends. Huang et al. [40] reported that EFs of a large cargo vessel were higher during maneuvering than during cruising. During cruising, the distance-based EFs of the gaseous and PM increased with increasing vessel speed. The fuel-based average EFs of organic pollutants including PAHs and n-alkanes in PM from various vessels were also reported by [41].

Different from above sampling from engine exhaust pipes, sampling from the gaseous plumes can also be used to determine the EFs. Alfödy et al. [42] measured SO_2, NOx and PM emissions in the plumes of the passing ships. The results showed an obviously increasing trend for SO_2 EFs with the increase of the engine power. A decreasing NOx emission factor was observed with the increase of the crankshaft speed. Lack et al. [43] showed the decrease of shipping SO_2 EFs from 49 g (kg fuel)$^{-1}$ to 4.3 g (kg fuel)$^{-1}$ when the fuel sulfur decreased from 3.15% to 0.07%. Beecken et al. [44] measured EFs of SO_2, NOx and PM of 300 ships in the Gulf of Finland and Neva Bay area. The results indicated a bi-modal distribution of the SO_2 EFs with an average of 4.6g (kg fuel)$^{-1}$in the lower mode and 18.2 g (kg fuel)$^{-1}$in the higher mode and a mono-modal distribution of the NOx EFs with an average of 58 g (kg fuel)$^{-1}$. Fig. 2 shows the frequency distribution of EFs for SO_2, NOx and PM.

Table 7 NOx emission factors per vessel type and size class for Spain [37].

NOx (g/kWh)	Size (m)	2000	2005	2010	2020	2030
Bulk carrier	<150	15.7	15.4	14.5	13.7	13.1
	≥150	17.3	16.6	15.8	14.9	14.2
Chemical tanker	<150	14.5	14.3	13.4	12.8	12.3
	150 - 250	16.6	16.0	15.4	14.5	13.9
	>250	17.3	16.4	15.7	14.7	14.1
Container ship	<150	14.2	14.1	13.0	12.6	12.6
	150 - 250	16.6	15.7	14.8	14.2	14.1
	>250	16.6	15.8	14.8	14.3	14.2
General cargo	<150	14.3	14.6	14.1	13.1	12.2
	150 - 250	17.6	17.5	17.1	15.6	14.1
	>250	17.6	17.6	17.1	15.6	14.1
LG tanker	<150	14.2	14.2	13.3	12.6	12.2
	≥150	17.3	16.5	15.8	14.9	14.2
Oil tanker	<150	14.5	14.2	12.8	12.4	12.5
	150 - 250	17.1	16.0	14.8	14.2	14.1
	>250	17.2	16.1	14.9	14.3	14.2
Ro - Ro cargo	<150	14.1	14.1	13.2	12.5	12.1
	150 - 250	14.4	14.5	13.9	13.4	13.0
	>250	13.5	13.7	13.1	12.6	12.4



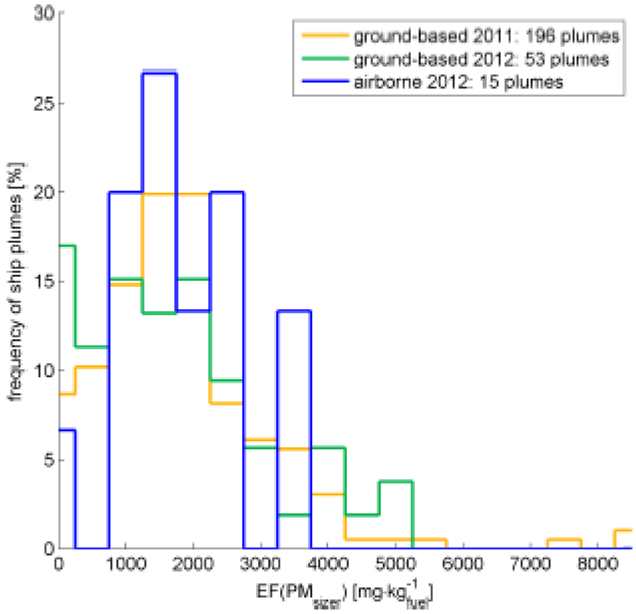


Fig. 2 Frequency distribution of emission factors for SO_2, NOx and PM [44].

2.3. Effect on environment

Both primary pollutants from ships and secondary pollutants generated by primary pollutants discharged into the environment under the influence of physicochemical factors have adverse impacts on the environment. The concentrations of pollutants due to ships and their contribution to atmospheric pollutants have been investigated by many researchers.

Unidentified vessels in the Pearl River Delta of China contributed to almost half of the overall ship gaseous emissions [45]. In the port of Leixões of Portugal, the docked ships contributed to more than 50% for NO_X concentration, while the ships in transit contributed below 1% [46]. Svindland [47] reported that the average annual SO_2 emissions from a feeder vessel in a pre- and post ECAs regulation were 4.243 and 0.449 g per TEU-km respectively. In contrast, SO_2 emissions of road transport sharply decreased by more than 94% due to the use of ultra low sulphur fuels (10 ppm sulfur content maximum). In a port site in Shanghai, ship emissions account for 36.4% of SO_2 [48].

Because nitric oxide (NO) emissions from ships can be quickly converted to NO_2 if there is sufficient ozone existing and NO_2 is one of the major air pollutants causing health concerns, many researches have been conducted to determine the effect of shipping NOx emissions on atmospheric NO_2. Ramacher et al. [49] simulated NO_2 concentrations from local shipping in three Baltic Sea harbour cities, as shown in Fig.3. They found that the maximum urban area affected by shipping NO_2 emission with the concentration of above 5 μgm^{-3} reached up to 17.42 km^2. Karl et al. [50] reported that the contribution of ship emissions to annual average NO_2 was above 40% over the Baltic Sea, 22–28% for the entire Baltic Sea region and 16–20% in the coastal land areas. In the Red Sea, due to maritime emissions, the NO_2 concentration spatially varied from 4.03×10^{14} to 41.39×10^{14} molecules/cm^2[51].

Besides the above-mentioned gaseous pollutants, PM from ships, especially fine particles ($PM_{2.5}$) have a negative environmental impact. In the northern EU area, the highest $PM_{2.5}$ emissions from ships were located in the near coast of the Netherlands, in the English Channel, near the southeastern UK and along the busiest shipping lines in the Danish Straits and the Baltic Sea [52]. In urban Shanghai, ships contributed 20-30% (2-7μgm^{-3}) to all $PM_{2.5}$ within 15 kilometers of coastal and riverside while emissions from ships in the inland off the costal line contributed 0.5-2 $\mu g\ m^{-3}$ to the $PM_{2.5}$ [53].

Ozone (O_3) in the atmosphere on the surface of the earth is produced by the photochemical reaction between NOx and volatile organic compounds (VOCs). Because it plays a key role in the photochemical smog formation, O_3 has attracted attention of researchers. In the Yangtze River Delta region of China, O_3, greatly affected by the ship emissions, had a high concentration of 50 $\mu g\ m^{-3}$ in the ship track region [54]. Over the Baltic Sea, because of ship emissions, annual mean O_3 concentrations were 15%–25% higher than over land [50].

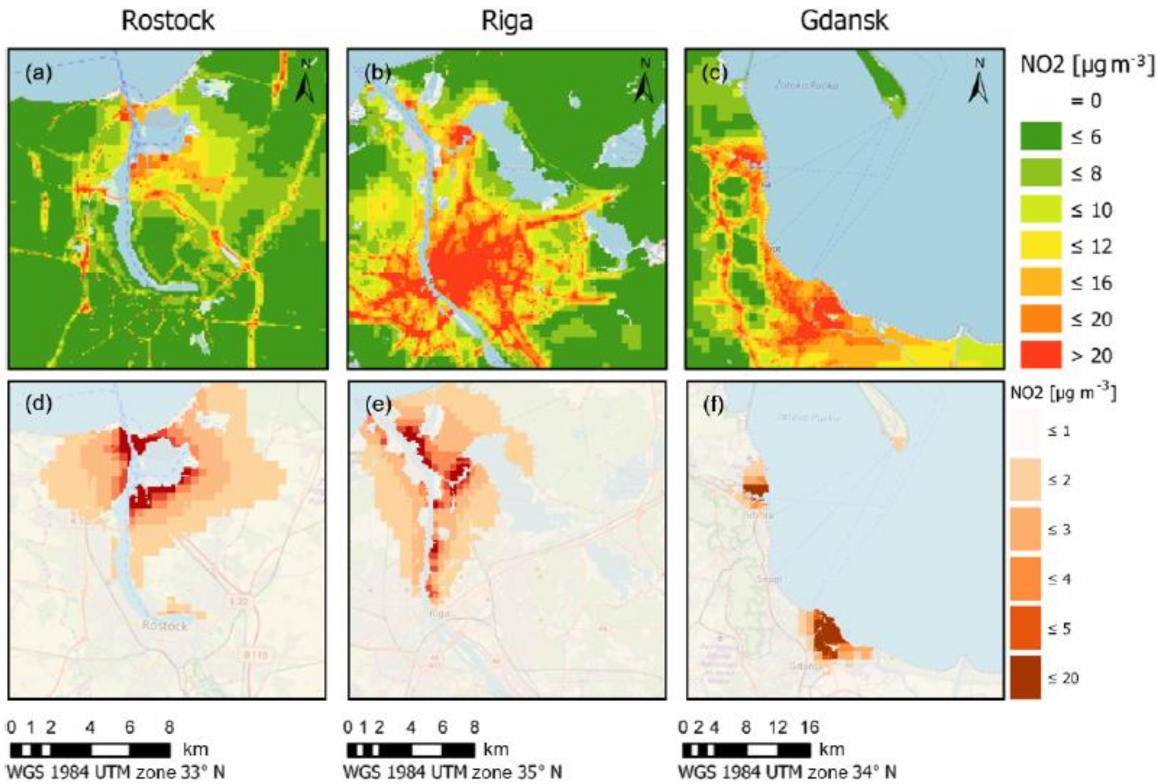


Fig.3 NO_2 annual mean concentrations and contribution of local shipping to annual mean NO_2 concentration [49].

The chemical mechanism of ozone formation has been extensively studied [55-58]. In brief, it involves a NOx cycle and a ROx cycle. In the NOx cycle, NO_2 is split int NO and atomic oxygen which will then combine with O_2 to form O_3. In the ROx cycle, the ROx radicals (RO, RO_2, HO_2 and OH) mainly from unsaturated VOCs oxidize NO to NO_2 which will then lead to formation of O3 by the NOx cycle.

3. Emission reduction technologies

In this section, the three aspects of emissions reduction strategies for marine diesel engines including fuel technologies, combustion improvement and post-treatment, are presented and discussed.

3.1. Clean alternative fuels

Ship fuels, such as HFO and marine diesel oil (MDO), have high sulfur and ash contents, high viscosity and density. The high sulfur content in fuels can cause a large amount of PM and SOx emissions from ship engines [59, 60]. Some clean fuels including biodiesel, methanol and LNG are considered as appropriate alternative fuels for propulsion of non-ocean-going ships and can reduce engine emissions due to low or no sulfur content. The properties of alternatives fuels and traditional fossil fuels are listed in Table 8.

Table 8 Properties of biodiesel, methanol, LNG, HFO, MDO and diesel [5, 61, 62, 63, 64].

Property	Biodiesel	Methanol	LNG	HFO	MDO	Diesel
Density at 15 °C (kg/m3)	890	795	443.5	934.8	<900	847
Viscosity at 40 °C (mm^2/s)	4-6	0.58	-	24.27(100 °C)	<11	2.72
Cetane number	50	3		>20	>35	51
Ash content (%)	-	-	-	0.042	<0.01	<0.01
Calorific value (MJ/kg)	37.5	20.26	50	41.62	42	42.5
Oxygen mass fraction (%)	11	50	-	0.65	-	0
Sulphur (ppm)	<10	-	-	<500000	<200000	<350

3.1.1. Biodiesel

Biodiesel contains about 11% oxygen and has a trivial amount of sulphur and high centane number. Biodiesel can be applied to diesel engines in a simple way by blending with any proportion of diesel. In spite of disadvantage of high production cost, biodiesel could be a good option for reducing diesel engine emissions (mainly SOx and particulate) in shipping sectors.

Emission tests of various marine diesel engines with biodiesel have been conducted by many researchers. Nikolic et al. [65] conducted an experiment on a low-speed two-stroke engine fueled by 7% and 20% blends of biodiesel with diesel and found a 30-70% reduction in SO_2 emission, a 26-72% decrease in NOx and a 28-64% decrease in CO. The use of pure biodiesel in two small four-stroke marine craft diesel engines also showed a decrease in NOx emissions and an increase in

CO emissions at light loads [66]. Gysel et al. [67] found a 4% reduction in NOx emissions and a 10% increase in CO emissions from a marine vessel with the blend. The reduction in NOx emissions of biodiesel blend was also reported in two four-stroke six-cylinder supercharged marine auxiliary diesel engines [68-70]. However, the use of biodiesel in some multi-cylinder marine diesel engines yielded higher NOx emissions [61-74].

Because high oxygen content in biodiesel can promote the oxidation of soot particles, diesel engines with biodiesel generally show a reduction in PM mass and PN. Khan et al.[75] used algae biodiesel in a marine vessel and found an overall reduction of 25% in $PM_{2.5}$. Ushakov et al. [76] conducted an experiment on a heavy-duty diesel engine with fish oil fuel and reported that total particle concentration and overall PM mass were reduced 67% and 79% respectively. The similar result on the decrease of PM mass and PN when B10 was used in a marine diesel propulsion engine was reported [77]. However, there are reported changes in particle number size distributions i.e. biodiesel can lead to increase of the nucleation mode particles and reduction in the accumulation particles. Nabi and Hustand [78] conducted diesel engine experiments with MGO-Jatropha biodiesel blend and reported an obviously decreasing PN in the accumulation mode but an increasing PN in the nucleation mode. The similar finding was reported by Tan et al. [79].

3.1.2 Methanol

Methanol is an oxygenated and sulfur-free fuel. Because it is can be produced from a wide range of sources such as coal, natural gas and biomass [80], it is not a problem for methanol production. A major challenge, however, is immiscibility of methanol with diesel. Therefore, engine modification including injection systems, fuel tanks and piping is required when methanol is used in a marine diesel engine. Safe storage of methanol on ships is also a concern due to the low flash point. There are two main methods by which methanol can be used in diesel engines: the premixed dual fuel [81-83], and the methanol-diesel blend with additives or fuel mixing tools [84-86].

Methanol is regarded as a technically viable option to reduce emissions from shipping [87]. Brynolf et al. [88] reported that methanol from natural gas as ship fuel would significantly improve the overall environmental performance as well as methanol derived from biomass. Gilbert et al. [89] found that methanol had a lower NOx emission factor (3 g/kWh) and a higher life-cycle GHG emission than the conventional fuels. Zincir et al. [90] found that partially premixed combustion of methanol in a marine engine at low speeds achieved lower NOx emissions ranged from 0.3 to 1.4 g/kWh than the NOx Tier III limits, zero SOx emissions and almost zero PM emissions. Ammar [91] found more than 75% reductions in NOx, SOx and PM emissions respectively from a methanol-diesel dual fuel engine installed on a cellular container ship. Paulauskiene et al. [92] reported that a blend with 10% biomethanol and 20% biodiesel was the most suitable alternative fuel for marine applications.

3.1.3. LNG

LNG is mainly composed of methane and has several advantages over other fossil fuels, including higher thermal efficiency and lower specific energy consumption, lower sulphur and carbon content. This makes it suitable for use as ship fuels. As of 1 May 2018 the world fleet totaled 253 LNG-fuelled vessels, growing by 36% over the past one year [93]. In terms of diesel engine propulsion system, two-stroke low speed DF diesel engines and medium speed four-stroke low pressure DF engines are the most commonly used in LNG-fuelled ships [94-96]. The representative low pressure gas injection system and high pressure injection system installed on two-stroke low speed diesel engines were developed by Wärtsilä and MAN respectively [97]. Accordingly, there are two modes for injecting gas into the combustion chamber, including a pressure below 1.6 MPa

[98], and high pressures of 25–30 MPa [99]. When used in four-stroke low speed engines, gas is injected into the intake port and ignited by a pilot injection of liquid fuel. The power of the engines is within the range of 720 kW to 17.55MW manufactured by Wärtsilä, MAN and MAK [96].

There are many studies on the environmental analysis of emissions of marine diesel engines using LNG. Banawan et al. [100] reported that a shift from diesel oil to DF (LNG/diesel) in a ship's main engine showed emissions reductions of 72 % for NOx, 91% for SOx, 10% for CO_2 and 85% for PM. A statistical analysis for two stroke diesel engines using HFO to LNG showed the decrease by LNG in average EFs of NOx, SOx, CO_2 and PM by 86%, 98%, 11% and 96% respectively[101]. Anderson et al. [102] measured the emissions from a LNG powered ship with four DF engines of 30400 kW at different loads. They found that EFs of NOx, CO_2, PN and PM for LNG were obviously lower than the values for marine fuel oils while CO and HC EFs were higher. Li et al. [103] also observed similar results of emissions from a high-speed marine DF diesel engine. Besides good environmental effects, LNG as a ship fuel also shows attractiveness in terms of cost effectiveness [100, 104]. Despites disadvantages of LNG such as flammability, methane slip and bunkering, the high thermal efficiency, good environmental benefit and favorable price make it a sustainable alternative to traditional fuels to be used in a marine DF diesel engine.

3.2. Addition of water

Adding water directly or indirectly into the cylinders can reduce NOx emission in exhaust gas due to thermal, dilution and chemical effects [105,106]. There are three methods of supplying water into the cylinders suitable for controlling NOx emissions in marine diesel engines: intake air humidification (IAH)/water injection, direct water injection (DWI) and fuel water emulsion. Table 8 shows qualitative comparison of water injection technologies. [-],[--],[+]and [++] indicate a negative, more negative, positive and more positive effect, respectively.

Table 8 Evaluation of water based NOx reduction methods [107].

	NOx reduction	Effect on PM	Variability of water addition	Effect on cold start	Lubricating oil dilution	Expense
Inlet manifold water injection	-	--	+	none	--	-
DWI-separate nozzle	-	--	++	none	-	--
Diesel FWE	+	++	--	--	-	-
Stratified diesel-water-diesel injection	++	++	++	none	none	--

3.2.1. IAH

In the IAH method, a set of injection water device requires to be installed on an engine to humidify the air. In the IAH systems several key parameters need to be considered such as air temperature before and after humidification, water droplet size, humidification location, engine load and water to fuel (W/F) ratio, because they have significant influence on engine emissions. In order to reduce more NOx, the humidity of the air is kept as saturated as possible when it enters the engine. If liquid water enters the cylinder with air, cylinder liner corrosion problems may occur. Currently this method is widely used in large marine diesel engines.

Previous researches on IAH have focused on emissions of diesel engines at different humidity. Nord [108] observed that NOx decreased by 51% while PM, HC and CO increased in a 6 cylinder diesel engine at the intake humidity from 32 to 53 g water/kg dry air. Rahai et al. [109] also observed a NOx reduction by 3.7% to 22.5% and increases in PM and CO when the relative humidity was increased from 65% to 75% and 95% using a steam generator in a small diesel engine. Larbi N and Bessrour J [110] and Asad U et al. [111] also found similar results of NOx reduction with the increased humidity. Subramanian [112] concluded that FWE method was more effective in simultaneously reducing NO and smoke emissions than injection method. Ni and Wang [113] numerically gave the explanation about NOx decrease and soot increase with air humidity from the physical and chemical point of view.

3.2.2. DWI

The DWI is another method for reducing NOx emission by injecting water directly into the cylinder head with a separate nozzle or by alternating fuel and water via a specially designed nozzle [107]. The storage space, weight of water and the cost due to engine modification and special nozzles are practical concerns for the ship owner/operator. The primary benefit of the DWI is that the timing and the mass of the injected water are variable and can be controlled. Bedford et al. [114] found that NOx emissions at 44% and 86% of full load decreased by about 46% and 70%, respectively. Chadwell and Dingle [115] also found that the DWI could reduce NOx by 42% without EGR and up to 82% with EGR. Sarvi et al. [116] found significant reduction in NOx and slight decreases in HC, soot and PM by using DWI in a turbo-charged diesel engine.

3.2.3. FWE

This method involves injecting a FWE fuel into the cylinders using the original nozzles. FWE fuel is prepared by mixing water and diesel fuel or other fuels homogeneously along with emulsifying agents using mechanical or ultrasonic emulsifiers. It is crucial for the formation of a stable emulsion to ensure smooth running of an engine. The FWE stability is influenced by many factors including type and content of emulsifying agents, water content and water droplet size, mixing speed and time and dispersion types [117]. The most commonly used emulsifiers are Span 80, Tween 60 and Tween 80 with the volume of below 4% and the content of water is commonly 5-30% with droplet size of below 40 μm [118].

When the FWE fuel is injected into the combustion chamber, the micro- explosion caused by water vaporization takes place because the boiling point of fuel is different from that of water and causes secondary atomization of emulsified fuel forming smaller droplets [119]. Thus, the fuel combustion is more efficient. Because of vaporization of water, the peak combustion temperature is lowered and thus NOx formation is reduced. Most studies on water in diesel emulsion showed NOx and PM reductions [112, 120-123]. Some researches showed the increase in CO and HC emissions when using FWE fuel compared to diesel fuel [112, 123-125], but there were opposite cases [120, 126].

Besides lower pollutant emission and higher combustion efficiency, FWE also has a cost advantage over other systems, because the engine structure does not need to be modified. The marine diesel engines operating on FWE fuel can reduce emissions and cut down the operating cost. However, FWE has a limit of fixed W/F ratio unable to adapt to the requirement of different engine operating conditions. As with other water methods, corrosion of the fuel supply system is a concern.

3.3. EGR

EGR is a NOx emission reduction technology by recirculating part of exhaust gas back to the combustion chamber. After the recycled exhaust and fresh air are mixed, the heat capacity of the mixture will increase thus lowering the combustion temperature and reducing NOx emissions. Internal EGR and external EGR are two modes of EGR. In the external EGR used in turbocharged diesel engines, it is subdivided into low pressure and high pressure loop EGR as shown in Fig.4, according to the position of the bypass. In a low pressure loop EGR, practical concerning issues include the fouling of diesel exhausts and special EGR pumping arrangement. To ensure that the turbine upstream pressure is higher than the boost pressure, a throttle or a venturi tube is employed in high pressure loop EGR. A variable geometry turbine is a good solution to supply the desired EGR driving pressure [127].

The EGR method as well as the water injection method can effectively reduce NOx emission of marine diesel engines. Larbi and Bessrour [128] measured emissions from a six-cylinder marine diesel engine and reported a NOx emission reduction of 12.3% at the EGR ratio of 10%. Verschaeren et al. [129] showed reductions of up to 70% of NOx emissions from a medium speed diesel engine with a high-pressure cooled EGR loop. Wang et al. [130] conducted an engine experiment in a marine diesel engine with EGR and found that NOx emissions decreased by up to 76% in the ECAs-EGR modes while CO increased. Zu et al. [131] used a venturi high-pressure EGR device in a turbocharged diesel engine and reported that NOx emissions decreased by about 25% at the EGR rate of about 8%.

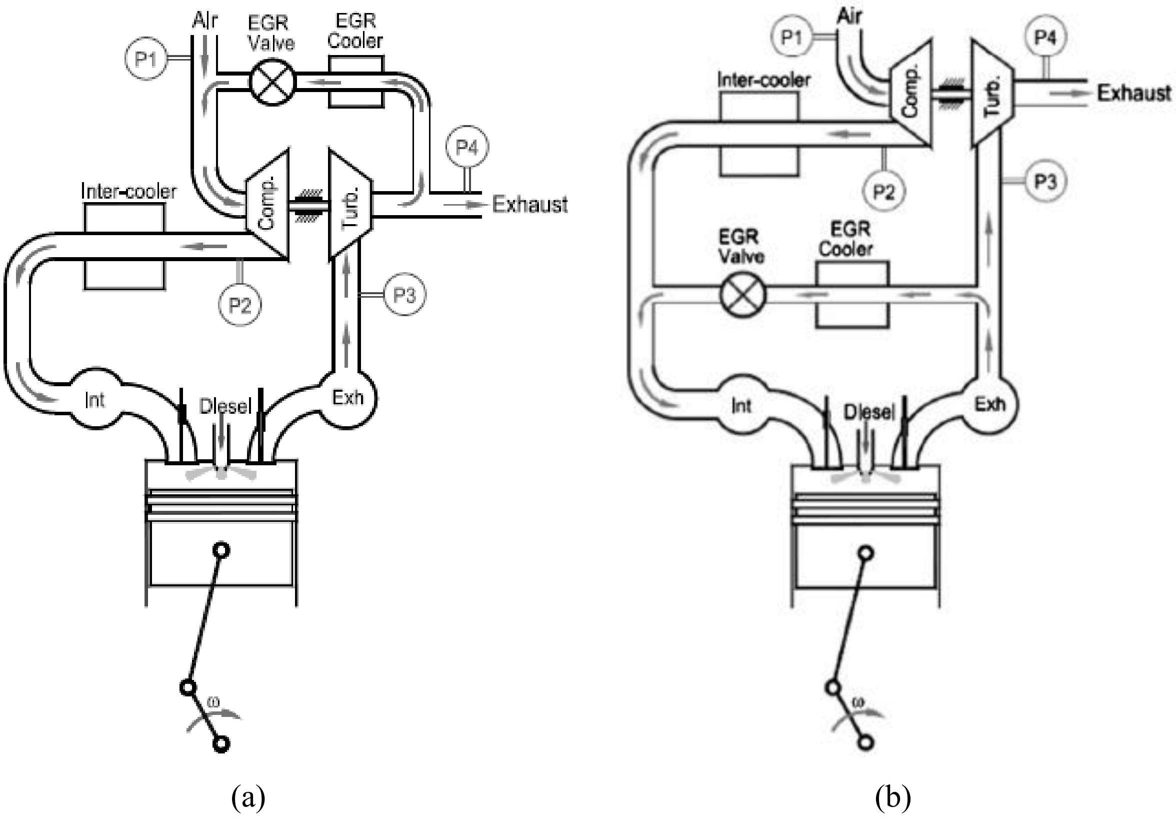


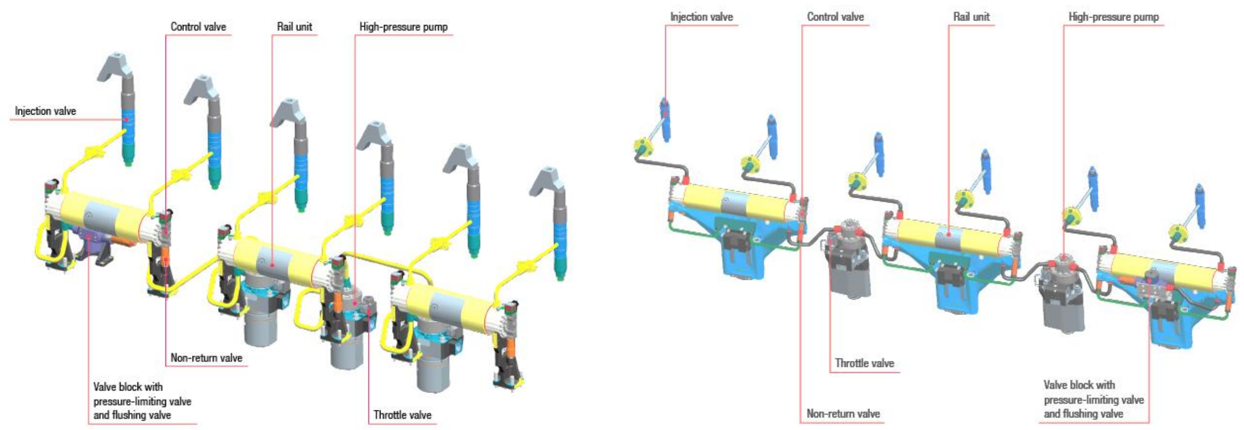
Fig. 4 Schematic diagram of (a) Low pressure and (b) high pressure loop EGR [127].

Recently, there is an attention on the importance of EGR control and the development of modelling technique for EGR control. Thangaraja and Kannan [132] addressed the necessity of the EGR control for implementing advanced combustion concepts. Nielsen et al. [133] presented a control-oriented model for the molar oxygen fraction in large two-stroke marine diesel engines with EGR. This nonlinear model achieved EGR closed-loop control at steady-state and transient conditions. Thereafter, Nielsen et al. [134,135] developed other EGR control methods for marine diesel engines and showed a reduction in smoke during loading transients. Llamas and Eriksson [136] also developed an EGR model controller for large marine diesel engines to be used to simulate the performance of EGR and various maneuvering scenarios of ships.

3.4. High pressure common rail fuel injection

High pressure common rail injection technology has been greatly developed in diesel engines due to the benefit from reduced emissions and fuel consumption. In a common rail system, arbitrary timing and multiple injections are available for NOx reduction. The high injection pressure enhances the fuel/air mixing and improves combustion leading to lower NOx and PM emissions.

The high-pressure common rail fuel injection system has been applied to marine diesel engines, such as W32CR engine [137], RT Flex engines [138], MAN 32/44CR engines and MAN 48/60 CR engines [139]. These marine diesel engines can be operated with HFO. To meet the requirement of low-cost, it is a trend for large-bore marine diesel engines to use HFO in high pressure common rail fuel injection systems. Distributed rail unit is also an important direction for high pressure common rail fuel injection technology. To avoid the deformation of the common rail at higher operating temperature, it is reasonable to separate the common rail into several rail units and to divide the fuel supply into several high-pressure pumps, shown in Fig.5.



(a) MAN 32/44CR (b) MAN 48/60 CR

Fig. 5 The MAN Diesel & Turbo CR injection system [138].

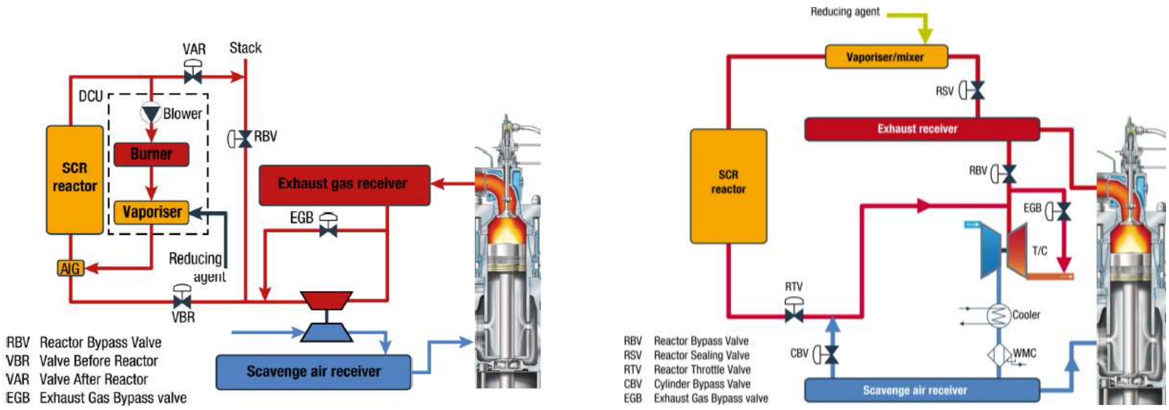
A few researches on high-pressure common rail fuel injection have shown obvious reductions in emissions from marine diesel engines. A pilot injection strategy in a two-stroke marine engine achieved a NOx reduction of 15% [140]. Imperato et al. [141] conducted a large-bore common rail engine experiment and reported that split injection reduced NOx emission by 42% without engine efficiency losses and soot increase. Goldsworthy [142] investigated the thermal efficiency and exhaust emissions of a heavy duty common rail marine diesel engine with ethanol–water mixtures and found that NOx emission decreased significantly with pre-injection and main injection of diesel and the injection into the intake air of 93% ethanol/water mixture. Liu et al. [143] investigated effects of injection strategies on low-speed marine engines with the dual fuel of natural gas and diesel. It was found that the appropriate pilot fuel injection timing and gas injection timing simultaneously reduced NOx, HC, CO and soot. However, Imperato et al. [144] reported that the pre-injection applied to a single-cylinder large-bore diesel slightly reduced NOx and increased HC, CO and soot.

3.5. Exhaust aftertreatment

3.5.1. De-NOx

Current denitration technologies for marine diesels include SCR, lean burn NOx capture technology, and low temperature plasma-assisted catalysis technology. They are derived from land-based applications. Among them, SCR is the most dominant and mature exhaust gas after-treatment technology for controlling NOx emissions from marine diesel engines. The urea–water solution is injected into the exhaust gas stream, where the reducing agent (NH_3) generated by urea thermolysis reacts with NOx and O_2 to form N_2 and H_2O. The reaction is favored by the presence of catalysts based on metal oxides such as V_2O_5 and WO_3.

According to the arrangement and configuration in the exhaust pipeline, SCR systems are divided into low pressure selective catalytic reduction (LP-SCR) and high pressure selective catalytic reduction (HP-SCR), shown in Fig.6. The LP-SCR and HP-SCR system are installed after and before the turbine, respectively. HP-SCR can be used for either low- or high-sulfur fuel, but LP-SCR is only applicable for fuels with sulfur content of not more than 0.1% due to the corrosion to the turbine blades caused by sulphur oxides [145]. Compared with HP-SCR, LP-SCR has higher flexibility for the arrangement and less effect on the performance of the diesel engine and the turbine. It is noted that HP-SCR has benefits of more compact design and higher exhaust heat utilization. Several valves are used to tune the gas flow to meet the requirements of various engine operations and emission control modes.



(a)LP-SCR (b)HP-SCR

Fig.6 LP-SCR and HP-SCR system [145].

Many simulation and experiment studies on SCR were carried out such as structure design and optimization of vaporizer and mixer, spray of urea solution and performance improvement. Du et al. [146] simulated the flue gas flow under different size and best deflector arrangement. Zhu et al. [147] optimized the structure of HP-SCR system and evaluated its performance. Verschaeren and Verhelst [148] investigated the strategies of the higher exhaust temperature to allow stable SCR operation. Ryu et al. [149] found that the SCR with a thinner metal catalyst reduced the engine exhaust gas pressure by 13%–28%. Ku et al. [150] investigated the effects of various factors on the conversion efficiency of urea solution. Besides, the high-efficiency and low-pollution catalysts, catalyst deactivation, ammonia leakage, soot blockage are also the focus of SCR research and development.

Many ship experiments and engine bench tests have been conducted on reducing NOx emission via the SCR. Lee [151] reported that the marine diesel with the SCR met IMO Tier III regulations. Gysel et al. [152] reported that the SCR reduced NOx by ~92% in a tugboat with two marine diesels. Lehtoranta et al. [153] conducted an experiment on a medium-speed marine diesel engine with the SCR and found an average reduction of NOx by 86.9% with HFO and 84.4% with light fuel oil respectively. The results showed that the metal oxides formed by oxidation of higher concentration of metals in HFO enhanced the hydrolysis. Jayaram and Nigam [154] conducted an experiment on three auxiliary engines on container vessels and reported that SCR reduced the NOx emission factor to 1.4-2.4g/kWh which corresponded to a reduction of 90–91% for HFO and 82–84% for marine distillate oil respectively. Zhu et al. [155] reported that the weighted average of NOx with low-sulfur exhaust gas was 3.08 g/kWh, lower than that of the IMO Tier III regulation while NOx with high-sulfur exhaust gas was 4.17 g/kWh, higher than that of the IMO Tier III regulation.

3.5.2. PM removal

Although there is currently no limiting value for PM in international regulations, aftertreatment of PM has still received attentions due to the harm of black smoke to human health and the environment. PM aftertreatment technologies of marine diesel engines mainly include DPF, diesel oxidation catalyst (DOC), continuously regenerating trap (CRT), electrostatic precipitator (ESP) and wet washing [156]. However, due to immaturity in PM removal, these technologies have not been widely deployed in marine diesel engines.

DPF is one of the most effective devices for diesel PM removal, which have been widely used for diesel automobiles. The DPF has a honeycomb structure filter to remove particles from the exhaust gas through inertial collision, physical retention and gravity sedimentation. The PM collection efficiency of the DPF is higher than 90% [157,158]. The continuously collected particles must be removed periodically. Otherwise the exhaust backpressure will increase, causing a decrease of the engine power. Accordingly, periodic DPF regeneration such as external heating, catalytic fuel additive, and fuel injection is indispensable [159].

When operated with high sulfur fuel such as HFO, the DPF become ineffective due to the clogging of filter pores by the coarse particles and catalyst deactivation by poisoning. To avoid filter blocking, it was suggested that DPF should be used with less than 0.05% sulfur fuels [160]. Despite this, a few tentative researches on DPF regeneration with high sulfur fuel are still ongoing. A diesel engine equipped with a DPF with a fuel borne catalyst was tested with high sulfur fuel at 1369 ppm [161]. It was found that the soot particles were efficiently filtered and that the filters are effectively regenerated during a short term. Kuwahara et al. [162] investigated the DPF regeneration with nonthermal-plasma-induced ozone in a marine diesel engine with 750 ppm sulfur fuel. The result showed a possibility of continuous regeneration at the exhaust temperature of 300℃.

The DOC is a device made from a ceramic or metal catalyst-coated carrier and can oxidize 90% HC and CO emissions and soluble organic fraction of PM to form CO_2 and H_2O [163]. The commonly used catalysts in the DOC are precious metal catalysts such as Pt and Pd. However, the current DOC technology used in marine diesel engines requires to be operated with low sulfur fuels, because high sulfur fuels cause catalyst deactivation by poisoning. Sulfur-resistant catalysts are currently a need for the DOC.

A CRT system, developed by Johnson Matthey Inc., uses a DOC in front of a DPF [164]. The CRT can simultaneously reduce PM, CO and HC from diesel engines and consists of two processes. In the first process, besides the oxidization of HC and CO, part of NO is converted into NO_2 by the DOC. In the second process, soot trapped in the DPF was oxidized by NO_2 and O_2 avoiding filter pores being clogged. The CRT can carry out continuous regeneration at most engine loads, instead of using a supplemental heat source. The typical CRT system can reduce PM, CO and VOCs by more than 85%, 80% and 70% respectively [164]. The result from the 4-cylinder turbocharged diesel engine experiment also showed a great decrease in soot mass concentrations and PN at every engine loads [165]. To achieve reliable regeneration with lower exhaust temperatures or lower NOx to PM ratio in the exhaust gas, a catalyzed continuously regenerating trap (CCRT), which is the upgrading product of the CRT, is developed and is widely used in NRMM. Just like the DPF and DOC, the CRT and CCRT are only suitable for marine diesel engines burning low sulfur fuels.

ESP technology is also an important technology to capture PM from diesel engines. In the ESP system, when the exhaust gas flows into the ESP, part of the ions generated by ionizing gases charge particles in a high-voltage electrostatic field and the charged particles will migrate to collecting plate under the action of electrostatic force. In designing the ESP component, onset voltage, sparkover voltage, voltage-current relationship, particle size, dielectric constant and residence time need to be taken into account [166]. The ESP has several advantages such as high efficiency even for ultrafine particles, low pressure drop with large gas volume, low operating costs and high reliability.

Based on the ESP, the wet ESP, the electrohydrodynamically electrostatic precipitator (EHD ESP) and the two stage ESP [167] were successively developed. Saiyasitpanich et al. [168] applied the wet ESP to a nonroad diesel engine with 500 ppm sulfur diesel fuel and found that 67–86% of mass- and number-based PM were removed. Yamamoto et al. [169] reported that the mass collection efficiency of 92.9% within the particle-size range of 30–500 nm was achieved for a marine diesel engine equipped with an EHD ESP operated with HFO. Another study of the EHD ESP in a small diesel engine using light oil showed the mass collection efficiency of 73.8% for particle size of 20–500 nm and the PN collection efficiency of over 90% for particle size of 300–5000 nm [170]. Kawakami et al. [171] found that the collection efficiency for particle size of 20-300 nm was over 90% for a diesel engine with a two stage ESP. However, the collection efficiency within the particle-size range of below 20 nm was not reported. Unlike the DOC and the

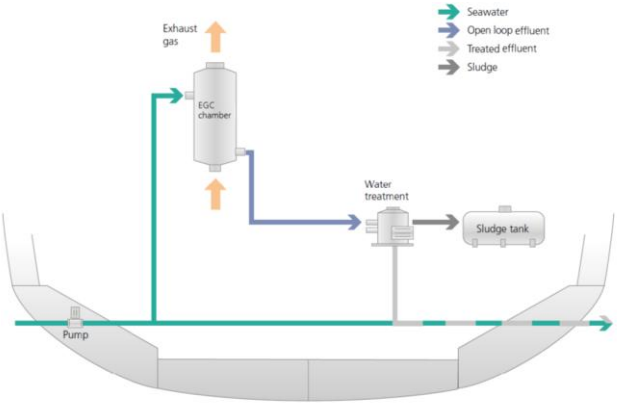
CRT, the ESP is suitable for diesel engines with high sulfur fuels, especially for large low speed marine diesel engines. Despites some disadvantages of ESP such as high capital costs, lower collection efficiency for high- and low-resistivity dust, it is a promising technology for PM removal of marine diesel engines.

3.5.3. De-SOx

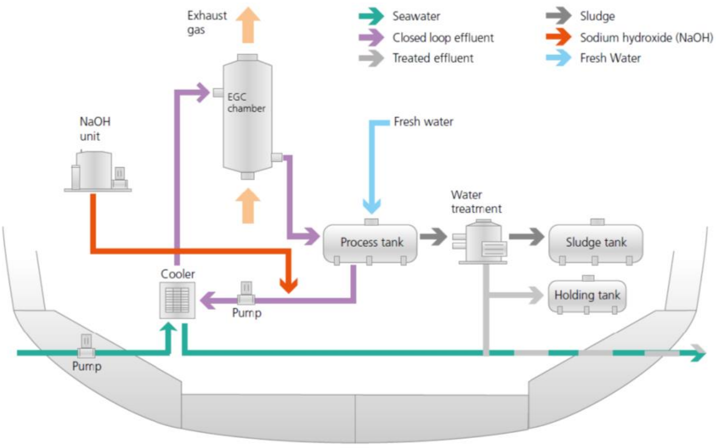
The simplest De-SOx method is to use the non-sulfur or low-sulfur content fuel in marine diesel engines. However, it is not practical to use these fuels in all ships due to the price gap between the low sulfur oil and high sulfur oil (HFO or residual oil). Therefore, besides using alternative clean fuels, exhaust aftertreatment methods seem to be more feasible to reduce SOx emissions of ships.

The commonly used De-SOx aftertreatment method is gas scrubbing, namely the exhaust gas cleaning system (EGCS), which is divided into the wet type and the dry type. Dry scrubbing was restrained in ships due to heavy equipment, instability, large space occupation of scrubbers [172]. Wet scrubbing is generally used in marine diesel engines. Wet scrubbing includes open loop system, closed loop system and hybrid system [173]. Fig.7 shows the open loop and closed loop EGCS arrangement. In the open loop system, the natural alkalinity in the seawater neutralizes SOx. In the closed loop system, the alkali liquid formulated from water and sodium hydroxide is used to desulfurize exhaust gases and washwater is continuously circulated. The open loop system has several advantages such as low operational cost and simple system, but it has poor desulfurization efficiency due to low seawater alkalinity and causes sea water pollution. The closed-loop system can overcome the defects of the open loop system and is used in any water area with almost zero emissions to the ocean. However, the closed loop system has a slightly higher operational cost compared with the open loop system. In some instances, a hybrid arrangement is operated in either open loop or closed loop modes as required, taking advantages of the open and loop systems, but has the disadvantages of high complexity, high capital cost and large space occupation. The optimal solution for using the hybrid scrubber is to operate the scrubber in the high-efficiency closed loop mode in coastal areas and in the low-efficiency open loop mode in the open sea.

Caiazzo et al. [174] reported a capture efficiency of up to 93% for SO_2 from a marine diesel engine with HFO by using the open loop system. Kuang et al. [175] concluded that the cascade-scrubbing solution achieved higher desulfurization efficiencies than the single open loop solution in a high-speed marine diesel engine. Wärtsilä has developed a full wet scrubber portfolio and has more than 704 scrubbers delivered or on order for more than 535 vessels up to the 3rd March, 2019 [176]. The closed desulfurization system developed by Wärtsilä was installed on board the 'MS Suula' with both high sulphur (3.4%) and low sulphur (1.5%) HFO and could achieve more than 98% desulfurization efficiency, 30-60% PM removal efficiency and 3-8% denitration efficiency at all loads and with all fuels [177]. MAN Diesel & Turbo tested three of the scrubber solutions on two-stroke engines in conjunction with some manufacturers and they showed high SOx and PM removal efficiency, as given in Table 8. Lehtoranta et al. [28] investigated the emissions from a cruise ship with a hybrid sulfur scrubber and a RoPax vessel with an open loop scrubber and reported that the scrubbers achieved effective decrease in SOx and low PM levels. However, the effect of a scrubber on PN was not unknown.



(a) Open loop



(b) Closed loop

Fig. 7. Open loop and closed loop EGCS arrangement [173].

Table 8 Summary of scrubber solutions tested [178].

Participants	Ship information	Scrubber	SOx removal /%	PM removal/%
Clean Marine MAN Diesel & Turbo	Banasol 7S50MC-C 9MW		73 (95, Salts add.)	35 (80, Salts add.)
Anlborg Industries Alfa Laval DFDS MAN Diesel & Turbo	Tor Ficaria 9L60MC-C 20MW		100 (NaOH)	79
APM MAN Diesel & Turbo	Alexander Mærsk 7S50MC 9MW		96 (NaOH)	73

3.5.4. Multi-pollutant removal

At present, the combination of different control technologies is often used to control multi-pollutants from land-based stationary sources. However, due to space restriction, operational instability and high cost of ships, the strategy cannot be applied in the ship exhaust pollution control. For this reason, integrated multi-pollutant control technologies for efficient emission control are receiving a lot of attentions.

Because NO is the main NOx component in diesel exhaust, the oxidation absorption method is often used to simultaneously remove NOx and SOx. Zhou et al. [179] used a wet scrubbing method combined with ozone injection method for De-SOx and De-NOx and found that 93% NOx and close to 100% SO_2 were simultaneously removed. Boscarato et al. [180] installed a monolithic Pt/Al_2O_3 oxidation catalyst and a seawater scrubber in a 1.5 MW marine engine and this integrated configuration achieved significant abatement of emissions. However, this system could hardly removel NOx if fuel sulpur is at 2%. Fang et al. [181] used urea+KMnO4 solution to remove SO_2 and NO and reported that SO_2 and NO were reduced by 98.78% and 53.05%, respectively. Han et al. [182] reported that the wet scrubbing system using the NaClO solution achieved more than 60% De-NOx and close to 100% De-SO_2.

The non-thermal plasma (NTP) can be used to control NOx and PM emissions from marine diesel engines. Balachandran et al [183, 184] used microwave plasma in a two stoke marine diesel engine and found almost 100% removal of NO and 90% removal of PM within the range of 10-365 nm. The result from a medium speed marine diesel engine with NTP reactors also showed significant reductions in NO and PM [185]. Kuwahara et al. [186] used the NTP combined with

NOx adsorbents in a 1 MW marine diesel engine and reported excellent efficiency for NOx removal. However, PM removal test was not conducted.

Sulfates account for 40-80% of PM in ship exhaust gas [187,188]. Because sulfates are easily soluble in water, it is feasible to wash off a part of PM using the wet dust removal technology. In addition to reducing most of the SOx, the aforementioned wet scrubbing can also reduce PM mass. However, the effect of the wet scrubbing on PN is rarely reported. The capture of ultrafine particles from diesel marine engines by the wet scrubbing system should be investigated.

Supergravity is a new high efficiency chemical process strengthening technology, which has the advantages of high mass transfer efficiency, short contact time, small size of equipment. It is used in the fields of chemical industry, environmental protection and energy, and can remove NOx, SOx, CO_2 and PM [189]. Fig.8 shows the three types of the reactors with different gas and liquid flow modes for the hypergravity technology. Chen et al. [190] conducted an experiment of air pollutant removal in a rotating packed bed and showed emissions reduction for CO_2 by 96.3%, SO_2 by 99.4%, NOx by 95.9% and total suspended particulate by 83.4% respectively. However, there is currently no report on the application of supergravity technology to the emission control of marine diesel engines. In any case, the use of supergravity in control of emissions from marine diesel engines, especially low-speed diesel engines, allowing for more time for chemical and physical reactions, is worth investigating.

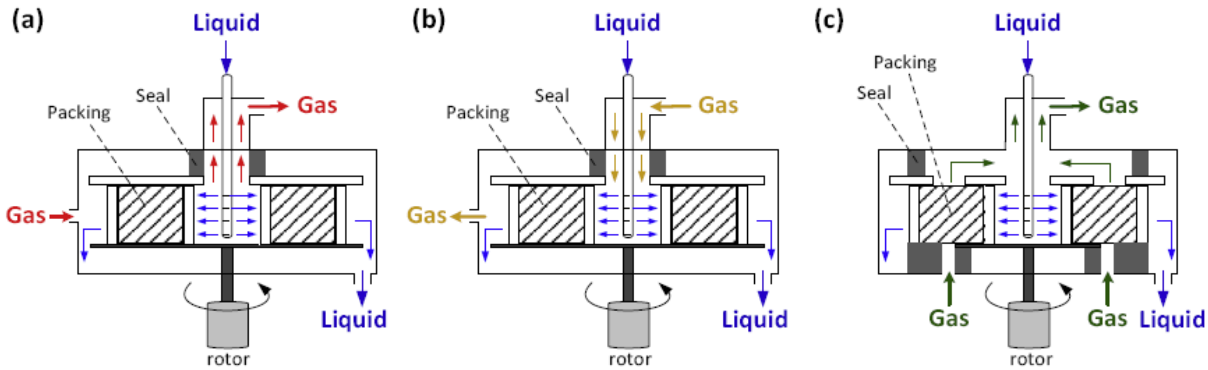


Fig.8. Hypergravity reactors with three gas and liquid flow modes: (a) countercurrent flow, (b) co-current flow and (c) cross flow [189].

3.6. Summary of emission reduction methods

Although some of automobile engine emission control methods can also be used for controlling marine diesel engine emissions, there are differences between them. Ship emission control routes still have their own characteristics. Table 9 summarizes the effects of the above-mentioned technologies on the reduction of marine diesel engine emissions. Some of them have been applied to ships and there are also a few in the research and development and experimental stages. When choosing the suitable ship emission reduction routes, several factors should be considered, such as ship type and usage, power rating, capital and operational costs, adaptability and compliance with the current and future emission regulations.

Table 9 Available methods for reducing ship emissions

Reduction method		Potential reduction/%			Reference
		NOx	PM	SOx	
Switching to clean fuel	Biodiesel	5-70	80	70	[65,76]
	Methanol	75	80	90	[90,91]
	LNG	70-85	85-95	95	[100,101]
Addition of water	IAH	5-50	-	-	[108,109]
	DWI	40-70	-	-	[114,115]
	FWE	50	-	-	[123,124]
EGR		10-70	-	-	[128-130]
Common rail fuel injection		10-40	40	-	[141, 143]
After-treatment	SCR	90	-	-	[152-154]
	DPF	-	90	-	[157,158]
	CRT, CCRT	-	90	-	[164]
	ESP	-	90	-	[169-171]
	Wet scrubbing	-	35-80	95	[178]
	Wet scrubbing+ oxidation absorption	50-90	-	95	[179, 181,182]
	NTP	95	90	-	[183, 184]

4. Conclusions and future scope

Marine diesel engines play a significant role in marine transport. However their exhaust emissions are less regulated and have caused serious concerns with regards to damages to the natural environment and human health. With the ever increasing awareness of the concerns, attentions have been paid to alleviate the emissions from the marine sector. The aim of this paper is to review the emission standards for marine diesel engines across the world and current status of marine diesel engine emissions, and examine various technologies and strategies for reducing ship diesel engine emissions that can be used to meet increasingly stringent regulations. The following conclusions can be drawn for the emissions control of marine diesel engines.

1. More stringent emission regulations for marine diesel engine have been formulated, including the emission limits (encompassing newly added PN), fuel sulfur content, and setting up emission control areas.
2. There are several ways to determine the ship's EFs, such as in the laboratory or on board, and from the exhaust pipes or from the gaseous plumes. Ship EFs (g/kWh) at light-load conditions are always higher than those at heavy-load operating modes.
3. Air pollution from ships has become the main source of pollution in ports, coastal areas and some sea areas with dense shipping routes and large ship flows, contributing up to 50% to NOx emissions.
4. Switching traditional marine fuels to clean fuels including biodiesel, methanol and LNG is a promising solution for reducing emissions from marine diesel engines. Biodiesel and methanol are more suitable for small and medium-sized ships while LNG has been used in large ships to achieve good cost-effectiveness.
5. FWE and EGR are commonly used in marine diesel engines to reduce NOx emissions. Common rail fuel injection has been used to large marine diesel engines, showing a simultaneous reduction in PM and NOx without sacrificing engine performance.
6. SCR is the most important and effective exhaust aftertreatment method for controlling marine diesel engine NOx emission with a De-NOx efficiency of 90%. The wet scrubbing

system can achieve 95% De-SOx, which is applied to large two-stroke marine diesel engines operated with high sulfur fuels. The current DPF, CRT and CCRT systems are suitable for removing PM emissions of marine diesel engines fueled with low sulfur fuels. ESP is a potential option for capturing PM from marine diesel engines using high sulphur fuels.

7. Most of the exhaust aftetreatment techniques are mature but they need to be used with appropriate integration and combination to achieve co-reduction of all pollutants and cost effective.
8. Exhaust aftertreatment can be deployed jointly with clean fuels. This paper reviewed currently available and in-service alternative fuels (biodiesel, methanol and LNG). Ammonia and hydrogen as potential future fuels should be investigated in the future. In addition, CRT and CCRT catalyst deactivation by poisoning is an issue that needs to be addressed. Then, new sulfur-resistant catalysts, ultra-fine particle treatment technology, and integrated treatment technology with cost-effective and automatic control are important development direction for ship exhaust emission control.

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