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Research Progress on Ship Exhaust Emission Characteristics and After-treatment Technologies

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Abstract

Ship emissions are important anthropogenic pollution sources that affect air quality in port cities and global climate change, mainly including air pollutants such as sulfur oxides, nitrogen oxides and particulate matter, as well as greenhouse gases such as carbon dioxide. The International Maritime Organization (IMO) has established a global emission control system centered on SO_x and NO_x limits, promoting the rapid development of ship exhaust after-treatment technologies. This paper systematically analyzes the environmental impacts of main ship pollutants, sorts out IMO emission regulations, focuses on the principles, application effects and economy of mainstream after-treatment technologies such as SCR, EGR and DPF, prospects the technology integration trends and existing challenges, so as to provide a reference for the formulation of ship emission reduction strategies.

Keywords

Ship emission; IMO regulations; exhaust after-treatment; SCR; EGR; emission control.

1. INTRODUCTION

Ship emissions are a significant anthropogenic source that affects air quality in port cities and contributes to global climate change. These emissions can be primarily categorised into two types: air pollutants that directly affect regional environments and human health, and climate-forcing agents that have global greenhouse effects. The former mainly includes sulfur oxides (SOx), nitrogen oxides (NOx), particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs). The latter is dominated by carbon dioxide (CO_2), along with non-CO_2 greenhouse gases such as methane (CH_4) [1]. Systematic analysis of ship emissions and their regulatory frameworks is a cornerstone of developing effective emission-reduction strategies.

2. MAJOR POLLUTANTS AND THEIR ENVIRONMENTAL IMPACTS

Ship-emitted air pollutants pose a significant threat to ecosystems and public health. Studies by scholars such as Karanasiou Alexandra indicate that particulate matter (PM2.5) can penetrate deep into human alveoli, damaging the cardiovascular system [2]. In contrast, larger particles, such as PM10, primarily affect the respiratory system. SOx is a major precursor to acid rain, harming aquatic ecosystems, and its atmospheric transformation into sulfate particles also contributes significantly to the pathogenesis of respiratory diseases. Long-term exposure to NOx (primarily emitted as NO and rapidly oxidising to NO2) significantly exacerbates respiratory conditions such as asthma in children.

3. IMO SHIP EMISSION CONTROL SYSTEM

The IMO has established a global ship emission control framework centered on mandatory limits for SO_x and NO_x.

3.1. Sulphur Oxides (SOx) Control

The IMO controls SOx emissions by limiting the sulphur content in marine fuels. As shown in Fig 1, its regulatory system adopts a dual-track approach with a "Global Limit" and stricter "Emission Control Area (ECA) Limits." The global limit was significantly tightened from a historical 4.5% to 0.50% effective 2020; whereas within ECAs such as the Baltic Sea and North Sea, a more stringent limit of 0.10% has been in force since 2015 [3].

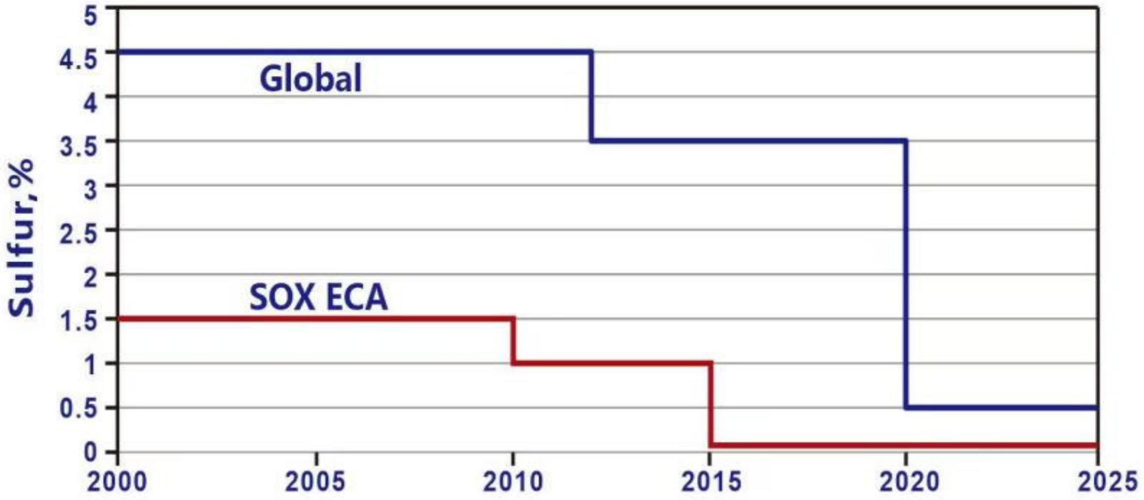


Figure 1. IMO Annex VI SOx emission limits.

3.2. Nitrogen Oxides (NOx) Control

The International Maritime Organisation (IMO) implements a phased approach to controlling nitrogen oxide (NO_x) emissions from marine diesel engines under MARPOL Annex VI, with progressively stricter limits defined by Tier levels. As illustrated in Fig 2, Tier I (effective from 2000) established a global baseline. Tier II (effective from 2011) tightened these limits across all engine speeds, mandating an average reduction of approximately 20% compared to Tier I for ships operating worldwide. The most stringent, Tier III (effective since 2016 in designated NO_x Emission Control Areas, NECAs), requires approximately an 80% reduction relative to the Tier I baseline and applies to new ships constructed for operation within NECAs. This ratcheting regulatory framework has been a primary driver of technological innovation in marine engineering, directly accelerating the development and adoption of high-efficiency after-treatment technologies, such as Selective Catalytic Reduction (SCR) and Exhaust Gas Recirculation (EGR), to ensure compliance.

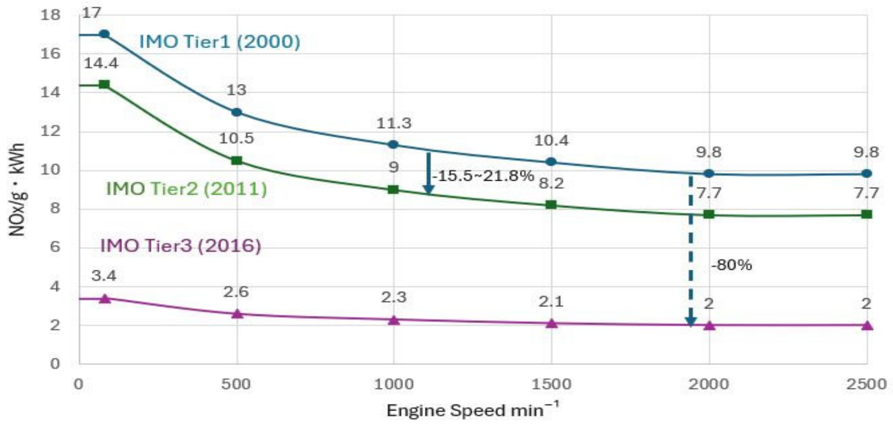


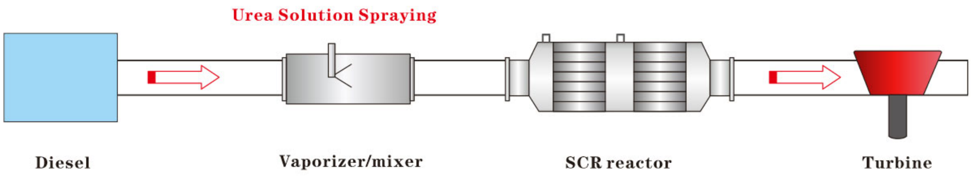
Figure 2. NO_x emission limits for marine diesel engines across IMO MARPOL Annex VI Tier levels[4]

4. MAINSTREAM TECHNOLOGIES AND APPLICATIONS OF SHIP EXHAUST AFTER-TREATMENT

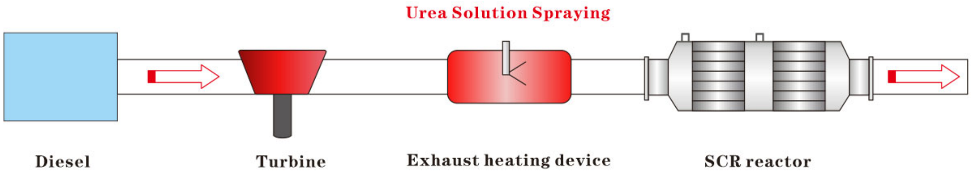
Under strict IMO regulations, exhaust after-treatment has become the core solution to meet emission reduction requirements.

4.1. Selective Catalytic Reduction (SCR) Technology

SCR technology uses ammonia (NH_3) generated by the thermal decomposition of urea as a reducing agent to convert NOx to nitrogen (N_2) and water (H_2O) over a catalyst. Its core lies in the precise control of catalytic reaction kinetics. Zhang Yunqiu et al. pointed out that marine SCR systems require differentiated structural designs for two-stroke and four-stroke diesel engines to adapt to the operational characteristics of low-speed engines, which feature large displacement and low exhaust temperatures (180-400°C) [5]. Simulation research by Zhang Yang indicated that a nonlinear model-predictive controller can precisely regulate urea injection rate, achieving a 93.8% NOx conversion rate under steady-state conditions with NH_3 slip below 10 ppm, thereby meeting the Tier III standard [6]. Zhu et al. further emphasised that SCR is the only IMO-recognised NOx reduction technology applicable to all ship types and power ranges. SCR systems can be classified as high- or low-pressure configurations based on pressure rating [7], and their typical processes are shown in Fig 3.



(1)HP–SCR



(2) LP–SCR

Figure 3. Flowchart of High-Pressure and Low-Pressure SCR Systems for Marine Diesel Engines.

4.2. Exhaust Gas Recirculation (EGR) and Particulate Matter Control

EGR technology reduces nitrogen oxide (NOx) emissions by recirculating a portion of the cooled exhaust gas into the cylinders, thereby lowering the in-cylinder combustion temperature and oxygen concentration. This technology can achieve a significant NOx reduction of 15-30%. The core components and operational workflow of this system are illustrated in Fig 4. However, research by Kim et al. indicates that while EGR effectively reduces NOx emissions, it often increases particulate matter (PM) emissions. Therefore, when adopting a deep denitrification strategy that combines EGR with Selective Catalytic Reduction (SCR), it is essential to integrate efficient particulate matter aftertreatment devices, such as Diesel Particulate Filters (DPF). This ensures synergistic control of pollutants and prevents the trade-off phenomenon in which increases in PM emissions accompany reductions in NOx.DPF uses a wall-flow ceramic substrate to capture soot, with a PM removal efficiency of more than 90%, requiring active/passive regeneration. Studies show that the daily PM2.5 emissions of a single medium-to-large container ship are equivalent to 500,000 China National IV trucks.

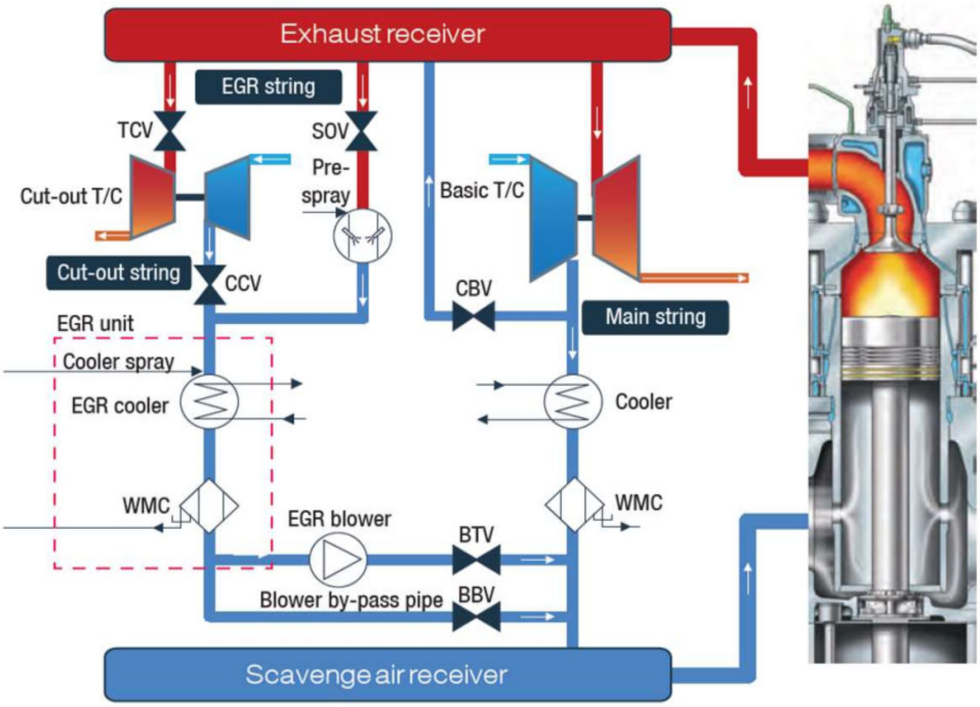


Figure 4. EGR System Diagram [8].

4.3. Technology Integration Trend and Economy

Ship exhaust after-treatment technologies achieve pollutant removal through physical and chemical processes, so their technological maturity and application scope are critical for compliance. According to the MARPOL Annex VI Tier III standard, NO_x emissions from marine diesel engines must be restricted below 3.4 g/kWh, even down to 2.0 g/kWh, and PM emissions are also subject to strict limitations [9]. Mainstream technical routes include Selective Catalytic Reduction (SCR), Exhaust Gas Recirculation (EGR), and Diesel Particulate Filters (DPF). Studies on the working principles, application performance, and system integration of these technologies have become key research focuses, with typical technical solutions and performance indicators summarized in Fig 5.

Exhaust after-treatment systems are developing towards high integration. SDPF (SCR-coated DPF) reduces space occupation by 20%–30% compared with conventional SCR+DPF systems. However, SDPF shows limited passive regeneration capacity under low engine loads, which may require additional heating to maintain catalytic activity. Economic analysis shows that SCR has obvious advantages in marine applications, with an operating cost of only 107.3 RMB per hour and power consumption accounting for only 0.46% of the main engine output, much lower than other denitrification technologies.

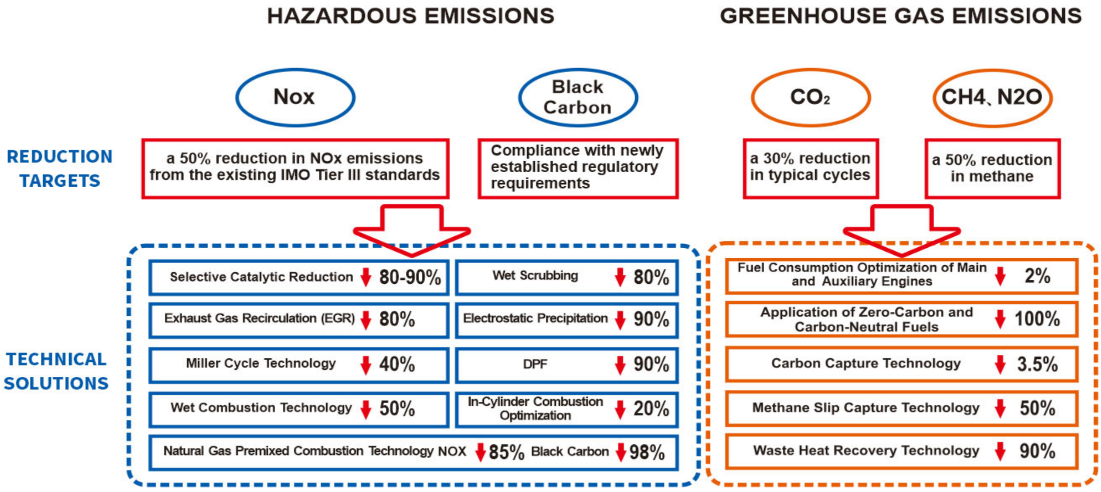


Figure 5. Ultra-Low Emission Solutions.

4.4. Ship Route Optimization Based on Intelligent Algorithms

Intelligent algorithms can further reduce ship energy consumption and emissions. Relevant studies are shown in Table 1.

Table 1. Research on Ship Route Optimization Based on Intelligent Algorithms.

Algorithm Name	Intelligent Applications in Ship Route Optimization
Genetic Algorithm	MARIE et al.[10] achieved optimized ship routes using a multi-objective genetic algorithm
Particle Swarm Optimization	WANG et al.[11] utilized a particle swarm optimization algorithm to optimize routes for ocean-going vessels, thereby improving the energy efficiency level of ships.
Ant Colony Algorithm	ZHANG et al.[12] based on big data analysis technology, implemented automatic ship route planning by employing the ant colony algorithm.
Dynamic Programming Algorithm	SHAO et al.[13] proposed a new dynamic programming algorithm for route optimization, which can reduce ship fuel consumption by approximately 3%.

5. EXISTING CHALLENGES AND FUTURE PROSPECTS

Current main challenges: catalyst sulfur poisoning caused by high-sulfur fuels; urea crystallization and blockage under low-temperature conditions; limited space in ship engine rooms; high energy consumption for DPF regeneration.

Future directions: low-temperature and high-activity SCR catalysts; low-energy DPF regeneration strategies; integrated systems for synergistic control of multiple pollutants; intelligent denitrification coupled with renewable energy; integration of after-treatment and energy systems for zero-carbon ships.

6. CONCLUSION

Ship exhaust after-treatment technology has become the core technical support to meet IMO near-zero emission requirements. The technological development has shifted from the single application of SCR/EGR to the synergistic control and high integration of NO_x and PM. SCR occupies a dominant position with high denitrification efficiency and excellent economy; integrated technologies such as SDPF achieve higher treatment efficiency in the limited space of ships. In the future, it is necessary to further improve the adaptability to high-sulfur fuels and low-temperature working conditions, upgrade to low-carbon and zero-carbon directions, and support the achievement of the full-life cycle carbon neutrality goal of ships.

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