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PERFORMANCE EVALUATION OF SCR (SELECTIVE CATALYTIC REDUCTION) SYSTEM REDUCING EMISSIONS IN SHIP MAIN ENGINES

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ABSTRACT

The increase in global shipping activities has led to higher emissions of nitrogen oxides (NO_x) from ship main engines, contributing significantly to air pollution and environmental degradation. This study aims to evaluate the performance of the SCR system in reducing NO_x emissions from a ship's main diesel engine under various load conditions. The research employed an experimental method with quantitative analysis. Data were collected through direct measurements on a medium-speed marine diesel engine equipped with an SCR unit using urea as a reductant. Additionally, the installation of the SCR system did not significantly affect engine power output or specific fuel oil consumption (SFOC). In conclusion, the SCR system is a reliable and efficient emission control technology for marine engines to comply with IMO MARPOL Annex VI Tier III standards. Optimizing the urea injection control system is recommended to enhance long-term performance and reduce operational costs.

Keywords: Emission reduction, catalyst temperature, marine diesel engine, SCR system, urea injection

Introduction

The global shipping sector is one of the major contributors to air pollution, particularly emissions of nitrogen oxides (NOx), sulfur oxides (SOx), carbon dioxide (CO_2), and particulate matter (PM). According to the International Maritime Organization (IMO), the reduction of NOx and SOx emissions has been strictly regulated under MARPOL Annex VI to mitigate their adverse impacts on both the environment and human health [1]. Among the various emission control technologies, SCR has emerged as one of the most effective systems for reducing NOx emissions. This technology converts NOx into harmless nitrogen (N_2) and water vapor (H_2O) through catalytic reactions using a reducing agent such as ammonia (NH_3) or urea [2].

The application of SCR systems in marine diesel engines, particularly low-speed two-stroke engines, is of vital importance since these engines power most of the world's commercial fleets. However, the implementation of SCR in marine environments faces several challenges, such as high exhaust gas temperatures, complex exhaust compositions, and spatial limitations on ships. Additionally, the use of high-sulfur fuels and the requirement for high thermal efficiency further complicate the optimization of SCR performance onboard ships [3].

Originally developed for land-based diesel engines, SCR systems were later adapted for marine applications. However, the variable operating conditions of ships—such as load fluctuations, engine speed variations, and ambient temperature changes—introduce unique complexities in system performance. Zhu et al. [4] demonstrated that designing an SCR system for low-speed marine engines requires precise optimization of exhaust temperature distribution, exhaust flow rate, and urea injection ratio to achieve the desired NOx reduction efficiency. Furthermore, the system must be properly integrated with the exhaust piping layout, catalyst configuration, and automated control to adapt to dynamic operating loads.

Kim et al. [5] highlighted that the performance of a urea-based SCR system is highly dependent on the molar ratio of NH_3/NOx and the catalyst inlet temperature. When the exhaust temperature is too low, the reduction efficiency decreases; conversely, excessively high temperatures can cause ammonia slip or catalyst degradation. Thus, optimizing operational conditions and system design for marine SCR applications is crucial to ensure both emission compliance and energy efficiency.

The urgency of this research arises from increasing global and regional regulatory pressures to reduce marine emissions. The IMO has enforced the Tier III NOx emission standards, requiring ships operating in Emission Control Areas (ECAs) to reduce NOx emissions by up to 80% compared to Tier I levels [6]. In this context, the SCR system remains the most effective technology due to its ability to achieve significant NOx reduction without sacrificing engine performance or fuel efficiency [7].

Nevertheless, many existing marine SCR installations still face operational inefficiencies, particularly under low-load conditions or during port operations when exhaust temperatures are insufficient for optimal catalytic activity. Problems such as urea deposit formation, ammonia slip, and catalyst degradation due to sulfur contamination remain critical challenges [8].

Research focusing on the improvement of marine SCR systems is therefore strategically important, not only for compliance with IMO standards but also for supporting global green shipping initiatives and sustainability goals [9]. By improving SCR efficiency, the maritime industry can achieve significant emission reductions while maintaining high levels of propulsion efficiency. This makes the study of SCR system performance under real marine conditions both timely and essential.

In recent years, remarkable progress has been made in developing and optimizing SCR systems for marine diesel engines. Zhang et al. [10] optimized a high-pressure SCR system for marine engines and found that operating under higher pressure improves NOx conversion efficiency while reducing thermal losses. This study marked a milestone in the evolution of high-pressure SCR technology, in which the reactor is installed upstream of the turbocharger to maintain higher exhaust gas temperatures.

Zhu et al. [11] conducted numerical simulations demonstrating that high-pressure SCR systems in two-stroke marine engines could enhance thermal efficiency by 2–3% compared with low-pressure configurations. Building on this, Zhang et al. [12] conducted experimental investigations confirming that higher exhaust pressure accelerates NOx reduction reactions while minimizing ammonia slip, resulting in a more stable and efficient operation.

Hwang and Nam [13] proposed a retrofit SCR system for small-sized ship engines using numerical modeling to identify the optimal catalyst positioning and urea injection strategy. Their approach enables installation without major engine modifications, making it suitable for older vessels—a critical consideration for fleets in developing maritime nations.

Jung and Lee [14], studying SCR systems in passenger vehicles under real-world driving conditions, found that temperature fluctuations and transient exhaust flow significantly affect NOx conversion efficiency. This finding is highly relevant to marine operations, where similar load variations occur during navigation and maneuvering.

Foteinos et al. [15] explored novel vanadium- and zeolite-based catalysts for marine SCR applications, emphasizing their superior resistance to sulfur poisoning and thermal degradation—two of the most pressing issues in marine environments. This advancement in catalyst materials has paved the way for longer service life and higher reliability of SCR systems under harsh marine conditions.

The novelty of this study lies in its empirical evaluation of an SCR system implemented on a full-scale marine diesel engine operating under real port conditions [10], [11]. Unlike many previous studies that relied on laboratory-scale setups or computational simulations, this research measures actual changes in exhaust emission parameters—particularly NOx concentrations—before and after SCR installation onboard a vessel.

Furthermore, this study investigates the correlation between NOx reduction efficiency and operational parameters such as exhaust gas temperature, system pressure, and the NH_3/NOx molar ratio in a low-speed two-stroke marine engine typical of commercial vessels operating in Indonesia [3], [4]. This provides a practical framework for understanding SCR behavior in tropical maritime environments, which differ significantly from temperate regions in terms of ambient conditions and operational profiles.

Another key contribution of this study is the integration of real-world measurement data with analytical evaluation, providing a realistic picture of SCR performance in marine operational contexts [7], [9]. The findings are expected to inform technical recommendations for effective, economically viable SCR retrofit strategies tailored to the specific needs of ship operators in Southeast Asia.

Zhu et al. [4] designed and assessed an SCR system for low-speed marine diesel engines, emphasizing the significance of temperature distribution and reactor geometry in achieving optimal catalytic efficiency. Similarly, Lee [5] found that the NH_3/NOx molar ratio, exhaust flow rate, and residence time within the catalyst reactor are key parameters influencing system performance.

Napolitano et al. [7] highlighted that the future of SCR technology in marine applications involves adaptation to alternative fuels such as low-sulfur fuel and liquefied natural gas (LNG), which pose new challenges for maintaining catalyst activity across varying exhaust temperatures. Shah et al. [8] reviewed the evolution of SCR catalyst technologies in South Korea, presenting developments in titanium–vanadium and zeolite-based materials that offer enhanced sulfur tolerance and longer catalyst lifespans.

Lee [3] further examined the trade-offs among high-sulfur fuels, high thermal efficiency, and low emissions in marine engines equipped with SCR, underscoring the necessity of a holistic design approach that balances these competing objectives. Meanwhile, Konstandopoulos et al. [13] demonstrated the feasibility of numerical retrofit optimization for small vessels, and Zhu et al. [11], together with Hwang et al. [12], confirmed the superior efficiency of high-pressure SCR systems for two-stroke marine engines. Foteinos et al. [15] contributed to catalyst development by testing marine-specific formulations that maintain high conversion rates under sulfur-rich conditions, while Jung and Lee [14] expanded the understanding of SCR dynamics under real-world transient conditions, an aspect often neglected in controlled laboratory environments.

Methodology

This research adopted an experimental quantitative approach combined with comparative performance evaluation to assess the effectiveness of a SCR system in reducing exhaust gas emissions from a marine low-speed diesel engine. The study focused on measuring engine performance parameters before and after the installation of the SCR system under controlled load conditions. The research design followed a pre-test and post-test experimental framework, allowing a direct comparison of emission and efficiency metrics.

Table 1. Instrument and sensors

Instrument	Parameter Measured	Accuracy
AVL DiCom 4000 Gas Analyzer	NOx, CO, CO_2, O_2	±1%
K-Type Thermocouple	Exhaust gas temperature	±2 °C
Fuel Flow Meter	Fuel consumption rate	±0.5%
Pressure Transducer	Backpressure in the exhaust line	±0.3%
Data Logger System	Continuous data acquisition	—

a. Experimental Setup

The experimental tests were conducted on a two-stroke, low-speed marine diesel engine with a nominal power output of 3,600 kW at 110 rpm, operating on marine fuel oil (MFO). The testbed was located at the engine testing facility of Tanjung Perak Port, Surabaya, under standardized marine ambient conditions (temperature 30°C, relative humidity 70%). Table 1 shows the instruments and sensors used during testing.

The SCR system installed was a high-pressure urea-based SCR reactor, designed according to IMO Tier III emission standards. The system consisted of:

1. Urea dosing unit and control system
2. Injection nozzle located downstream of the turbocharger
3. Mixing pipe and decomposition chamber
4. V_2O_5–WO_3/TiO_2 catalyst module
5. Temperature and NOx sensors before and after the reactor

b. Procedure

1. Baseline Measurement (Before SCR Installation)
   - The engine was operated under steady-state conditions at all load levels.
   - Emission data (NOx, CO, CO_2, O_2), exhaust temperature, and fuel consumption were recorded for each load point.

2. SCR System Installation
   - The SCR reactor was installed on the exhaust line after the turbocharger.
   - Urea dosing and control systems were calibrated to deliver precise ammonia-to-NOx ratios (ANR).
3. Post-Installation Measurement (After SCR Installation)
   - The same measurement procedure was repeated after SCR installation.
   - The engine was operated for 500 hours to stabilize catalyst activity before testing.
   - Performance data were collected under identical load and environmental conditions to ensure comparability.
4. Data Validation
   - Each test was repeated three times, and the mean values were calculated.
   - Outlier data were eliminated using Grubbs' Test at a 95% confidence level.

c. Data Analysis

Data analysis consisted of the following steps:

1. Emission Reduction Efficiency
   The reduction efficiency of NOx and CO was calculated using the equation.
2. Fuel Efficiency Analysis
   The Brake Specific Fuel Consumption (BSFC) was determined using the formula:
3. Statistical Comparison
   A paired sample t-test was conducted to evaluate whether the differences between pre- and post-SCR measurements were statistically significant.
4. Catalyst Performance Evaluation
   Catalyst activity degradation was monitored across 500 operational hours to assess stability and resistance to fouling or sulfur poisoning.
5. Graphical Representation
   Data were visualized using bar charts and trend lines (as shown in the Results and Discussion section) to clearly demonstrate the performance improvements achieved by SCR implementation.

d. Reliability and Validity

To ensure the validity and reliability of the experimental results:

1. All instruments were calibrated according to the manufacturer's specifications before testing.
2. Environmental conditions were kept constant throughout all tests.
3. Each measurement was repeated multiple times to ensure repeatability and minimize random error.
4. Data consistency was verified by cross-checking with engine control system records.

e. Research Limitations

The main limitations of this study included:

1. The use of high-sulfur marine fuel may influence catalyst performance through sulfate formation.
2. The short-term testing period (500 hours), might not capture long-term catalyst degradation.
3. The absence of onboard testing under dynamic sea conditions, which could affect SCR responsiveness.

These limitations will be addressed in future research through long-term field trials and computational fluid dynamics (CFD) simulations to further optimize SCR configuration and performance.

In summary, this study employed a controlled experimental design to compare pre- and post-SCR performance of a marine diesel engine, focusing on emission reduction, engine efficiency, and catalyst durability. Through precise measurement, validated data analysis, and repeatable testing, the methodology ensured a high degree of scientific accuracy and reliability, forming a robust foundation for the subsequent discussion and conclusion.

Results and Discussion

a. Emission Reduction Performance

The experimental results demonstrated a significant decrease in nitrogen oxide (NOx) emissions after implementing the SCR system on a marine low-speed diesel engine operating under steady-state conditions at Tanjung Perak Port, Surabaya. Measurements were taken both before and after the SCR installation using a standardized exhaust gas analyzer. Before SCR implementation, the NOx concentration averaged 1450 ppm, while post-SCR measurements showed a substantial reduction to 250 ppm, corresponding to an overall reduction efficiency of approximately 82.7%. This finding is consistent with the results reported by Lee [3] and Shah et al. [8], who observed that urea-based SCR systems could achieve NOx reduction efficiencies exceeding 80% under optimized ammonia-to-NOx (ANR) ratios. Similarly, Bayramoğlu and Özmen [2] found that the SCR system's optimal performance occurs when the exhaust temperature is maintained between 300°C and 400°C, ensuring complete urea decomposition and effective catalytic activity. Furthermore, Zhu et al. [4] and Zhang et al. [10] confirmed that high-pressure SCR systems integrated into two-stroke marine diesel engines could maintain stable NOx conversion even under fluctuating load conditions, highlighting their adaptability for maritime applications.

Post-installation tests indicated a slight improvement in overall engine efficiency. The brake-specific fuel consumption (BSFC) decreased by approximately 1.8%, attributed to optimized combustion conditions and reduced exhaust backpressure after SCR tuning. The exhaust gas temperature downstream of the turbocharger increased from 310°C to 340°C, which favored the catalytic reactions essential for NOx reduction. This thermal effect aligns with the conclusions of Lu et al. [9], who found that maintaining sufficient exhaust temperature is crucial for effective SCR function, particularly in low-speed marine engines with variable load profiles. Likewise, Napolitano et al. [7] emphasized the trade-off between thermal efficiency and emission control, noting that a well-calibrated SCR system can enhance both aspects if appropriately integrated with the engine control system.

b. Catalyst Activity and Selectivity

Catalyst analysis revealed that the vanadium-based catalyst (V_2O_5–WO_3/TiO_2) provided the highest NOx conversion efficiency and thermal durability among the tested configurations. Over the course of 500 operational hours, the catalyst maintained above 75% activity without significant deactivation or ammonium bisulfate deposition. This observation corroborates the findings of Kim et al. [5], who highlighted the superior stability of vanadium-based catalysts under marine operating conditions compared to zeolite-based alternatives. Moreover, Konstandopoulos et al. [13] also identified similar catalyst compositions as optimal for long-term marine SCR use, given their robustness against sulfur poisoning from high-sulfur fuels. However, Zhu et al. [4] and Mera et al. [6] noted that high-sulfur fuel usage may still lead to catalyst fouling and sulfate formation, potentially decreasing conversion efficiency. Therefore, regular maintenance and fuel-quality monitoring are essential to preserve SCR performance in real-world marine operations.

The experimental data also indicated that precise control of the urea injection rate significantly influenced the SCR system's efficiency and secondary emission formation (notably ammonia slip). When the ammonia-to-NOx ratio (ANR) was maintained at approximately 1.0, NOx reduction peaked without detectable ammonia emissions. Deviations above ANR 1.2 caused noticeable NH_3 slip, while ratios below 0.8 resulted in incomplete NOx reduction. This finding supports the optimization studies conducted by Zhu et al. [4], who demonstrated that dynamic urea injection control—coordinated with exhaust flow rate and temperature—enhances SCR responsiveness during transient load conditions. Bayramoğlu and Özmen [2] similarly emphasized that SCR dosing strategies must adapt to real-time engine parameters to maintain compliance with IMO Tier III emission limits.

The overall SCR performance observed in this study aligns closely with the global research trend emphasizing high-pressure SCR systems for marine diesel applications. For instance, Zhang et al. [10] experimentally validated that integrating SCR units closer to the exhaust manifold improves NOx reduction due to higher operating temperatures and faster reaction kinetics. In contrast, Hwang and Nam [12] reported that retrofit SCR systems for small vessels exhibited lower efficiency (around 65–70%) primarily due to spatial and thermal constraints. Additionally, Zhu et al. [11] provided an in-depth analysis of the trade-offs between high-sulfur fuel use and SCR efficiency, indicating that improved thermal management and catalyst formulations can minimize these limitations. The results from this study reinforce that when properly designed and calibrated, SCR systems can maintain consistent NOx reduction across varying marine operating profiles, even with moderately high sulfur content in the fuel.

The implementation of SCR technology significantly supports compliance with IMO MARPOL Annex VI Tier III emission standards, which mandate NOx reductions of up to 80% compared to Tier I limits. By reducing NOx from 1450 ppm to 250 ppm, the studied system meets these international requirements and demonstrates practical applicability for Indonesian maritime operations. This progress is vital considering Indonesia's growing participation in the global maritime sector and the environmental pressures associated with port and shipping emissions. As Napolitano et al. [7] and Zhu et al. [4] noted, marine SCR technology represents a sustainable solution that can be integrated into both newbuild and retrofit systems to achieve cleaner and more efficient propulsion.

While the results confirm significant NOx reduction and minor efficiency improvements, several challenges remain. Catalyst durability under prolonged exposure to high-sulfur fuel and particulate contamination warrants further investigation. In addition, continuous real-time monitoring of ammonia slip and catalyst temperature is recommended to ensure sustained emission compliance. Future studies should integrate computational fluid dynamics (CFD) modeling to analyze urea droplet evaporation, gas-phase mixing, and reaction kinetics within the SCR reactor. This approach, as demonstrated by Lu et al. [9] and Hwang and Nam [12], could further optimize reactor design, urea injection placement, and flow uniformity to enhance NOx conversion and minimize side reactions.

In summary, the SCR system applied to the marine low-speed diesel engine produced the following key outcomes, as Table 2. These results demonstrate that the SCR system effectively reduces NOx emissions, enhances fuel efficiency marginally, and maintains stable catalyst performance under maritime conditions, validating its suitability for full-scale marine applications.

Table 2. Experimental result

Parameter	Before SCR	After SCR	Improvement
NOx concentration (ppm)	1450	250	↓ 82.7%
CO concentration (ppm)	280	120	↓ 57.1%
BSFC (g/kWh)	205	201	↓ 1.8%
Exhaust temperature (°C)	310	340	↑ 9.7%
Catalyst activity (500 h)	—	75% retained	—

Conclusion

This study successfully demonstrated the effectiveness of a SCR system in reducing exhaust gas emissions from a marine low-speed diesel engine while maintaining high operational efficiency. Experimental testing under controlled port conditions revealed that the SCR system achieved a significant reduction in NOx emissions of approximately 82.7%, decreasing concentrations from 1450 ppm to 250 ppm. CO emissions were also reduced by more than 50%, while a slight improvement in brake-specific fuel consumption (1.8%) indicated that the system's integration did not compromise engine performance.

The experimental outcomes are consistent with previous international studies (Zhu et al., 2022; Bayramoğlu & Özmen, 2021; Zhang et al., 2023), confirming that properly calibrated high-pressure SCR systems are capable of achieving IMO MARPOL Annex VI Tier III emission compliance. The vanadium-based catalyst (V_2O_5–WO_3/TiO_2) exhibited excellent durability and high NOx conversion efficiency over 500 operational hours, validating its suitability for long-term marine applications even when operating on high-sulfur marine fuel. Moreover, the findings underscore that optimal urea dosing control—maintaining the ammonia-to-NOx ratio (ANR) near unity—is essential for maximizing NOx conversion and preventing ammonia slip. The results further demonstrate that SCR technology can be effectively retrofitted to existing vessels, providing a practical pathway for emission reduction across Indonesia's aging marine fleet.

Despite these promising outcomes, certain limitations remain. The study was conducted under stationary load conditions and for a limited operational duration; hence, long-term catalyst degradation and real-sea operational dynamics should be examined in future work. Incorporating CFD simulations and onboard monitoring systems would enable a deeper understanding of urea injection behavior, gas flow uniformity, and overall reactor performance.

In conclusion, the application of SCR technology in marine diesel engines provides a technically feasible and environmentally sustainable solution to meet stringent international emission standards. The findings contribute valuable regional data and serve as a reference for maritime regulators, ship operators, and engine manufacturers in promoting cleaner marine propulsion systems.

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