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Environmental performance evaluation of a retrofit exhaust gas recirculation-diesel particulate filter system for simultaneous nitrogen oxides and particulate matter reduction in a medium-speed marine diesel engine

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ABSTRACT

The study experimentally evaluated the environmental and operational performance of a combined exhaust gas recirculation–diesel particulate filter (EGR–DPF) retrofit system installed on a Yanmar S185L-ST medium-speed marine diesel engine under representative marine operating conditions. The retrofit configuration was designed to simultaneously reduce nitrogen oxides (NOx) and particulate matter (PM) emissions while maintaining acceptable engine performance and operational stability. Experiments were conducted under different engine speed and load conditions along the propeller characteristic curve. The results showed that the EGR system effectively reduced NOx emissions under all investigated operating conditions, with reduction efficiencies ranging from 4.28% to 11.69%. The highest NOx reduction was observed at 79% rated speed and 50% engine load. The DPF system demonstrated strong PM filtration capability, with PM reduction efficiencies ranging from 28.13% to 97.67%, particularly under medium and high engine speed conditions. Evaluation of brake-specific fuel consumption (BSFC) indicated that the retrofit system did not significantly deteriorate engine performance, and stable engine operation was maintained throughout the experiments. The results confirm that the proposed EGR–DPF retrofit configuration provides a practical, low-cost, and environmentally effective solution for reducing emissions from existing marine diesel engines, particularly for inland and coastal vessels operating in developing countries.

Keywords: marine diesel engine, exhaust gas recirculation, diesel particulate filter, emission reduction, retrofit emission control system.

INTRODUCTION

Maritime transportation plays a vital role in the global economy, accounting for approximately 80–90% of international trade by volume and supporting economic activities in both developed and developing countries (UNCTAD, 2023; Caban et al., 2017). However, marine diesel engines are also recognized as major contributors to atmospheric pollution, emitting significant amounts of nitrogen oxides (NOx), particulate matter (PM), sulfur oxides (SOx), carbon monoxide (CO), and greenhouse gases (GHGs) (Zimakowska-Laskowska et al., 2026). Among these pollutants, NOx and PM are of particular environmental concern because of their adverse effects on air quality, climate change, ecosystems, and human health (Šarkan et al., 2022; Kendra et al., 2023; Šarkan et al., 2025). Exposure to diesel exhaust emissions has been linked to respiratory diseases, cardiovascular disorders, premature mortality, and environmental degradation, especially in densely populated port cities and coastal regions (WHO, 2021; Corbett et al., 2007).

The shipping sector is a major source of anthropogenic air pollution worldwide. According to the International Maritime Organization (IMO), marine transportation contributes approximately 15% of global NOx emissions and a considerable proportion of PM emissions associated with fossil fuel combustion (IMO, 2020). Previous studies by James and Paul (1997) and Eyring et al. (2010)

demonstrated that emissions from international shipping significantly influence coastal air quality and regional atmospheric chemistry. The environmental impacts of marine emissions have become increasingly serious due to the rapid growth of global shipping activities and the continued operation of aging marine fleets in many developing countries. In response to these concerns, the IMO introduced stricter regulations under Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL), including the implementation of IMO Tier II and Tier III emission standards for marine engines, particularly within Emission Control Areas (ECAs) (IMO, 2017). These regulations have increased the demand for effective emission reduction technologies suitable for both newly manufactured and existing marine diesel engines.

Among diesel engine pollutants, NOx is primarily formed under high-temperature combustion conditions through the thermal oxidation of atmospheric nitrogen. PM emissions mainly consist of soot particles generated during incomplete combustion under fuel-rich conditions. Simultaneous reduction of NOx and PM emissions remains a major challenge because technologies that reduce NOx emissions often increase PM formation, while PM control strategies may adversely affect NOx reduction (Heywood, 2018; Hurtova et al., 2019; Kuranc et al., 2021). Consequently, the development of integrated emission control systems capable of reducing both pollutants simultaneously has become an important research priority in marine environmental engineering.

Several technologies have been developed to control diesel engine emissions, including selective catalytic reduction (SCR), exhaust gas recirculation (EGR), diesel oxidation catalysts (DOC), water injection systems, alternative fuels, and diesel particulate filters (DPF). Among these methods, EGR is widely considered one of the most effective approaches for NOx reduction in diesel engines (Rimkus et al., 2026). The EGR principle involves recirculating a portion of the exhaust gases back into the intake air stream, thereby reducing oxygen concentration and increasing the heat capacity of the intake mixture. This process lowers peak combustion temperatures and suppresses thermal NOx formation. Previous studies reported that EGR can reduce NOx emissions by approximately 5–50%, depending on engine type, operating conditions, and EGR rate (Zheng et al., 2004; Pandhare et al., 2011; Ladommatos et al., 2000). Arumugam et al. (2015) further demonstrated that optimized EGR operation can significantly improve NOx reduction while maintaining acceptable combustion stability in compression ignition engines.

Despite its effectiveness for NOx reduction, EGR often increases PM emissions because reduced oxygen concentration inside the combustion chamber promotes incomplete fuel oxidation and soot formation. Therefore, EGR alone cannot provide comprehensive emission control. To overcome this limitation, DPF systems have been widely applied for PM removal. Wall-flow DPF systems are capable of trapping and oxidizing soot particles with filtration efficiencies typically exceeding 80–95% under favorable operating conditions (Majewski and Khair, 2006; Johnson, 2009). Konstandopoulos et al. (2000, 2005) also demonstrated that ceramic wall-flow DPF systems can achieve highly efficient soot filtration under both steady-state and transient operating conditions. Consequently, the integration of EGR and DPF technologies represents a promising approach for simultaneous reduction of gaseous and particulate emissions from diesel engines.

In recent years, many studies have investigated combined EGR–DPF systems for automotive and heavy-duty diesel engines. Guan et al. (2017) reported that integrated EGR–DPF systems can effectively reduce both NOx and PM emissions while maintaining acceptable engine performance. Similarly, Merkisz et al. (2014) observed that the complementary interaction between EGR and DPF technologies significantly improves overall emission control efficiency in compression ignition engines. Beatrice et al. (2015) further demonstrated that combined EGR–DPF systems provide superior emission reduction performance compared with individual control technologies. Nevertheless, most existing studies have focused on automotive (Caban et al., 2024; Dittrich et al., 2023; Szpica et al., 2025), or land-based diesel engines (Gardyśnki et al., 2020; Lipskis et al., 2021; Matijosius et al., 2026), while investigations concerning retrofit applications for medium-speed marine diesel engines remain relatively limited.

This issue is particularly important in developing countries, where many inland and coastal vessels continue to operate using conventional diesel engines without advanced emission control systems. In many cases, replacing existing engines with modern low-emission technologies is economically impractical for small and medium-scale marine transport operators. As a result, there is a growing need for retrofit solutions that are technically simple, cost-effective, environmentally beneficial, and compatible with existing engines (Winebrake et al., 2009).

Vietnam has an extensive inland and coastal waterway transportation network in which marine diesel engines are widely used for cargo vessels, fishing boats, and passenger transport. Many of these engines have been operated for long periods and were manufactured before the implementation of modern emission standards. Consequently, emissions from marine diesel engines have become a significant environmental concern, particularly in urban waterways and coastal areas with high vessel density. Developing practical retrofit technologies suitable for existing marine diesel engines is essential to support environmentally sustainable maritime transportation and improve coastal environmental quality.

Despite the increasing number of studies on diesel engine emission control technologies, several important research gaps remain. Most previous studies have focused on automotive diesel engines or advanced electronically controlled heavy-duty engines operating under road transportation conditions. Comparatively limited attention has been given to retrofit applications for conventional medium-speed marine diesel engines commonly used in inland and coastal vessels in developing countries. Furthermore, many existing studies mainly emphasize emission reduction efficiency, while relatively few simultaneously evaluate NOx reduction, PM filtration performance, fuel consumption characteristics, operational stability, and practical retrofit feasibility under representative marine operating conditions.

Another important limitation is that many advanced emission control systems require complex electronic control technologies, expensive after-treatment devices, or substantial engine modifications, which may not be economically feasible for small and medium-scale marine transport operators. Therefore, there remains a strong need for simple, low-cost, and environmentally effective retrofit solutions that can be practically implemented on existing marine diesel fleets while maintaining acceptable engine performance and operational reliability.

Accordingly, the primary objective of this study is to experimentally evaluate the environmental and operational performance of a combined exhaust gas recirculation (EGR) and diesel particulate filter (DPF) retrofit system installed on a conventional Yanmar S185L-ST medium-speed marine diesel engine. The study specifically investigates the NOx reduction efficiency of the EGR system under varying engine speed and load conditions, evaluates the particulate matter (PM) filtration performance of the DPF unit, assesses the effects of the retrofit configuration on brake-specific fuel consumption (BSFC) and engine operational stability, and examines the overall feasibility of applying the proposed retrofit strategy in practical marine applications.

The present study proposes and experimentally investigates a combined EGR–DPF retrofit configuration specifically designed for conventional medium-speed marine diesel engines, with particular emphasis on simplicity, retrofit feasibility, low implementation cost, and stable operation under realistic marine conditions. The main contributions of this research are threefold. First, it provides experimental evidence regarding the simultaneous reduction of NOx and PM emissions using a practical and economically feasible retrofit configuration. Second, it demonstrates that substantial emission reductions can be achieved without significant deterioration in fuel consumption performance or engine stability. Third, the study contributes important technical and environmental insights for the development of sustainable emission mitigation strategies for existing marine diesel fleets, particularly in developing countries where aging vessels continue to dominate maritime transportation systems.

METHODS

Engine and test bench

The experiments were carried out on a Yanmar S185L-ST marine diesel engine, as shown in Figure 1. The engine is a medium-speed, four-stroke, six-cylinder in-line diesel engine equipped with a turbocharger. It has a rated power output of 442 kW at 900 rpm and is representative of propulsion engines commonly used in medium-sized inland and coastal vessels in Vietnam. The main technical specifications of the engine are summarized in Table 1.

The engine was connected to an ATE-705LC hydraulic dynamometer, which was used to apply and control engine load during the experiments.

Table 1. Main technical specifications of the Yanmar S185L-ST diesel engine

No.	Parameter	Value	Unit
1	Engine type	Medium-speed, four-stroke, turbocharged diesel engine	–
2	Cylinder bore	185	mm
3	Piston stroke	230	mm
4	Cylinder displacement	37.09	dm³
5	Compression ratio	13.6	–
6	Rated power	442	kW
7	Rated speed	900	rpm
8	Specific fuel consumption	272	g/kWh

Figure 1. Conventional Yanmar S185L-ST used in the experimental investigation

The dynamometer enables accurate measurement of engine torque, rotational speed, and brake power under different operating conditions. The performance characteristics of the dynamometer are presented in Figure 2.

All operating parameters, including engine speed, load, fuel consumption, exhaust temperature, and emission data, were continuously monitored and recorded using the integrated data acquisition system of the experimental test bench. Prior to testing, all measuring instruments were calibrated according to the manufacturer's recommendations to ensure measurement reliability and repeatability.

EGR–DPF retrofit system

The exhaust gas recirculation–diesel particulate filter (EGR–DPF) retrofit system was installed on the test engine according to the configuration shown in Figure 3. The system was designed to simultaneously reduce nitrogen oxides (NOx) and particulate matter (PM)

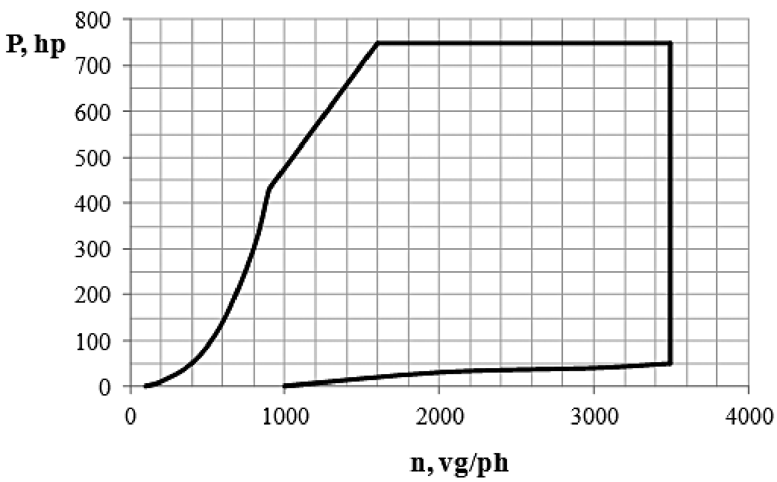

Figure 2. Performance characteristics of the ATE-705LC hydraulic dynamometer

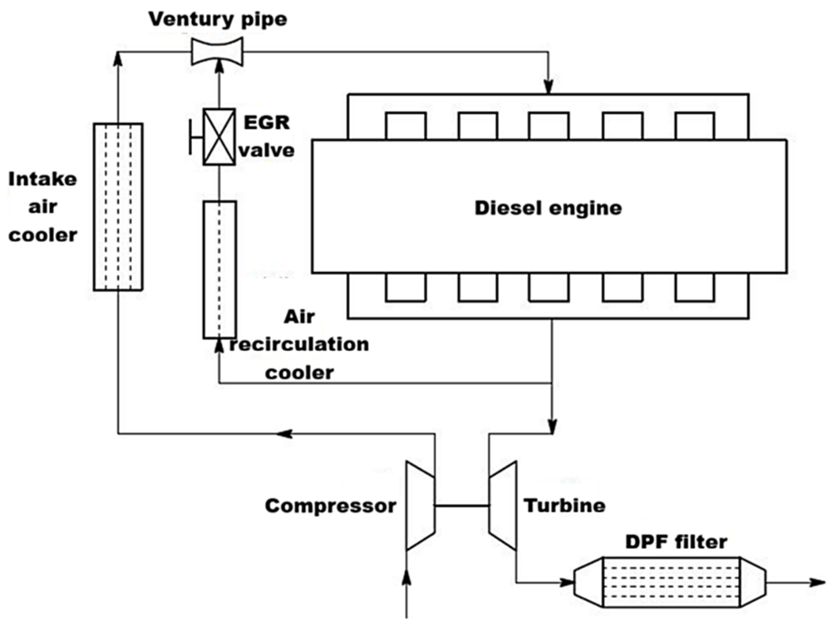

Figure 3. Schematic diagram of the EGR–DPF retrofit system

emissions while maintaining acceptable engine performance.

In this configuration, a portion of the exhaust gas was extracted upstream of the turbine using a high-pressure EGR arrangement. The recirculated exhaust gas passed through an EGR cooler to reduce gas temperature before entering the intake system. The EGR flow rate was regulated using an EGR control valve and mixed with the intake air through a venturi mixer installed in the intake line. Meanwhile, the exhaust gas downstream of the turbine was directed through a wall-flow diesel particulate filter (DPF) for PM removal before being discharged into the atmosphere.

The retrofit configuration was developed based on previous studies on EGR–DPF integration and diesel emission control systems, whereas the detailed design principles and preliminary calculations were adapted from earlier investigations on high-pressure EGR configurations and diesel after-treatment systems (Zheng et al., 2004; Konstandopoulos et al., 2005). Based on previous experimental studies, the EGR rate was maintained below 25% to achieve a compromise between NOx reduction and PM formation while minimizing adverse effects on engine performance and combustion stability (Pandhare et al., 2011).

The selection of the EGR pipe diameter was initially determined through theoretical calculations and subsequently optimized using simulation results. A pipe diameter of 60 mm was finally selected to ensure adequate recirculated gas flow under different operating conditions.

The DPF employed in this study was a regenerative wall-flow filter installed in the exhaust line downstream of the turbine. The main geometric parameters of the DPF are presented in Table 2.

The overall EGR–DPF configuration was developed as a practical retrofit solution for marine diesel engines operated by small and medium-scale transport operators, where cost effectiveness and ease of installation are important considerations.

Table 2. Main geometric parameters of the DPF used for the Yanmar S185L-ST diesel engine

No.	Description	Symbol	Value	Unit
1	Filter core length	LDPF	310	mm
2	Filter core diameter	DDPF	299	mm
3	Filter core volume	VDPF	2.23	L
4	Total filter length	L	540	mm
5	Cell density	nDPF	25	cells/cm²

Test conditions

The experiments were performed under operating conditions representative of practical marine engine operation. Marine diesel engines commonly operate at relatively high load conditions, typically in the range of 85–90% of rated power during normal service. However, in order to comprehensively evaluate the influence of the EGR–DPF retrofit system on engine performance and emissions, the experiments were conducted over a wide operating range from 25% to 100% of rated power.

The engine load was varied along the propeller characteristic curve with load increments of 25%. Accordingly, the test conditions included 25%, 50%, 75%, and 100% of the rated engine load. In addition, the 85% load condition was specifically investigated because it represents a typical operating point for marine propulsion engines in practical applications.

At each load condition, the EGR valve opening was adjusted from 0% to 100% with increments of 20% to evaluate the effects of EGR operation on NOx emissions, PM emissions, fuel consumption, and overall engine performance. The investigated parameters included engine brake power, brake specific fuel consumption, exhaust gas temperature, NOx concentration, and PM emissions.

Commercial diesel oil (DO) commonly used for inland marine vessels in Vietnam was used throughout the experiments. The fuel had a density of approximately 0.82–0.86 g/cm³, a cetane number above 46, and sulfur content complying with Vietnamese regulations for inland marine fuel. Exhaust emissions were measured using a Testo 350 exhaust gas analyzer, which simultaneously measured NOx, CO, CO_2, HC, and O_2 concentrations.

Before data acquisition, the engine was operated for a sufficient stabilization period to ensure steady-state conditions. Measurements were repeated under identical operating conditions to improve data reliability, and the average values were used for subsequent analysis.

The uncertainty of the measured parameters was estimated based on instrument calibration data and manufacturer specifications. The uncertainties associated with NOx concentration, PM emissions, fuel consumption, and engine operating parameters remained within acceptable limits for laboratory-scale engine experiments.

RESULTS

NOx emission reduction

The experimental results presented in Figure 4 show that the EGR–DPF system effectively reduced NOx emissions under all investigated operating conditions. Tests were performed at three representative engine speeds corresponding to 63%, 79%, and 91% of the rated speed along the propeller characteristic curve, with the EGR valve opening maintained at 40%. In all tested cases, the engine operating with EGR produced lower NOx emissions compared to the conventional operating mode without exhaust gas recirculation.

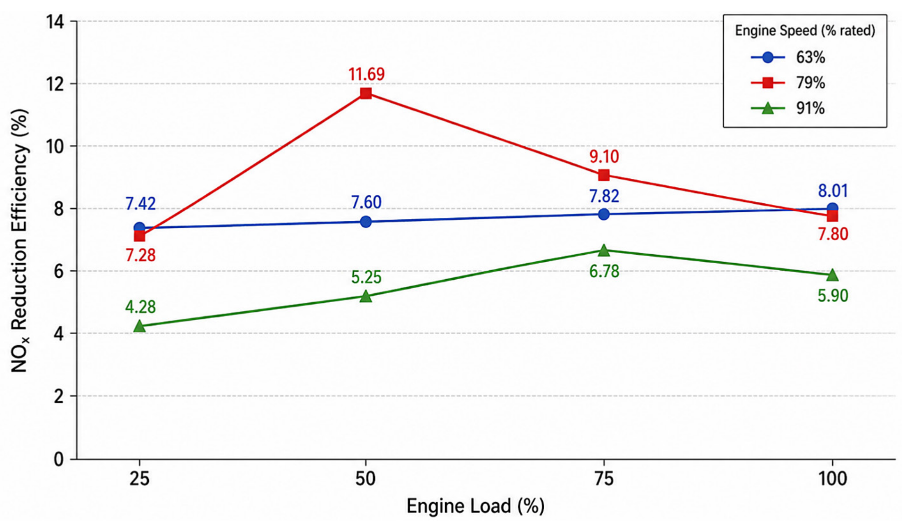

Figure 4. NOx reduction efficiency of the EGR–DPF system under different engine speed and engine load conditions

At 63% of the rated speed, the NOx reduction efficiency ranged from approximately 7.42% to 8.01% as the engine load increased from 25% to 100%. The relatively stable reduction efficiency indicates that the EGR system can operate effectively under medium–low speed conditions without large fluctuations in combustion behavior. Under these conditions, the recirculated exhaust gas dilutes the intake oxygen concentration and increases the specific heat capacity of the intake mixture, thereby reducing peak combustion temperature and suppressing thermal NOx formation.

At 79% of the rated speed, the reduction efficiency increased slightly, ranging from 7.28% to 11.69% depending on engine load. The highest reduction was observed at approximately 50% load, while lower reductions occurred at higher load conditions. This behavior can be explained by the interaction between combustion temperature, oxygen availability, and the EGR rate. At medium loads, the combustion process remains sufficiently stable while the reduced oxygen concentration effectively suppresses NOx generation. Similar trends have been reported by Heywood (2018), who noted that EGR is most effective under medium-load diesel engine operation due to favorable combustion temperature conditions.

At 91% of the rated speed, the NOx reduction decreased to approximately 4.28–6.78%. The lower reduction efficiency observed at high engine speed can be attributed to higher in-cylinder temperatures and shorter combustion durations, which reduce the influence of recirculated exhaust gases on the combustion process. Under high-load conditions, the increased fuel injection quantity and elevated combustion temperature promote thermal NOx formation despite the presence of EGR. Similar observations were reported by Ladommatos et al. (2000), who showed that the effectiveness of EGR decreases at high engine load because the combustion temperature remains sufficiently high to sustain NOx formation.

Generally, the results confirm that the EGR system provides a moderate but stable reduction in NOx emissions under representative marine engine operating conditions. Although the NOx reduction obtained in this study is lower than the values reported for some modern electronically controlled diesel engines, the achieved reductions remain significant for a retrofit system applied to a conventional medium-speed marine engine. Previous studies have reported NOx reductions ranging from 5% to 20% depending on engine type, EGR configuration, and operating conditions (Pandhare et al., 2011; Zheng et al., 2004).

The results also indicate that the selected EGR rate below 25% provides a reasonable compromise between NOx reduction and combustion stability. Excessive EGR rates may further reduce NOx emissions but can lead to incomplete combustion, increased smoke formation, and deterioration in engine efficiency. Therefore, the selected operating range is considered suitable for practical retrofit applications in marine diesel engines.

PM emission characteristics

The experimental results presented in Figure 5 indicate that the application of EGR increases particulate matter (PM) emissions upstream of

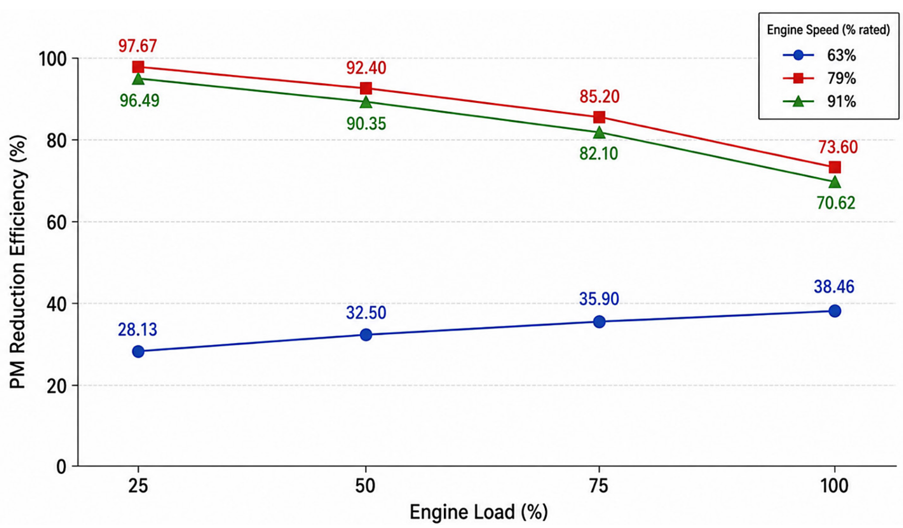

Figure 5. PM reduction efficiency of the EGR–DPF system under different engine speed and engine load conditions

the filter because the recirculated exhaust gases reduce the oxygen concentration inside the combustion chamber. Lower oxygen availability suppresses complete fuel oxidation and promotes soot formation during combustion. However, the diesel particulate filter (DPF) demonstrated a strong capability to remove PM emissions across all tested operating conditions.

At 63% of the rated speed, the PM reduction efficiency of the DPF ranged from 28.13% to 38.46% depending on engine load. Although the filtration efficiency at low speed was relatively moderate, the DPF still maintained stable operation under low and medium load conditions. The lower filtration efficiency observed at this operating range may be related to reduced exhaust gas temperature and lower exhaust flow velocity, which can limit soot oxidation and filtration performance.

At 79% of the rated speed, the PM reduction efficiency increased significantly, ranging from 73.60% to 97.67%. The highest filtration efficiency was achieved under low and medium load conditions. The improved performance at this speed is mainly associated with higher exhaust gas temperatures and increased exhaust flow rates, which enhance particle trapping and regeneration processes inside the DPF. Similar results were reported by Johnson (2009), who showed that wall-flow DPF systems can achieve PM removal efficiencies above 90% under favorable exhaust temperature conditions.

At 91% of the rated speed, the DPF continued to maintain high PM reduction efficiency, ranging from 70.62% to 96.49% over the investigated load range. Although a slight decrease in efficiency was observed at higher loads, the filtration performance remained highly effective even under high-speed engine operation. The minor decrease at full load may be caused by increased exhaust flow rates and higher soot loading inside the filter, which can temporarily reduce filtration efficiency.

In general, the combined EGR–DPF configuration successfully enabled simultaneous control of NOx and PM emissions. While EGR alone tends to increase PM formation due to oxygen dilution, the DPF effectively compensates for this drawback by removing most of the generated soot particles before exhaust release. This complementary behavior between EGR and DPF has also been reported in previous diesel engine studies (Merkisz et al., 2014; Guan et al., 2015).

The PM reduction efficiencies obtained in this study are consistent with earlier investigations on wall-flow DPF systems, where filtration efficiencies commonly exceed 80–95% under steady-state operating conditions (Majewski and Khair, 2006). The results confirm the suitability of the proposed retrofit system for practical emission control in medium-size marine diesel engines.

Impact on engine performance

In addition to emission characteristics, the influence of the EGR–DPF system on engine performance was evaluated through brake-specific fuel consumption (BSFC) and overall engine operating stability. The experimental results presented in Figure 6 indicate that the engine maintained stable operation over the entire range of investigated conditions after installation of the EGR–DPF system. The BSFC values varied with engine speed and engine load, reflecting

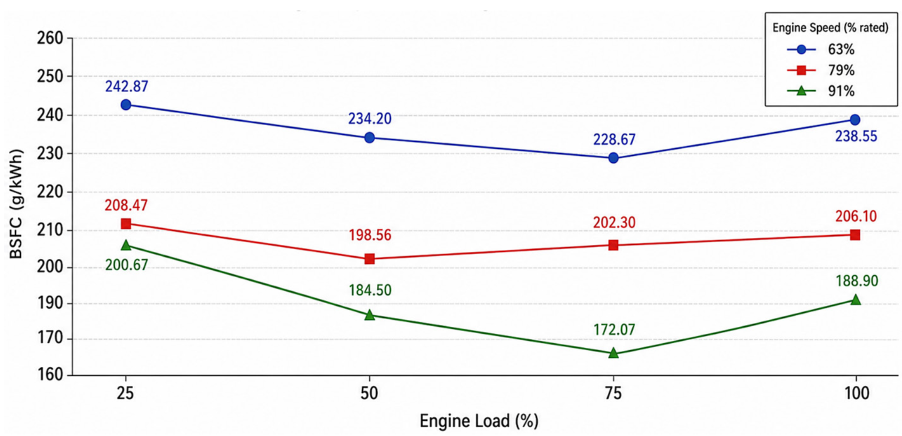

Figure 6. Brake-specific fuel consumption (BSFC) under different engine speed and engine load conditions

changes in combustion efficiency and fuel utilization under different operating regimes.

At 63% of the rated speed, the BSFC ranged from 228.67 to 242.87 g/kWh as engine load increased from 25% to 100%. The minimum fuel consumption was observed at approximately 75% load, indicating that the engine achieved its highest combustion efficiency under medium-load conditions. Slightly higher BSFC values at low loads may be associated with incomplete combustion and increased heat losses, whereas the increase at full load may result from richer fuel operation and elevated thermal losses.

At 79% of the rated speed, the BSFC ranged from 198.56 to 208.47 g/kWh, with the minimum value observed at 50% load. This result suggests that the engine operates most efficiently in the medium-load region where combustion conditions are relatively stable and turbocharger performance is favorable.

At 91% of the rated speed, the BSFC ranged from 172.07 to 200.67 g/kWh. The lowest value occurred at approximately 75% load, indicating improved thermal efficiency under high-speed medium-load operation. The reduction in BSFC at higher engine speeds is mainly associated with improved air–fuel mixing and enhanced turbocharging efficiency.

On the whole, the results indicate that the EGR–DPF retrofit system does not significantly deteriorate engine performance. The observed BSFC values remain within the normal operating range for medium-speed marine diesel engines. These findings are consistent with previous studies showing that moderate EGR application generally causes only a slight increase in fuel consumption when the EGR rate is maintained below critical levels (Zheng et al., 2004; Pandhare et al., 2011).

The stable engine operation observed in this study demonstrates that the proposed retrofit system can achieve emission reduction without causing severe penalties in fuel economy or engine reliability. This is an important consideration for marine transport operators, where fuel cost and operational stability are critical factors.

DISCUSSION

The present study demonstrates that the combined EGR–DPF retrofit system can effectively reduce both NOx and PM emissions from a conventional medium-speed marine diesel engine while maintaining stable engine operation and acceptable fuel consumption characteristics. The results indicate that the interaction between engine speed, engine load, exhaust gas temperature, and EGR rate strongly influences the overall emission reduction performance of the system. From an environmental perspective, the reduction of NOx and PM emissions is highly important because these pollutants contribute significantly to air pollution, acid rain, photochemical smog, and adverse human health impacts in coastal and port areas. Marine diesel engines remain one of the major sources of NOx and PM emissions in coastal and port areas, and integrated in-cylinder and after-treatment technologies have become increasingly important for meeting stringent IMO emission regulations (Ni et al., 2020; Yongming et al., 2024). Therefore, improving emission control performance through retrofit technologies can provide direct environmental benefits for marine ecosystems and urban coastal environments.

The NOx reduction results confirmed that the EGR system was more effective under medium-speed and medium-load operating conditions. The highest NOx reduction efficiency of 11.69% was achieved at 79% rated speed and 50% engine load. Under these conditions, combustion temperatures remained sufficiently high for stable combustion but low enough for the EGR system to suppress thermal NOx formation effectively. In contrast, lower reduction efficiencies were observed at high engine speed and high load because combustion temperatures increased significantly, reducing the influence of recirculated exhaust gases on the combustion process. Similar trends have also been reported in recent marine engine studies, where EGR exhibits higher NOx reduction efficiency under medium-load operation, whereas its effectiveness decreases at high engine load because of elevated combustion temperatures (Abdelhameed and Tashima, 2023; Yongming et al., 2024). Environmentally, the observed NOx reduction is important because NOx emissions are key precursors of ozone formation and secondary particulate pollution, both of which negatively affect air quality and public health in densely populated port cities.

Although the NOx reduction efficiencies obtained in this study were lower than those reported for advanced electronically controlled marine engines, the results remain practically significant because the retrofit system was installed on a conventional medium-speed diesel engine without major engine modification. This finding is especially important for developing countries and small marine transport operators, where replacing old engines with modern low-emission systems is often economically difficult (Ni et al., 2020). The proposed retrofit approach provides a practical and environmentally beneficial alternative for improving emission performance while minimizing investment cost and engine downtime. The adoption of retrofit systems on existing marine fleets could contribute to gradual emission reduction at regional and national scales without requiring immediate fleet replacement.

The PM emission results further highlight the complementary relationship between EGR and DPF technologies. The application of EGR alone tends to increase soot formation because oxygen dilution suppresses complete fuel combustion. However, the DPF successfully compensated for this drawback by removing a large proportion of PM emissions before exhaust release. The highest PM reduction efficiencies exceeded 90% under medium and high engine speed conditions, confirming the strong filtration capability of the wall-flow DPF system. These results are consistent with previous investigations reporting PM removal efficiencies of 80–95% under stable diesel engine operation (Johnson, 2009; Ni et al., 2020). From an environmental and health perspective, this result is highly significant because fine particulate matter emitted from marine diesel engines is strongly associated with respiratory diseases, cardiovascular disorders, and visibility reduction in urban coastal regions.

The lower PM reduction efficiency observed at 63% rated speed can mainly be attributed to lower exhaust gas temperatures and reduced exhaust flow velocity. Under these conditions, passive regeneration inside the DPF becomes less effective because soot oxidation reactions occur more slowly. This finding has important practical implications for marine engines operating for long periods under low-load conditions, such as harbor maneuvering or inland waterway transport. In such applications, additional regeneration strategies, including active regeneration or periodic high-load operation, may be required to maintain stable long-term DPF performance. Effective regeneration management is essential not only for maintaining engine efficiency but also for preventing excessive soot accumulation and secondary pollution risks.

The BSFC results indicate that the retrofit system did not significantly deteriorate engine performance. Fuel consumption remained within the normal operating range for medium-speed marine diesel engines, and the engine maintained stable operation throughout the experiments. The lowest BSFC values were generally observed under medium-load conditions, where combustion efficiency and turbocharger performance were most favorable. Although EGR can slightly increase fuel consumption because of reduced oxygen concentration and slower combustion, the increase remained limited because the EGR rate was maintained below 25%. Similar observations were reported by Ni et al. (2020), who concluded that moderate EGR application can reduce NOx emissions without causing severe penalties in engine efficiency. This balance between emission reduction and fuel economy is environmentally important because excessive fuel consumption can indirectly increase greenhouse gas emissions and operating costs.

From a practical implementation perspective, the proposed EGR–DPF retrofit system offers several advantages for medium-size marine vessels currently operating with conventional diesel engines. Recent studies have also highlighted that integrating EGR with complementary technologies offers a practical pathway for complying with increasingly stringent IMO emission requirements while maintaining engine efficiency (Yongming et al., 2024). First, the retrofit configuration can help ship operators comply with increasingly strict emission regulations, including the International Maritime Organization (IMO) Tier II and partial Tier III emission requirements in specific operating regions. Second, the system can be installed without complete engine replacement, thereby reducing retrofit cost and minimizing operational interruption. Third, the stable BSFC results suggest that the system can be applied without causing major increases in fuel consumption, which is a critical consideration for commercial marine transport. In environmental terms, widespread adoption of retrofit technologies could substantially reduce pollutant emissions from aging marine fleets, particularly in developing countries where older diesel engines remain dominant.

However, practical implementation also requires attention to several operational factors. Continuous EGR operation may increase soot deposition and corrosion inside the intake system if exhaust gas cleaning is not properly maintained. Similarly, long-term DPF operation requires periodic monitoring of soot loading and regeneration efficiency to avoid excessive back-pressure, which may negatively affect engine durability and fuel economy. Therefore, regular maintenance schedules and monitoring systems should be integrated into practical marine applications. Environmental monitoring programs may also be necessary to evaluate long-term reductions in atmospheric pollutant concentrations near ports and shipping corridors after retrofit implementation.

The results of this study suggest that the most suitable operating condition for the proposed retrofit system occurs under medium engine load and medium engine speed, where NOx reduction, PM filtration, and fuel efficiency achieve a favorable balance. These operating conditions are representative of many practical marine transport activities, including inland cargo transport and coastal navigation. Consequently, the proposed retrofit system has strong potential for real-world implementation in existing marine fleets, particularly in regions where older diesel engines continue to dominate commercial vessel operation. The environmental benefits of such implementation may include improved coastal air quality, reduced human exposure to harmful pollutants, and support for sustainable marine transportation development.

Despite the promising results, several limitations should be acknowledged. The experiments were conducted under steady-state operating conditions and at a fixed EGR valve opening of 40%. In real marine operation, engine load and speed frequently fluctuate, which may influence emission behavior and DPF regeneration performance. Future studies should investigate transient operating conditions, long-term durability, sulfur fuel effects, and optimization of adaptive EGR control strategies for marine diesel engines. In addition, economic analysis and life cycle assessment would provide valuable information regarding the cost-effectiveness and environmental benefits of large-scale retrofit implementation.

CONCLUSIONS

This study evaluated the environmental and operational performance of a combined EGR–DPF retrofit system installed on a Yanmar S185L-ST medium-speed marine diesel engine under representative marine operating conditions. The results showed that the proposed system can reduce both NOx and PM emissions while maintaining stable engine operation and acceptable fuel consumption.

The EGR system reduced NOx emissions under all tested operating conditions. The highest NOx reduction efficiency was 11.69% at 79% rated speed and 50% engine load, while the overall reduction ranged from 4.28% to 11.69%. The best performance was achieved at medium engine speed and medium load, where combustion conditions were most suitable for EGR operation. Although the NOx reduction was lower than that reported for some modern electronically controlled engines, it is still significant for a simple retrofit system applied to a conventional marine diesel engine.

The DPF system showed excellent PM filtration performance, especially at medium and high engine speeds. PM reduction efficiencies ranged from 28.13% to 97.67%, with values above 90% under several operating conditions. The DPF effectively removed the additional soot produced by the EGR system. The lower PM reduction efficiency at low engine speed was mainly caused by lower exhaust temperatures, which reduced passive regeneration inside the filter. Generally, the combined EGR–DPF system effectively controlled both gaseous and particulate emissions.

Engine performance was only slightly affected by the retrofit system. Brake-specific fuel consumption (BSFC) remained within the normal range for medium-speed marine diesel engines, and the engine operated steadily throughout the tests. The results indicate that keeping the EGR rate below 25% provides a good balance between emission reduction, fuel economy, and engine stability. Therefore, the system can improve environmental performance while maintaining engine reliability without causing significant losses in engine efficiency or reliability.

From a practical point of view, the proposed retrofit system is suitable for existing marine vessels, especially in developing countries where many aging diesel engines are still in service. The system is simple, relatively low in cost, and can be installed without replacing the original engine. Large-scale application of this retrofit technology could help improve air quality in coastal areas, reduce harmful emissions, and support more sustainable marine transportation.

REFERENCES

1. Abdelhameed, E., & Tashima, H. (2023). EGR and Emulsified Fuel Combination Effects on the Combustion, Performance, and NOx Emissions in Marine Diesel Engines. *Energies*, 16(1), 336. https://doi.org/10.3390/en16010336.
2. Arumugam, K. & Senthilkumaar, J. & K., Umanath & Praveen, M.. (2015). Performance Combustion and Emission Characteristics of DI Diesel Engine with Use of Alternate Mechanism. *Applied Mechanics and Materials*. 766-767. 1153-1158. 10.4028/www.scientific.net/AMM.766-767.1153.
3. Beatrice, Carlo & Konstandopoulos, Athanasios & Kostoglou, Margaritis & Di Blasio, Gabriele & Imren, Abdurrahman & Denbratt, Ingemar. (2015). Impact of Combination of EGR, SCR, and DPF Technologies for the Low-Emission Rail Diesel Engines. *Emission Control Science and Technology*. 1. 213-225. https://doi.org/10.1007/s40825-015-0020-0.
4. Caban, J., Brumerčík, F., Vrabel, J., Ignaciuk, P., Misztal, W., Marczuk, A. (2017). Safety of maritime transport in the Baltic Sea. MATEC Web of Conferences, 18th International Scientific Conference - LOGI 2017, 134, 00003. https://doi.org/10.1051/matecconf/201713400003.
5. Caban, J.; Seńko, J.; Ignaciuk, P. (2024). Laboratory Tests of Electrical Parameters of the Start-Up Process of Single-Cylinder Diesel Engines. *Energies*, 17, 2155. https://doi.org/10.3390/en17092155.
6. Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V. and Lauer, A. (2007) Mortality from Ship Emissions: A Global Assessment. *Environmental Science & Technology*, 41, 8512-8518. http://dx.doi.org/10.1021/es071686z.
7. Dittrich, A., Procházka, R., Popelka, J., Dong, N. (2023). Effect of HVO CNG dual-fuel operation mode on emissions and performance of CI engine. *Engineering for Rural Development*, 22, pp. 58–63.
8. Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, O., Grainger, R.G., Moldanova, J., Schlager, H. and Stevenson, D.S. (2010) Transport Impacts on Atmosphere and Climate: Shipping. *Atmospheric Environment*, 44, 4735-4771. http://dx.doi.org/10.1016/j.atmosenv.2009.04.059.
9. Gardyński, L., Kałdonek, J., Caban, J. (2020). Testing of Lubricating Properties of Mixtures of Diesel And RME Biofuels with the Addition of Linoleic Acid. *The Archives of Automotive Engineering – Archiwum Motoryzacji*, 87(1), 57-66. https://doi.org/10.14669/AM.VOL87.ART5.
10. Guan, W., Pedrozo, V., Zhao, H., Ban, Z., and Lin, T.. (2017). Investigation of EGR and Miller Cycle for NOx Emissions and Exhaust Temperature Control of a Heavy-Duty Diesel Engine. *SAE Tech. Pap*. https://doi.org/10.4271/2017-01-2227.
11. Heywood, J.B. (2018) Internal Combustion Engine Fundamentals. McGraw-Hill Education.
12. Hurtová, I., Sejkorová, M., Verner, J. (2019). A study of diesel particulate filter impact on engine oil quality. 23rd International Scientific Conference on Transport Means, 2-4 Oct. 2019, Palanga, Lithuania, Transport Means - Proceedings of the International Conference, 2019, pp. 691–695.
13. International Maritime Organization (IMO). (2017). MARPOL Annex VI and NTC 2008 with Guidelines for Implementation. London: IMO. https://wwwcdn.imo.org/localresources/en/publications/Documents/Supplements/English/QQC664E_092020.pdf.
14. International Maritime Organization (IMO). (2020). Fourth IMO Greenhouse Gas Study 2020. London: IMO. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf.
15. James J. Corbett and Paul Fischbeck. 1997. Emissions from Ships. *Science* 278, 823-824. https://doi.org/10.1126/science.278.5339.823.
16. Johnson, Timothy. (2008). Diesel emission control in review. *SAE International Journal of Fuels and Lubricants*. 1. 68-81. https://doi.org/10.4271/2008-01-0069.
17. Johnson, Timothy. (2009). Review of Diesel Emissions and Control. *International Journal of Engine Research*. 10. 275-285. https://doi.org/10.1243/14680874JER04009.
18. Kendra, M., Skrúcaný, T., Dolinayová, A., Čamaj, J., Jurkovič, M., Csonka, B., Abramović, B. (2023). Environmental burden of different transport modes– Real case study in Slovakia. *Transportation Research Part D: Transport and Environment*. 114, 103552. https://doi.org/10.1016/j.trd.2022.103552.
19. Konstandopoulos, A.G., Kostoglou, M., Vlachos, N., and Kladopoulou, E. (2005). *Progress in Diesel Particulate Filter Simulation*. SAE Tech. Pap. https://doi.org/10.4271/2005-01-0946.
20. Konstandopoulos, Athanasios & Kostoglou, Margaritis & Skaperdas, Vangelis & Papaioannou, Eleni & Zarvalis, Dimitrios & Kladopoulou, Evdoxia. (2000). Fundamental Studies of Diesel Particulate Filters: Transient Loading, Regeneration and Aging. SAE 2000 World Congress. https://doi.org/10.4271/2000-01-1016.

21. Kuranc A., Caban, J., Šarkan, B., Dudziak, A., Stoma, M. (2021). Emission of selected exhaust gas components and fuel consumption in different driving cycles. *Communications - Scientific Letters of the University of Žilina*, 2021, 23, 4, B265-B277. https://doi.org/10.26552/com.C.2021.4.B265-B277.
22. Lipskis, I.; Pukalskas, S.; Droździel, P.; Barta, D.; Žuraulis, V.; Pečeliūnas, R. (2021). Modelling and Simulation of the Performance and Combustion Characteristics of a Locomotive Diesel Engine Operating on a Diesel–LNG Mixture. *Energies*, 14, 5318. https://doi.org/10.3390/en14175318.
23. Matijošius, J.; Rimkus, A.; Gruodis, A.; Chiavola, O.; Recco, E. (2026). Simulation of Diesel Engine Properties Using Different Mixtures of Fuels by Means of a Feed-Forward Neural Network: 1. Validation and Prediction of Energetical Parameters. *Energies*, 19, 888. https://doi.org/10.3390/en19040888.
24. Merkisz, J., Pielecha, J., Radzimirski, S. (2014). Production and in-service conformity. In: New Trends in Emission Control in the European Union. Springer Tracts on Transportation and Traffic, vol 4. Springer, Cham. https://doi.org/10.1007/978-3-319-02705-0_5.
25. Ni, Peiyong & Wang, Xiangli & Li, Hu. (2020). A review on regulations, current status, effects and reduction strategies of emissions for marine diesel engines. *Fuel*. 279. 118477. https://doi.org/10.1016/j.fuel.2020.118477.
26. Pandhare, Amar & Zende, Kiran & Joglekar, A. & Bhave, S. & Padalkar, Atul. (2011). Effect of EGR on the exhaust gas temperature and exhaust opacity in compression ignition engines using jatropha oil as fuel. *Applied Mechanics and Materials*. 110-116. 431-436. https://doi.org/10.4028/www.scientific.net/AMM.110-116.431.
27. Rimkus, A., Žaglinskis, J., Pukalskas, S. (2026). Effects of hydrotreated vegetable oil and diesel blends on combustion, energy performance, and emissions of a compression ignition engine under EGR-controlled operation. *Journal of Marine Science and Engineering*, 14(7), 665.
28. Šarkan, B., Kuranc, A., Sejkorova, M., Caban, J., Loman, M. (2022). Comparison of the exhaust emissions of heavy-duty vehicle engines powered by diesel fuel (DF) and natural gas (LNG) in real operation conditions. *Przemysł Chemiczny,* 101(1), 37-41. https://doi.org/10.15199/62.2022.1.2.
29. Šarkan, B., Loman, M., Stopka, O., Caban, J., Małek, A. (2025). Quantifying the volume of particulate matter at bus stations. *Promet – Traffic & Transportation*, 2025, 37(1), 19–35. https://doi.org/10.7307/ptt.v37i1.675.
30. Szpica, D.; Borawski, A.; Mieczkowski, G.; Kuszewski, H.; Jaworski, A.; Hunicz, J. (2025). Comparative evaluation of performance parameters of conventional and waste fuels for diesel engines towards sustainable transport. *Energies*, 18, 5081. https://doi.org/10.3390/en18195081.
31. UNCTAD (2023). Review of Maritime Transport 2023. United Nations Conference on Trade and Development. https://unctad.org.
32. Winebrake, James & Corbett, James & Green, E.H. & Lauer, Axel & Eyring, Veronika. (2009). Mitigating the health impacts of pollution from ocean-going shipping: an assessment of low-sulfur fuel mandates. *Environmental Science & |Technology*. 43. 4776-82. https://doi.org/10.1021/es803224q.
33. World Health Organization (2021). WHO global air quality guidelines. particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. Executive Summary.
34. Yongming Feng, Zhiqiang Du, Jinbo Qu, Yuanqing Zhu, Shuaichao Zheng. (2024). Optimization and 4E analysis of integration of waste heat recovery and exhaust gas recirculation for a marine diesel engine to reduce NOx emissions and improve efficiency. *Journal of Cleaner Production*. 461, 142611, https://doi.org/10.1016/j.jclepro.2024.142611.
35. Zimakowska-Laskowska, M., Bogdanowicz, A., Kniaziewicz, T. (2026). Assessment of exhaust gas concentration uniformity in a marine engine duct based on dual-point sampling and CFD modelling. *Combustion Engines*, 205(2), 3–16. https://doi.org/10.19206/CE-208912.