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COMPARISON OF EXISTING METHODS FOR PURIFYING GASES FROM SHIP PROPULSION ENGINES

D. Uspenskis*, P. Bronowski, A. Semeniscevs

Ltd. WTM Solutions
25-62 Aviacijas Str., Riga, LV-1057, LATVIA
*e-mail: du070984@gmail.com

This study presents a comprehensive review of current technologies used to reduce exhaust gas emissions from ship propulsion systems in maritime transport. It compares the operational principles, environmental impacts, and economic feasibility of each method. The analysis highlights the advantages and limitations of established and emerging solutions, with particular attention to their effectiveness in pollutant removal and waste generation. The findings underscore the urgent need for integrated and sustainable emission control technologies, and identify hydrogen-based propulsion and microwave technology or electrochemical systems as promising directions for future development.

Keywords: *Carbon reduction, environmental technology, gas purification, maritime pollution, ship emissions.*

1. INTRODUCTION

As of 2024, the global shipping industry accounts for approximately 3 % of total carbon dioxide (CO_2) emissions [1]. This environmental footprint has intensified calls for decarbonising maritime transport, which remains a cornerstone of international trade.

Achieving substantial emissions reductions in the sector requires modernising ship propulsion technologies to comply with tightening international regulations while maintaining operational and economic viability. A successful transition would position maritime transport as a cleaner and more competitive mode of freight movement [2].

Ongoing efforts focus on implementing technologies that either reduce or eliminate emissions of pollutants generated by the combustion of fossil fuels. Primary targets include sulphur dioxide (SO_2), CO_2, carbon monoxide (CO), nitrogen oxides (NO_x), and particulate matter [2]–[4]. These pollutants contribute not only to climate change, but also to acidification, respiratory diseases, and degradation of marine ecosystems.

This paper reviews both existing and emerging methods of exhaust gas purification in the shipping sector, evaluating their technical mechanisms, efficiency, environmental trade-offs, and readiness for large-scale deployment.

2. PRESENT METHODS FOR REDUCING GAS EMISSIONS FROM SHIP PROPULSION ENGINES

2.1. Exhaust Gas Cleaning Systems

Exhaust Gas Cleaning Systems (EGCSs), commonly referred to as scrubbers, are onboard devices used to reduce air pollutants, in particular sulphur oxides (SOx), from marine engine exhaust. These systems allow ships to meet increasingly stringent emissions regulations without switching to low-sulphur fuels. EGCSs primarily rely on water-based processes to "wash" pollutants from the exhaust stream [5].

There are three main types of industrial scrubbers: wet, dry, and semi-dry, each employing distinct mechanisms to remove pollutants [6], [7].

Dry scrubbers use dry sorbents, typically calcium hydroxide or calcium carbonate, to react with gaseous pollutants. These reactions produce solid by-products that are collected and removed as dry residue.

Wet scrubbers utilise liquid oxidizers, such as sodium hydroxide (NaOH), ammonium hydroxide (NH_4OH), potassium hydroxide (KOH), or magnesium hydroxide ($Mg(OH)_2$), to neutralize and absorb exhaust gases, particularly SO_2. Variants include:

- open-loop systems, which use untreated seawater and discharge the treated effluent directly into the sea;
- closed-loop systems, which employ freshwater mixed with chemical additives in a recirculating process, minimising discharge;
- hybrid systems, which can alternate between open- and closed-loop modes depending on environmental conditions and local regulations [8].

Hybrid scrubbers are equipped with GPS-based automation that enables real-time switching between operating modes to ensure compliance with maritime emission regulations and to optimise operational efficiency. Open-loop operation is generally allowed in open waters, while closed-loop systems are required in restricted areas, such as Emission Control Areas (ECAs).

Semi-dry scrubbers, also known as spray dryer absorbers, combine elements of both dry and wet scrubbing. They spray a lime-water slurry into the exhaust stream. As the water evaporates, the pollutants react with lime, forming a dry residue that is captured in a dust collector.

In achieving the main goal of reducing sulphur pollution in the air, scrubbers show excellent efficiency of up to 80–95 %. However, in the cleaning process they absorb harmful gaseous pollutants and dust, which leads to the formation of significant volumes of hazardous solid waste and wastewater. Although some of this waste undergoes further treatment, it is often released into the marine environment. Studies indicate that these discharges contribute to ecological degradation, including lowered pH levels, increased turbidity, and the introduction of persistent pollutants such as heavy metals, soot, and organic compounds. These substances can accumulate in seawater, posing long-term environmental risks [5], [9].

2.2. Selective Catalytic Reduction (SCR) for NO_x Control

A NOx reduction controller, most implemented as a Selective Catalytic Reduction (SCR) system, is a widely used technology on marine vessels to reduce NO_x emissions. It involves injecting a urea-based solution into the exhaust stream, which thermally decomposes to form ammonia. The ammonia then reacts with NO_x over a catalyst, typically vanadium-titanium based, converting it into nitrogen (N_2) and water vapour.

SCR systems can achieve NO_x reduction efficiencies of up to 99 % [10]–[12]. However, their implementation requires a dedicated onboard infrastructure for urea storage, injection, and temperature management, which adds to vessel complexity and operating costs.

While SCR is highly effective for NO_x removal, it does not address other harmful pollutants in marine exhaust, such as CO_2, sulphur oxides (SO_x), CO, volatile organic compounds (VOCs), or heavy metals. Thus, its environmental benefit is limited to NO_x abatement alone. Over time, the catalyst deactivates and must be replaced. Spent SCR catalysts, due to their content of vanadium and other heavy metals, are typically classified as hazardous waste and require specialised, often costly, disposal or recycling processes [13], [14].

2.3. Onboard Carbon Capture and Storage

Onboard Carbon Capture and Storage (OCCS) refers to the process of capturing CO_2 emissions from ship engines and storing them onboard for subsequent offloading, utilisation, or permanent sequestration. Typically, this is achieved through post-combustion capture technologies, which extract CO_2 from exhaust gases and compress it into liquid form for storage [15], [16].

While OCCS has the potential to reduce greenhouse gas emissions, it presents several important limitations. The system is designed to capture only CO_2 and does not address other pollutants such as SO_x, NO_x, CO, VOCs, or heavy metals.

CO_2 purity achieved during capture varies between 75 % and 95 %, depending on the technology used and engine configuration. High-purity CO_2 can be reused in industrial processes, such as food-grade applications or enhanced oil recovery. However, lower purity often necessitates long-term geological storage, which may offset the environmental benefits due to additional handling, energy use, and emissions [17].

OCCS is also energy-intensive. Capturing, compressing, and liquefying CO_2 requires significant energy input, which reduces the net emissions savings. In particular, the cooling process needed for liquefaction imposes substantial energy demands and engineering constraints aboard ships [18], [19].

Ultimately, OCCS does not eliminate emissions but rather transfers them from the atmosphere to another containment medium – liquefied industrial waste – raising concerns about long-term sustainability and practicality in maritime applications.

2.4. Calcium Looping Technology

Calcium Looping (CaL) is a gas capture technology being explored for application in marine propulsion systems. It operates by absorbing CO_2 and SO_2 from engine exhaust using calcium-based sorbents. Once absorbed, the captured gases can be stored or utilised in downstream processes [20], [21]. CaL systems have demonstrated capture efficiencies of approximately 80–90 % for both CO_2 and SO_2 under laboratory conditions [22].

Despite its promising performance, the technology is still in the testing phase and presents significant limitations. The process relies on chemical absorption, often involving calcium oxide (CaO), which reacts with CO_2 and SO_2 to form calcium carbonate and calcium sulphite/sulphate. This results in the production of large quantities of solid waste, typically in the form of chalk-like material.

However, this residue is not pure calcium carbonate; rather, it is contaminated with hydrocarbons, sulphur compounds, and heavy metals. As such, it is considered hazardous waste and unsuitable for reuse or simple disposal. Furthermore, the CaL process does not eliminate other greenhouse gases or toxic substances present in exhaust gases from conventional fuel-powered engines.

Another concern is the lack of provision for the management or disposal of the waste material generated. While the technology effectively captures CO_2 and SO_2, it merely transfers the environmental burden from atmospheric emissions to solid waste. Without a sustainable strategy for handling this by-product, the long-term viability of CaL in maritime applications remains questionable.

2.5. Integrated Exhaust Gas Purification Systems

To reduce emissions from ship propulsion systems, a multi-stage gas purification method has been developed that combines several treatment technologies. This integrated system incorporates catalytic oxidation, chemical absorption, and particulate separation to target multiple pollutant classes [23].

The process begins with the ozonation of NO_x, converting nitric oxide (NO) into more soluble compounds such as nitrogen dioxide (NO_2) and dinitrogen pentoxide (N_2O_5). These, along with SO_2, are then removed through wet scrubbing with a sodium hydroxide (NaOH) solution in a purpose-designed marine scrubber.

Following the initial pollutant removal, the exhaust stream proceeds to a CO_2 capture stage, where a mixed chemical solvent is used to absorb carbon dioxide. The captured CO_2 is then compressed and liquefied for onboard storage.

Despite its comprehensive design, this system presents significant operational and environmental challenges. It requires large volumes of chemical reagents and involves complex, space-intensive infrastructure, both onboard and in port facilities. Additionally, the process produces substantial quantities of hazardous waste, including toxic sludge and contaminated wash water, which must be further treated or securely stored.

Discharging treated water into the marine environment, as proposed by system manufacturers, poses a risk to marine ecosystems due to the potential introduction of pollutants such as heavy metals and residual reagents. Overall, the high operational costs, logistical complexity, and environmental trade-offs limit the system's practical value and sustainability.

3. PROMISING METHODS FOR REDUCING GAS EMISSIONS FROM SHIP PROPULSION ENGINES

3.1. Plasma-Catalytic Hybrid Systems

Plasma-catalytic hybrid systems represent a promising approach for treating exhaust gases from marine engines. These systems combine non-thermal plasma technologies with catalytic processes to enhance the removal of pollutants such as SO_x and NO_x, contributing to improved marine air quality [24], [25].

In this approach, non-thermal plasma generates reactive species, such as ions, radicals, and excited molecules, which interact with exhaust gases, initiating oxidation reactions that decompose harmful compounds. The presence of a catalyst accelerates these reactions, improving efficiency and selectivity in pollutant conversion.

The synergy between plasma and catalytic components allows for effective pollutant removal at lower temperatures than conventional thermal processes [26], [27]. This reduces energy consumption and makes the system suitable for integration into existing shipboard configurations with minimal modification.

Laboratory studies demonstrate significant removal efficiencies for SO_x and NO_x, positioning plasma-catalytic systems as a viable candidate for next-generation marine emission control technologies. However, further research is required to evaluate long-term stability, scalability, and performance under real-world maritime conditions.

3.2. Advanced Oxidation Processes

Advanced Oxidation Processes (AOPs) offer a promising method for treating exhaust gases from marine engines, particularly in targeting sulphur compounds and VOCs. These processes rely on the generation of highly reactive species like primarily hydroxyl radicals (OH), which rapidly oxidize a wide range of pollutants [28], [29].

Hydroxyl radicals are among the most powerful oxidizing agents and can break down complex organic and inorganic pollutants into less harmful substances, such as carbon dioxide and water. AOPs can be implemented using several techniques to generate these radicals, including:

- ultraviolet (UV) activation of hydrogen peroxide (H_2O_2);
- ozone (O_3) decomposition;
- Fenton-like reactions involving iron-based catalysts and H_2O_2 [30].

These reactions occur at relatively low temperatures and can be integrated into shipboard systems without significantly redesigning existing exhaust systems. AOPs have demonstrated effectiveness in degrading sulphur species, VOCs, and other persistent pollutants that conventional scrubbing methods may fail to remove completely [31].

However, the practical application of AOPs in maritime contexts remains limited. Challenges include the need for precise control of reaction conditions, safe handling of chemical reagents (e.g., hydrogen peroxide, ozone), and the management of any secondary waste produced. Depending on the specific AOP and the pollutants being treated, some potential by-products include: inorganic salts if the contaminants contain elements like nitrogen or sulphur, short-chain organic acids, nitrated by-products [32], [33]. These might be toxic and require further treatment. Additionally, most data supporting their effectiveness come from controlled laboratory environments, and further research is needed to assess performance under real shipboard conditions.

3.3. Electrochemical CO_2 Separation

Electrochemical CO_2 Separation (ECC) is an emerging technology designed to selectively capture carbon dioxide from ship exhaust gases using electrochemical reactions. It presents a potentially more energy-efficient and modular alternative to conventional CO_2 capture methods, such as chemical absorption with amines or physical scrubbing [34], [35].

ECC systems operate by applying an electric current across specialised membranes or electrodes that facilitate the selective transport of CO_2 molecules. This process can be tuned to capture CO_2 with high selectivity, while minimising the capture of other exhaust gases. This is achieved by carefully selecting the electrode materials, electrolyte composition, and operating conditions within the electrochemical cell. By manipulating these parameters, the ECC process can be optimised to preferentially capture and separate CO_2 from other gases, leading to high purity CO_2 streams. One of the key advantages of ECC is its compatibility with renewable energy sources, which could further reduce the carbon footprint of onboard emission control systems [36], [37].

Compared to traditional systems, ECC offers several benefits:

- lower energy consumption, due to operation at ambient temperatures;
- compact and scalable design, making it suitable for integration on various ship types;
- minimal use of chemical solvents, reducing hazardous waste generation.

Despite its promise, ECC is still at the conceptual or early pilot stage. Key challenges include:

- material durability under harsh exhaust gas conditions;
- CO_2 selectivity and throughput at high flow rates typical of marine engines;
- system stability during long-term operation at sea.

Further research and development are needed to optimise the technology for maritime applications and to validate its performance in operational environments.

3.4. Membrane Gas Separation

Membrane gas separation is a developing technology for removing specific pollutants, such as SO_x, NO_x, and CO_2, from ship exhaust gases. It operates by selectively allowing certain gas molecules to pass through a membrane, based on their permeability and solubility, thereby separating them from the exhaust stream [38], [39]. This method offers a compact and modular solution compared to traditional techniques like amine-based absorption. It is particularly well-suited for applications involving lower concentrations of CO_2, which is typical in marine engine exhaust [40].

Membranes are engineered to favour the transport of target gases, such as CO_2 or SO_x, over inert or less permeable gases. This selective separation is driven by differences in diffusion rates across the membrane material. In maritime systems, most membrane technologies today are primarily optimised to capture CO_2 while allowing other exhaust components to pass through, resulting in cleaner emissions.

However, membrane performance depends heavily on the composition of the exhaust stream. For example, the relatively low concentration of CO_2 compared to oxygen can reduce separation efficiency. Additionally, exposure to high temperatures and corrosive compounds in ship exhaust can degrade membrane materials, impacting durability and long-term operation [41].

Despite these challenges, membrane gas separation remains a promising technology due to its small footprint, potential for automation, and low operational energy demands. Ongoing research focuses on improving membrane materials and configurations to enhance selectivity, stability, and resistance to fouling in harsh marine environments.

3.5. Microwave Technology

Microwave (MW) technology is an emerging approach to reducing emissions from marine engines. It works by generating microwave radiation, typically at 2.45 GHz, which interacts with exhaust gases directly or in combination with catalysts or plasma to promote pollutant decomposition.

Microwaves are a form of electromagnetic radiation that transfer energy by inducing molecular vibrations and ionization in gas-phase compounds. This results in accelerated chemical reactions at lower temperatures compared to conventional thermal processes. In many configurations, microwave energy is used to generate non-thermal plasma (NTP), enabling the breakdown of pollutants such as NO_x, SO_x, CO, hydrocarbons (HC), and particulate matter (PM) under mild conditions [42]–[45].

A typical system includes:

- a microwave generator (e.g., magnetron or solid-state amplifier;
- a reaction chamber, where the gas interacts with microwave radiation;
- an optional catalyst, which enhances the reaction rate and selectivity.

Microwave-assisted exhaust treatment offers several advantages: multi-pollutant removal capability, compact system design, suitable for retrofitting on ships, minimal secondary waste generation.

However, there are still some unresolved issues. These include the energy demand of continuous microwave generation, the durability of components in marine environments, and the lack of large-scale field data. While laboratory results are promising, full-scale maritime validation is needed to assess long-term stability, cost-effectiveness, and integration with existing propulsion systems.

3.6. Zero-Emission Fuels (Hydrogen)

In the search for long-term solutions to maritime emissions, hydrogen has emerged as one of the most promising zero-emission fuels. Its use in marine applications has the potential to eliminate emissions of CO_2, SO_x, NO_x, CO, and particulate matter, common by-products of conventional marine fuels such as heavy fuel oil and marine diesel [46], [47].

Hydrogen can be utilised in fuel cells or combustion engines, producing only water vapour as a by-product. However, the adoption of hydrogen in the maritime sector requires a complete redesign of propulsion systems, as well as the development of safe and efficient storage solutions for compressed or liquefied hydrogen and the creation of a global supply chain to support hydrogen production, transport, and bunkering infrastructure.

One of the most significant challenges is the current method of hydrogen production. Approximately 90 % of global hydrogen is still produced from fossil fuels, primarily through steam methane reforming, which results in considerable CO_2 emissions. In contrast, hydrogen produced via electrolysis powered by renewable energy, the so-called “green hydrogen”, currently accounts for less than 0.1 % of the global supply. To realise its environmental potential, the shipping industry must transition toward green hydrogen, which requires substantial investment and policy support [48].

Despite these challenges, hydrogen remains a viable long-term solution for decarbonising maritime transport. It is particularly well-suited for short-sea shipping, ferries, and auxiliary power systems. The scalability of hydrogen technologies and their compatibility with renewable energy integration make them central to future maritime emission strategies.

4. CONCLUSIONS

A comparative analysis of current technologies for reducing gas emissions from ship propulsion systems reveals that no existing solution fully eliminates pollutant formation or waste generation associated with maritime transport. While several methods demonstrate high efficiency in targeting specific pollutants, all are accompanied by environmental trade-offs, operational complexity, or waste management challenges.

As summarised in Table 1, technologies such as scrubbers, selective catalytic reduction (SCR), onboard carbon capture and storage (OCCS), and calcium looping provide partial mitigation.

Table 1. Comparative Characteristics of Current Emission Reduction Technologies for Marine Propulsion Systems

Technology	Target pollutants	Removal efficiency	Removal efficiency	Removal efficiency	Removal efficiency
Dry scrubber	SO_x, PM	SO_x: ≤80 %, PM: ≤50 %	Medium	Solid sludge	Yes
Wet scrubber	SO_x, PM	SOx: ≤97 %, PM: ≤80 %	Large	Contaminated wash water	Yes
Semi-dry Scrubber	SO_x, PM, partial NO_x	SOx: ≤95 %, NO_x: <30 %, PM: ≤70 %	Large	Solid sludge, wash water	Yes
Hybrid scrubber	SO_x, PM	SOx: ≤95 %, PM: ≤75 %	Large	Solid sludge, wash water	Yes
SCR (Selective Catalytic Reduction)	NO_x	NOx: ≤99 %	Medium	Spent catalyst, ammonia slip	Yes (Tier III)
OCCS (Onboard Carbon Capture and Storage)	CO_2	CO_2: ≤85 %	Very large	Liquefied CO_2 (requires storage)	Partial
Calcium looping	CO_2, SO_2	CO_2: ≤90 %, SO_2: ≤90 %	Very large	Regenerated solids (hazardous)	No
Integrated system	NO_x, SO_x, CO_2	NO2: ≤90 % SO2: ≤95 % CO_2: ≤85 %	Large	Solid and liquid hazardous waste	Yes

However, these systems often result in the production of hazardous waste like sludge, contaminated wash water, or CO_2 requiring long-term storage, which poses ongoing environmental risks. In many cases, pollutants are not neutralized but simply shifted from one medium (air) to another (solid or liquid waste).

None of the currently deployed methods effectively address the full range of harmful emissions, especially particulate matter, CO_2, NO_x, SO_x, and volatile organics, without producing secondary pollution. Moreover, compliance with regulatory standards (e.g., MARPOL Annex VI) does not necessarily equate to a net positive environmental outcome.

In contrast, hydrogen-based propulsion systems offer a fundamentally cleaner alternative. Hydrogen, when produced from renewable sources, emits no greenhouse gases or hazardous residues. Despite the significant infrastructure, economic, and technological hurdles involved in transitioning to hydrogen, it represents the most viable long-term path toward zero-emission maritime transport.

Nonetheless, immediate environmental challenges require interim solutions. Emerging technologies, such as plasma-catalytic systems, microwave-assisted decomposition, advanced oxidation processes, membrane separation, and electrochemical CO_2 capture, are still under development but hold potential for cleaner, more efficient exhaust treatment. As outlined in Table 2, these technologies vary in maturity, scalability, and effectiveness, but several show promise for integration into next-generation emission control strategies.

Table 2. Comparative Overview of Emerging Emission Control Technologies for Marine Engines

Technology	Description	Target pollutants / efficiency	Development stage
Plasma-Catalytic Hybrid Systems	Plasma-assisted catalytic oxidation	CH_4/VOCs: 95 %, NO_x: 80 %	Laboratory/pilot scale
Advanced Oxidation Processes (AOPs)	UV, ozone, H_2O_2-based radical oxidation	VOCs: Up to 90%	Early R&D
Electrochemical CO_2 Separation (ECC)	Electrochemical CO_2 capture via electrodes	CO_2: 60–70 %	Conceptual stage
Membrane Gas Separation	Selective gas permeation	CO_2: 70–85 % (dependent on exhaust composition)	Pre-commercial trials
Microwave-Assisted Emission Control	Microwave-induced decomposition	CH_4/VOCs: 99 %; NO_x/SO_x/ CO: ~80 %	Under certification

Ultimately, addressing marine pollution demands both short-term implementation of hybrid treatment systems and long-term structural transformation through alternative fuels. Coordinated global efforts, investment in innovation, and stringent environmental assessment are essential to realising sustainable maritime operations.

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