A Review of Various Non-Emission Reduction Methods in Marine Diesel Engines

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Abstract

NO_x has been described as one of the most harmful gases produced under high-temperature conditions from combustion chambers of marine diesel engines. Researchers have stressed the adverse effects of marine diesel engine emissions on human health and other biological systems. The International Convention on the Prevention of Pollution from Ships (MARPOL Annex VI) established NOx global emission limits. It provided a platform to encourage technological innovations toward reduction in NO_x emissions. Several specialized methods have been in application for NOx emission reductions, but their operational processes and technical efficiencies remain poorly understood. Therefore, a comprehensive review has been conducted on various NO_x emission reduction methods, classified into primary and secondary methods. The formation process of NOx was assessed in detail, and the multiple methods in application toward NO_x emission reduction were evaluated based on their technological efficiencies. It was established that scavenge humidification and SNCR- selective noncatalytic reduction is the most efficient NOx emission reduction method, given their emission reduction potentials at 80% and 95%, respectively.

Keywords: marine diesel engine; emission; humidity.

Introduction

International trades and logistical operations worldwide mainly rely on shipping as a transportation medium. United Nations Conference on Trade and Development (UNTAD) reported in 2019 that global sea trade accounted for more than 11 billion tons of trade. There has been reported an increase in the number of merchant ships in operation worldwide with immense negative impacts on the environment and human health[1,2]. Ships transport large quantities of essential goods through the world's oceans and emit high and varying quantities of nitrogen oxides (NO_x), which are detrimental to the environment.NO_x gas is a harmful gaseous emission released into the environment and, upon reaction in the atmosphere, forms photochemical smog[3,4]. The Committee on the Protection of Marine Environment (MEPC) is under International Maritime Organization (IMO). The Committee is responsible forthe regulatory framework developed to prevent air pollution under The International Convention for the Prevention of Pollution from Ships (MARPOL) Convention, Annex VI Regulations

(13.8 and 5.3.2) of NO_x Technical Code 2008[5-7]. There have been reported cases of non-compliance to regulations and existing laws aimed at reducing ships' emissions of NO_x pollutants. In this paper, various NO_x emission reduction methods in marine diesel engines have been comprehensively reviewed. This was to provide the most updated knowledge on NO_x emissions reduction technologies, assess the technical efficiency of the technologies, and offer recommendations for necessary improvements.

Nitrogen Oxides Pollutants

Fossil fuels are subjected to combustion for power generation in marine diesel engines, thus releasing greenhouse gases considered very harmful to the environment[8]. Typical emission contains primary greenhouse gases such as methane (CH_4), NO_x, and carbon dioxide (CO_2)[9]. NOx is a term for a group of predominantly nitric oxide (NO) with small percentages of nitrogen dioxide (NO_2) and nitrous oxide (N_2O)11. In atmospheric chemistry, the nitrogen concentration in natural air is about 79.05%10. Nitrogen remains inactive mainly in the marine diesel engine combustion process. However, a small part is oxidized to form NO_x pollutants[12]. During the combustion process in marine diesel engines, NO_x is included within the burning fuel spray under high combustion temperature conditions, providing an avenue for the reaction of nitrogen and oxygen to form nitric oxide (NO) and nitrogen dioxide (NO_2)[13]. More NO_x is included in the chamber at high temperatures and longer residence time. The quantity of NO_x reaches a maximum amount when the actual fuel-air ratio becomes close to the stoichiometric value[14]. NO_x formation occurs within 20° of the crank's rotation after the beginning of combustion in the marine diesel engine—NO_x forms as both front-propagated flame and post-flame gases. However, at high-pressure combustion conditions in marine diesel engines, the flame reaction zone becomes very thin and shortens flame residence time in the zone[15].

Primary sources of NO_x Pollutants

Many researchers have reported on the formation of NO_x at high-temperature conditions, like at temperatures greater than 1800K; diatomic nitrogen is formed following air oxidation in marine diesel engine combustion chamber[16,17]. The thermal NO_x trail occurs at high gas temperature conditions, and under this condition, thermodynamic steadiness favors (NO) formation through molecular nitrogen and oxygen dissociations[18,19]. The strong triple bond in the N_2 molecule requires high temperature for breaking its radicals into $N_2 \rightarrow 2N$ and $O_2 \rightarrow 2O$, and NO_x is also produced naturally by lightning.According to Zeldovich's mechanisms, thermal NO_x requires high activation energy and is quickly formed at high temperatures, as shown in Eq 1-3[20]. The most important for a stoichiometric and lean premixed combustion (a thermal mechanism) occurs where temperatures are more significant than 1527 °C. The NO_x creation process, known as hot spots, is very nonlinear since there are regions of higher temperatures above average temperature, and they play a more significant role in determining the produced amount of NO_x. NO can also disintegrate to form N_2 and O_2. However, this happens seldomly. Thus, almost all of the NO_x emitted is NO,which is equally described as a thermal effect[21,22].

$N_2+O \rightarrow NO+N$ (Eq. 1)
$N+O_2 \rightarrow NO+O$ (Eq. 2)
$N+OH \rightarrow NO+H$ (Eq. 3)

Fuel NO_x contributes to the oxidation of volatile nitrogen contained in fossil fuel at initial combustion phases before the reaction of volatile nitrogen to form intermediaries that are oxidized into NO or exist freely as N_2 for release into the atmosphere. Fuel NO_x can produce 50% and 80% of total emissions through fossil fuel and coal combustions, respectively, and this has been described as a dilution effect[23]. Prompt NO_x refers to the reaction between atmospheric nitrogen, N_2, and radicals of fossil fuel (CH_2, CH, and C fragments) for the formation of fixed species of nitrogen comprising nitrogen monohydride (NH), hydrogen cyanide (CHN), dihydrogen cyanide (H_2CN) and chloroacetophenone (CN or CN gas), that is liable to oxidation to form NO. Prompt NO_x is in minimal concentration in fossil fuels containing nitrogen,which has equally been described as a chemical effect.

Primary and Secondary NO_x Pollutants Reduction Methods

Several emission reduction methods have been identified and associated with different technical and operational challenges. Primary NO_x reduction methods focus on reducing emission components' production at the combustion phase of fossil fuels through controlling combustion processes, lowering oxygen-nitrogen concentrations, and reducing associated combustion temperature21. Secondary treatment technologies do not focus on combustion engines and boilers' working operations but target emission reduction associated with land-based stationary sources later converted or "marinized" for onboard usage ships. Operators' compliance with NO_x emission limits is becoming challenging, associated with a considerable cost, and regulations that limit emissions are becoming stricter.

Fuel Blending for NO_x Pollutants Reduction

The mixture of hydrocarbon composites (ethane, methane, etc.) and diesel causes the lowering of cetane numbers and reduced flame temperature due to increased flame ignition delay[24]. Another study reported that the absorption of combustion released heat energy, causing the evaporation of hydrocarbon compounds with high latent heat, leading to a decrease in flame temperature[25]. It has been claimed in several types of research that the use of blended Fuel in marine diesel engines has the potential to reduce NO_x emission[26-28]. Blended Fuel potentially lowers combustion heating value and particulate matter to about 75%[29]. Due to the constant amount of carbon, several experiments have demonstrated that blended Fuel has a significant effect on NO_x reduction[30,31]. It has been reported that different additives can be used in blended Fuel as a catalyst to reduce peak combustion temperature[32-34].

Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) technology has been reported as another technique deployed to reduce NOx emission35,36 efficiently. EGR uses a turbochargerto recycle exhaust gas, significantly reducing NOx emission[37-39]. EGR is recommended for application in low-speed marine diesel engines and operates from the turbine side downstream of the turbocharger to the compressor inlet of the engine[40]. Low-speed marine diesel engines are driven by heavy fuel oil (HFO), which produces heavily laden sulphur, metals, and other components in the exhaust gas. These components must be eliminated from the exhaust gas before its recirculation into the scavenge space of the marine diesel engines[18].EGR has been considered inappropriate for engines using HFO due to challenges associated with cleaning the exhaust gas before recirculation. Despite this, EGR is still being recommended for use by top manufacturers of marine diesel engines (Wartsila, MAN Diesel, and Mitsubishi), especially for HFO fuel using engines with inbuilt scrubber systems. In early 2011, MAN Diesel manufacturer claimed that EGR technology could reduce NO_x emission to 50 or 60%. NO_x emission reduction was driven by adding CO_2 into combustion air to decrease peak combustion temperature owing to the high specific gravity of CO_2 in comparison to air[33,41-44]. EGR emission reduction technology remains increasingly utilized in main propulsion and auxiliary engines of board ships[45]. The technology, as claimed, can reduce NO_x emission levels to about 60% and equally has the potential to reduce emissions during sea passage and port stay.

Slide Fuel Valve

The fuel injector slide valve was used by industry and regulators as a green engineering piece to reduce NO_x emission even to 20 years old marine diesel engines. The nozzle design of the slide fuel valve has been redesigned by eliminating a minute channel (sac volume) which retains a small amount of Fuel after injection. The retained Fuel drips into the engine combustion chamber and burns incompletely. SAC located within valve seating is referred to as the small volume between the fuel injector's fuel flow path and the injector's final metering of the injector[46]. This technology improved engine efficiency and cylinder condition. Slide valve strategy is specific to MAN B&W 2-stroke slow-speed engines mainly used for ship propulsions and, in 2004, was built into all new MAN B&W two-stroke engines. The main advantages of this system include reduced fuel consumption due to complete removal of (SAC) volume, NO_x reduction potential at about 30%, and dependence on operational load[47].

Miller Cycle (Dynamic/Variable Valve Actuation)

The Miller cycle represents the Otto Cycle's modification from shorteningthe compression stroke followingthe expansion stroke to reducing fuel consumption and exhaust gas emissions with the inclusion of NO_x[48]. The Miller cycle utilizes variable valve actuation (VVA) and advanced turbocharging systems for NO_x emission reduction in marine diesel engines. The main advantage of the Miller cycle is the reduction of fuel consumption by the consistent guarantee of the expansion ratio being more significant than the compression ratio. Research has shown that the Miller cycle's early inlet valve closure (EIVC) system utilizes high values of boosted air pressure through two-stage turbocharging compared to conventional marine diesel engine operations[49]. Extreme values of EIVC in conjunction with increased boost pressure resulted in a remarkable emission reduction of engine NO_x up to 50% without deterioration of brake-specific fuel consumption (BSFC)[50,51].

Split Fuel Injection

Split fuel injection,referred to as premix charged compression ignition, is known for its single-stage combustion process. Large fuel volumes are burnt, reducing cylinder temperature, unlike normal compression ignition engines. In split fuel injection, combustion occurs after some injection timing variations and guaranteed proper fuel-air mixture[52]. Another study reported that injections into the engines lower the combustion temperature and pressure, and a significant reduction in NOx emission is recorded with a split injection system compared to that of single injection[53,54].

Fuel Emulsion System

A fuel emulsion system houses two immiscible fluids (e.g., water and diesel) whereby one of the fluids is in fine dispersion in the combustion chamber; like in a water/diesel fuel emulsion system, water is found to be in continuous dispersion as fine droplets in the diesel fuel. [70-75] Previous studies reported that water in the emulsion system is liable for a reduction in combustion temperatures[55-57]. In another study, the researchers have established that usinga water-fuel emulsion system could reduce NO_x emission to about 50%, with every 1% of water utilized, accounting for a corresponding percentage point of NOx emission reduction[58]. Usinga fuel emulsion system without engine modifications could lead to the maximum amount of water and decreased emission quantity of NO_x being limited to about 10 - 20%. The engine can equally not meet its rated power output[56,59]. Using water in the fuel emulsion system improves the combustion efficiency of CI engines and overall enhances engine performance. A percentage increase of water in the emulsion system up to about 20% will increase the motor torque, power, and brake thermal efficiency. The brake-specific fuel consumption (BSFC) is determined by some critical variables like the total Fuel utilized, burnt quantities of diesel fuel, and exhaust gas temperature known to be decreased with increasing water percentage[60,61].

Direct Water Injection

Direct Water Injection (DWI) is a well-established technology. This technology has the potential for NO_x emission reduction of up to 50% and is considered deployable for main propulsion and auxiliary engines61. Still, it is associated with limited usage on board ships due to Fuel's extremely high sulphur content exposed to acidic attack on the engine piston crown. The introduction of water into the combustion system of the marine diesel engine has been described as a NO_x emission reduction strategy and simultaneously reduces PM emissions. Another researcher described water injection as internal cooling, and fully independent water injection is required for in-cylinder injection of the water system[62,63]. This direct water injection method provides the platform for water injection in large quantities without impacting negatively on the diesel engine reliability, and previous studies reported that injection timing, water consumption, NOx emission, and other parameters could be subjected to careful optimization for enhanced efficiency of the direct water injection system[64-66].

Scavenge Humidification

This requires the introduction of water mist into a scavenging system and has been described as one of the simplest techniques for water displacement into an engine combustion chamber[67]. This technique has been in application for several decades and is designated for boosting power and preventing the knocking of SI engines[68]. Water mist can be generated from engine waste heat in the exhaust gas or compressed scavenging air. Steam can be used in place of water mist in certain engine applications[69,70]. The integration of steam injection systems into diesel engines has shown that the combustion temperature will decrease as the vapor in the steam increases. Some researchers have concluded that steam injection could reduce the concentration of CO and CO_2 emission[71]. The water or steam injection method was normally applied to in-flight engines, but in recent years, the research on diesel and gasoline engines has been extended[72]. Research has shown that the water injection method is very efficient since it can account for more than 80% reduction in NO_x emission as reported by[67,73].

Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) has demonstrated a strong capacity to reduce marine diesel engines' NO_x emissions. This has resulted in several companies being involved in SCR solutions manufacturing[74]. SCR requires the treatment of exhaust gases with ammonia or urea before being fed through a catalytic converter at temperatures above 250°C to break down NOx into water and nitrogen. SCR's efficiency is known to be limited by temperature. At low exhaust temperatures, hydrogen sulfate is formed with a great tendencyto cause operational obstructions to the catalytic converter. SCR requires special space requirements, which must have urea system storage for potential reduction of NO_x emission. Following the history of engine operations at port areas, engine temperatures decrease in the transition and maneuvering modes, with high exhaust temperatures going below 250°C. Integrating scrubber or waste heat recovery systems into the SCR technology is responsible for the drop in exhaust temperature below 250°C, which does not guarantee the operational efficiency of the SCR system. The efficiency of the SCR is equally impacted by high sulphur content fuel, which may be used in the marine diesel engine75. Most SCR systems are installed on 4-stroke diesel engines, and their applicability is limited to 2 stroke main propulsion engines.

Exhaust Gas Scrubber

An exhaust gas scrubber (EGS) functions by the removal of sulphur and PM through a dry or wet scrubbing interface from the exhaust flow of the engine. One of the main advantages of sulphur stripping from the exhaust gas is that the ship can use high sulphur fuels and meet the requirements of the IMO and Emission Control Area (ECA)[76-80]. There are two types of scrubbers, namely dry and wet scrubbers, with the most used being the wet scrubbers of different configurations (open-loop, closed-loop, and hybrid). Open-loop systems utilize seawater; closed-loop uses freshwater, while seawater-freshwater combinations apply to the hybrid configuration.In open-loop wet scrubber systems, exhaust gases are sprayed with seawater, leading to the reaction of SO_x with wash water to form sulphuric acid, which becomes neutralized by the natural alkalinity of seawater. Seawater serves as the wash water in the system, and the wash water is subjected to treatment after utilization in the scrubber. Then, the Closed-loop scrubber systems on board freshwater are utilized and subjected to mixing with caustic soda (NaOH) to serve as wash water. It remains very uncertain if port permits are required to discharge scrubber effluents in confined waters of port areas. It has the potential for 98% and 5% reductions in SO_x and NO_x emissions, respectively.

Conclusion

The following was detected whilereviewing recent progress in water/steam addition to fluids combustion systems. Few studies have investigated the various methods. The current research situation in this field leads to the following findings:

1. It has been established that scavenge humidification has the potential for NOx reduction to greater than 65%, associated with lower operating cost, and provides opportunities for future Improvement compared to others. However, the requirement for special water quality and high tendencies of corrosion attacks remained the major drawbacks of scavenging humidification.
2. SCR has the potentiality of NO_x emission reduction to 95% through ammonia injection into the exhaust gas system. The implementation of some special operations, as recommended, will have a positive influence on NOx emission control expenditures and the temperature needs of SCR. However, the main drawbacks remained the high catalyst cost, high-temperature requirement, and short catalyst service life.
3. It can be noted that the commercial applicability for direct water injection in liquid Fuel-burning for low-NOx technologies has not yet been proved. Further, when using different types of standard fuels and wastes with a particular focus on alternative uses of those fuels in developing sustainable energy, thermal-physical effects and chemical kinetics of water injection should be studied on combustion features and emissions.
4. When liquid Fuel is burned with the steam injectors, NOx can be reduced by 34% following current environmental regulations with a high level of fuel consumption and low carbon monoxide CO concentration (EN:267).
5. The efficiency reduction of NOx depends on a range of parameters, including steam levels, jet speeds, injection site, and delivery mechanism. Excess humidity may have a negative impact on the combustion process in the combustion zone, creating effects like excessive cooling of the combustion chamber, flame extinguishing, fuel under-burning, CO rise, etc. Specific applications, therefore, require different studies.
6. Moisture effects on liquid fuel combustion NOx emissions in burners are determined by two basic mechanisms: chemical and physical. The first Impact is to raise the concentration of active hydroxyl radicals that effectively oxidizeblack carbon precursors in steam injection into the combustion zone, boosting carbon fuel burnout and minimizing the number of harmful combustion products. The second Effect is related to the fuel mixture and steam dilution, reducing the flame temperature and thermal NOx concentration.
7. Moisture for combustion can be autonomously generated from the combustion heat of Fuel, i.e., no additional energy sources are necessary. Thus, combustion technologies may be applicable in remote areas where high-quality fuels cannot produce thermal and electrical

energy. Nonetheless, there is still a large build-up of unused industrial and transportable fuel waste.

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Conflict of Interest
The authors declare that they have no conflict of interestconcerning the research.

Authors Contribution
All authors contributed in this research paper.

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