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Review of Nitrogen Oxides (NOx) Reduction Methods Used on Marine Diesel Engine

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ABSTRACT

Reducing nitrogen oxide (NOx) emissions is of great importance in terms of environmental sustainability and air quality. This study is a review that examines various applications aimed at reducing NOx emissions. Below is a summary of the evaluation of technologies, including the common rail system, exhaust gas recirculation (EGR), Miller cycle, direct water injection, emulsified fuel, and selective catalytic reduction (SCR). The common rail system, EGR, and Miller cycle can generally be considered as combustion control-based methods for reducing NOx within the cylinder. Direct water injection and emulsified fuel aim to lower temperatures inside the cylinder by utilizing the high internal heat of evaporation of water. Selective catalytic reduction is a technology where NOx in the exhaust gas is converted into nitrogen gas and water vapor through the use of a catalyst. This study evaluates the effectiveness and applicability of various technologies used to reduce NOx emissions. Each method may have different advantages and disadvantages. Additionally, there may be certain limitations and variations depending on the application areas of these methods. Therefore, a careful assessment is necessary to determine the most suitable technology or combination of technologies for reducing NOx emissions.

Keywords: Marine diesel engine, NOx, EGR, Emulsified fuel, SCR, water injection.

Gemi Dizel Motorunda Azot Oksitleri (NOx) İndirgeme Yöntemlerinin İncelenmesi

ÖZ

Azot oksit emisyonlarının azaltılması, çevresel sürdürülebilirlik ve hava kalitesi açısından büyük önem taşıyan bir konudur. Bu çalışma, NOx emisyonlarını azaltmaya yönelik çeşitli teknolojilerin incelendiği bir derleme çalışmasıdır. Aşağıda, common rail sistemi, egzoz gazlarının geri dönüşümü, Miller çevrimi, suyun direct enjeksiyonu, emülsife yakıt ve seçici katalitik indirgeme gibi teknolojilerin incelenmesine yönelik bir özet sunulmuştur. Common rail sistemi, egzoz gazlarının geri dönüşü ve miller çevrimi genel olarak silindir içindeki yanmanın kontrolüne dayalı NOx indirgeme yöntemleri olarak düşünülebilir. Su enjeksiyonu ve emülsife yakıt ise suyun yüksek buharlaşma iç ısısından faydalanarak silindir içindeki sıcaklıkların düşürülmesini amaçlamaktadır. Seçici katalitik indirgeme ise egzoz gazında bulunan

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NOx'un bir katalizör yardımıyla azot gazına ve su buharına dönüştürüldüğü bir teknolojidir. Bu çalışma, NOx emisyonlarını azaltmak için kullanılan çeşitli teknolojilerin etkinliğini ve uygulanabilirliğini değerlendirmektedir. Her bir yöntem, farklı avantajlara ve dezavantajlara sahip olabilmektedir. Bunun yanında, yöntemlerin bazı kısıtlamaları da olabilir ve uygulama alanlarına bağlı olarak farklılık gösterebilir. Bu nedenle, NOx emisyonlarının azaltılması için en uygun teknoloji veya teknoloji kombinasyonunu belirlemek için dikkatli bir değerlendirme yapılması gerekmektedir.

Anahtar Kelimeler: Gemi dizel motorları, NOx, EGR, Emulsified fuel, SCR, su enjeksiyonu.

1. Introduction

Factors such as population growth, economic growth and urbanization around the world have increased the interest in internal combustion engines day by day (Akinpelu et al., 2023). Internal combustion engines are widely used in a wide range of vehicles. In addition, power plants use internal combustion engines for electricity generation. These engines, which work with the combustion of fossil fuels like natural gas or oil, are widely preferred in electricity generation. In the agricultural sector, internal combustion engines are used in agricultural machinery and tractors. These machines provide power and motion to run farm work. In areas such as the construction industry, mining, ports, transport and logistics, these engines are used for the operation of large machines and the transport of heavy loads. Among the reasons for the widespread use of internal combustion engines in these sectors are factors such as high power generating capacity, durability, easy accessibility, energy density and operating costs (Chehrmonavari et al., 2023).

Internal combustion engines are widely used in fields such as power generation and transportation. However, various harmful emissions are released into the atmosphere during the combustion process of these engines. These include various pollutants that are commonly associated with combustion processes in engines. These pollutants encompass hydrocarbons (HC), which are organic compounds consisting of hydrogen and carbon atoms. Particulate matter (PM) refers to microscopic solid or liquid particles suspended in the air, originating from incomplete combustion or other sources. Carbon monoxide (CO) is a colorless and odorless gas produced when carbon-containing fuels are burned incompletely. Lastly, nitrogen oxides (NOx) represent a group of compounds formed during high-temperature combustion, primarily from the reaction between nitrogen and oxygen in the air (Gonca & Genc, 2021). NOx emissions are an important problem, especially due to high diesel combustion temperatures. NOx gases formed as a result of the reaction of nitrogen and oxygen have unfavorable consequence on ecological and human wellness. It degrades air quality, can cause respiratory ailments and damage to the respiratory system.

Many countries and regional organizations have set exhaust emission standards to reduce NOx emissions of internal combustion engine vehicles. These standards require the development of technologies and exhaust systems used in vehicles. For example, Euro standards in Europe, EPA standards in the United States and Japanese Emissions Standard in Japan aim to control NOx emissions (*DieselNet: Engine Emission Standards*, n.d.).

In this context, various regulations on emissions from ships have been introduced in Annex 6 of the MARPOL (International Convention for the Prevention of Pollution from Ships) constituted by the International Maritime Organization (IMO) for the reduction of emissions from ships (*IMO | Marine Commercial | YANMAR*, n.d.). As a result of these regulations, some design changes and advanced systems placement applications were required on ships.

The rules that first came into force as Level 1 (Tier I) became more stringent as the deterioration in environmental pollution became more evident. While the Tier I and Tier II limits are applied globally, Tier III is only found in the NOx Emission Control Areas.

2. NOx Reduction Methods

Methods of reducing nitrogen oxides from ships can be grouped under two headings. The first of these methods is applied before or during combustion, but the second is the methods applied after combustion.

2.1 Primary Methods

In the primary methods, it is aimed to reduce the amount of NOx that may occur after combustion before the nitrogen gas enters into the cylinder or by making some applications during combustion in order to reduce the nitrogen oxide release. These methods are as follows; common rail system, exhaust gas recirculation, Miller cycle application, Direct water Injection (DWI), fumigation of water into the intake air, Water-fuel emulsion, Water vapor injection methods.

2.2 Common Rail System

In the conventional system, there is one high pressure fuel pump per cylinder, whereas in the Common Rail system, high pressure fuel is supplied to the system by using a single fuel pump, and electronically controlled valves are provided to ensure fuel passage to the injector of each cylinder.

The Comman Rail (CR) system is a diesel direct injection system. This system is clearly superior to the same type of systems used so far in terms of exhaust gas emission, fuel consumption, noise generation and operating system. The Common Rail system deliver fuel to the injectors by way of a common line at a pressure of up to 2000 bar. The electronic control unit regulates this high-pressure contingent on the load and engine speed.

If we look at the advantages it provides (Schommers et al., 2000);

• Improves the formation of air-fuel mixture,

• Injection pressure can be selected freely within wide limits,

• The start of fuel injection and the amount of fuel injected can be freely determined,

• Combustion is ecological and economical.

• The spraying time can be controlled very variable.

The results of a study conducted by Xu-Guang et al. (Xu-Guang et al., 2012) demonstrate that increasing the rail pressure within an appropriate range leads to an increase in NOx emissions. However, under heavy load conditions, as the injection angle is delayed, there is a decrease in NOx emissions. Zhou et al. (Zhou et al., 2017)conducted a study on the effects of different post-injection strategies on a diesel engine with a common rail line that provides extra high pressure. The results showed that compared to a post-injection angle of 5 °CA, the NOx concentration decreased by 14.43% at a post-injection angle of 25 °CA. This reduction can be attributed to the increase in post-injection angle, which leads to a decrease heat release rate and in cylinder temperature at the equal crankshaft angle, thus helping to mitigate NOx formation to some extent. Badami et al. (Badami et al., 2001) conducted an investigation to analyze the effects of pilot injection timing and quantity on NOx emissions. The study focused on a passenger vehicle diesel engine that was having a common rail fuel injection system. The pilot injection timing was varied in the range of 32° to 10° crank angle degrees during the experiment. Additionally, the pilot injection amount was adjusted up to 15% of the entire injected amount. As the pilot injection fuel quantity increased, the NOx production increased due to the higher average temperature in the combustion chamber. Similarly, the advancement of the pilot injection also increased NOx emissions.

2.2.1 Exhaust Gas Recirculation (EGR)

Exhaust gas recirculation (EGR) is another commonly used method for mitigating NOx emissions. It is in principle based on the exchange of some of the fresh intake air with exhaust gases. In this way, the O2 and N_2 molecules in the fresh air are replaced by CO2 and H2O in the exhaust gases. However, peak temperatures in the combustion chamber within the combustion chamber will drop slightly and there will be reductions in NOx formation (Nielsen et al., 2015).

Generally, EGR is expressed as a percentage by mass or by volume. In volumetric terms, the EGR ratio is the ratio of the mass of the total intake air to the volume of the exhaust gas recirculated from the exhaust side. In general, this ratio is expected to be between 10-20% for compliance with TIER II regulation and 30-40% for compliance with TIER III regulation (2012).

One of the biggest advantages of EGR application is that it reduces peak temperatures in a combustion chamber and therefore reduces noise and vibrations in the engine. The disadvantage of this application is that the combustion in the combustion chamber will deteriorate, resulting in performance losses in the engine. However, there will be increases in PM emissions. It will also cause an enhance in specific fuel consumption. The deterioration of engine lubricating oil due to the effect of carbon molecules coming from the exhaust will increase the wear on the engine (Rajesh kumar & Saravanan, 2015).

Esakki et al (Esakki et al., 2022) examine the impact of exhaust gas recirculation , which has been studied experimentally, on the performance, combustion, energy and emissions behaviour of a common rail direct injection engine. In these experiments, biodiesel derived from waste oil mixtures of the leather industry and diesel fuel are used. The research aims to evaluate engine output parameters using different EGR rates (5%, 10%, and 15%). The results demonstrate that NOx emissions are lower for all tested fuels compared to clean diesel. The highest reduction in NOx emissions is observed at an EGR rate of 15%. Patil et al. (Patil & Thirumalini, 2021) stuied the effect of various temperatures of cooled exhaust gas recirculation on the performance and emission characteristics was investigated using a diesel and Diesel-Karanja biodiesel blend (80%-20%). They found that the NO emission mitigates by approximately 350-450ppmC when using the diesel-Karanja mixture with an EGR rate above 15%. However, reducing the EGR coolant temperature has a undesirable impact on NO emission. In another study investigation conducted by Wang et al. (Z. Wang et al., 2017), they proposed an internal criterion that combines EGB (exhaust gas bypass), CB (cylinder bypass) and EGR (exhaust gas recirculation) as a means to effectively reduce NOx emissions. By implementing the EGR system in conjunction with EGB and CB, NOx emissions from the engine were successfully lowered to levels below 3.4 g/kWh. Three different modes were established to assess the result of the EGR system:

ECA-EGR mode, low-EGR mode and non-EGR mode. The study investigated the impact of these modes on NOx emissions, engine power, fuel consumption, and overall emissions. Accordingly, it could be completed that when the engine operates in the ECA-EGR mode, it is capable of meeting the NOx emission requirements specified by IMO Tier III.

2.2.2 Miller Cycle

The Miller cycle is a thermodynamic cycle patented in 1957 by Ralph Miller. The Miller cycle was first used in turbocharged and supercharged petrol engines. However, it has also been tested on diesel engines with the effect of strict emission rules in recent years (Gonca, Sahin, Parlak, Ayhan, et al., 2015).

It operates on the basis of the closing of the valve after the bottom dead point (BDC) in the cycle realized by late closure of the intake manifold. In this cycle, a portion of the air taken into the cylinder along the suction stroke is again sent out of the suction valve with the cylinder moving up again. Thus, gain from compression work is provided (Gonca et al., 2013).

In another cycle by R.H Miller, the intake valve closes before the piston achives the lower dead point. In this case, the cylinder continues to move to the lower dead point and the pressure in the cylinder is reduced slightly. When the piston starts its upward movement again, less work is done to compress it compared to the diesel-cycle (Gonca, Sahin, Parlak, Ust, et al., 2015).

In the study conducted by Li et al. (Li et al., 2019) presented a technical approach to reduce NOx emissions by applying the Miller cycle and ethanol to a turbocharged diesel engine. The application of the Miller cycle resulted in a reduction in NOx emission values in the range of 8.5% to 12.9% compared to the conventional Diesel cycle. Also, Wang et al. (Y. Wang et al., 2007) conducted an analytical investigation to reduce NOx emissions from a petrol engine using the Miller cycle. The obtained results clearly show that the implementation of the Miller cycle leads to lower exhaust temperatures and decreased NOx emissions in comparison to the Otto cycle.

2.2.3 Direct Water Injection (DWI)

The DWI into the cylinder is another effective technique employed to reduce NOx emissions in diesel engines. In this system, water is sent directly to the combustion chamber via a different injector (S. Zhu et al., 2019).

The advantage of DWI over fumigation is that lower percentages and more effective results can be achieved (Ayhan, 2016). The advantage of using emulsified fuel is that the water content of the fuel can be adjusted according to need. The disadvantage of this system is that it is very difficult to place a second injector on the engine top cover (Bedford et al., 2000).

Studies have shown that the direct injection of water into diesel engines can lead to a significant reduction in NOx emissions, with potential reductions of up to 70%. In Fig. 1, this system is simply schematized.

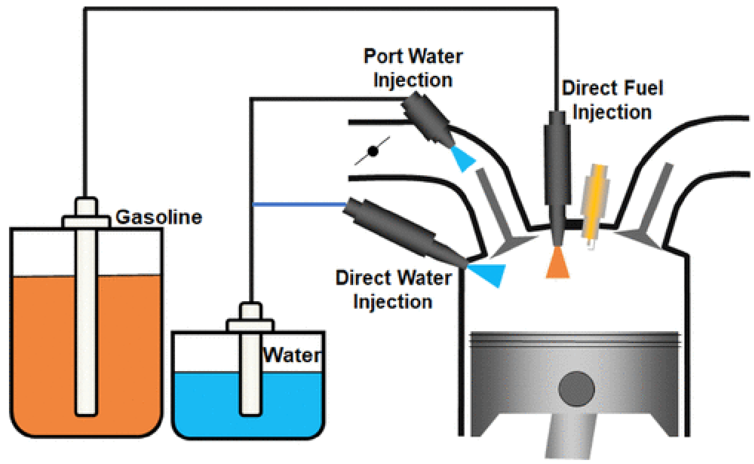

Figure 1: The schematic drawing of DWI unit (Singh et al., 2020).

In their study, Ayhan and Ece (Ayhan & Ece, 2020) performed water injection at ratios of 10%, 20%, 40%, 60%, 80%, and 100% of the fuel mass. The results obtained showed reductions in NOx emissions up to 61%. In another study by (Ayhan, 2020), electronic controlled direct water injection (DWI) was used to reduce NOx emissions emmited from a diesel engine fuelled with sunflower oil methyl ester. Significant reductions of up to 56% in NOx emissions were observed.

2.2.4 Fumigation of Water into Intake Air

Water fumigation from the intake manifold is one of the commonly used methods in ship diesel engines (Ma et al., 2014). With this method, water can be sent to the combustion chamber without important modifications on the engine.

The main benefit of this system is that it can be easily integrated into existing engines. In addition, water can be sent to the combustion chamber very close to the homogenous. Some other benefit of this approach is that water increases the volumetric efficiency due to the cooling effect and does not cause changes in fuel properties (Şahin et al., 2014).In this method, the amount and time of water sent to the intake manifold is important (Tauzia et al., 2010). The sprayed water must evaporate fully into the suction air and the spraying time should be done when the valve is open. If all the sprayed water does not evaporate in the suction air, liquid water particles degrade the oil film on the cylinder surface. Spraying when the valve is closed causes water to accumulate behind the valve, as well as corrosion in the valves and the intake manifold (Ayhan, 2016). The main disadvantage of fumigation is that the amount of water dispensed is much higher than other water-doped methods for a important decrease in NOx emissions (Hountalas et al., 2007).

The system is simply physically positioned on the water injector intake manifold. Water pressurized by a pump is injected into the intake manifold at the desired crank angle by means of the electronic control unit (ECU).

In the study conducted by Gowrishankar et al. (Gowrishankar et al., 2020), a relative assessment of adding water to diesel through emulsion and fumigation methods was carried out to reduce smoke and nitrogen oxides emissions in a small-bore diesel engine. It was found that both methods led to a decrease in NOx emissions. Şahin et al. (Şahin et al., 2014) conducted an experimental study to investigate the impact of water injection into the intake air on the exhaust emissions and performance of the turbocharged common-rail direct injection automotive diesel engine belonging to the brand of Renault and K9K 700 model. The water ratios were approximately set at 2%, 4%, 6%, 8%, and 10% (by volume). The peak reduction in NOx emissions was obtained as 12.489% for a 9.400% water ratio. The water ratios were approximately set at 2%, 4%, 6%, 8%, and 10% (by volume). The maximum reduction in NOx emissions was obtained as 12.489% for a 9.400% water ratio.

2.2.5 Emulsified Fuel

Emulsified water fuel mixture is one of the emission reduction methods used in diesel engines. Emulsion fuels are used by mixing water in a specific mass or volume without making any changes in the engine system.

When these methods are applied to a diesel engine, considering the parameters such as complexity, loss of volume, operational difficulty and cost, the use of emulsified fuel is the most appropriate method. In this application, water is homogeneously mixed into the fuel by various methods. The resulting emulsified fuel is injected from the injector into the cylinder. Thus, NOx emissions are reduced by preventing high temperatures in the cylinder.

The main advantage of this method is that it can be applied without any modification on the engine. The disadvantages are that the diesel and water cannot be kept homogeneously for a long time, the fuel water ratio cannot be changed and the engine is jerky during load transitions.

Tamam et al. (Mohd Tamam et al., 2023) conducted a study to investigate the performance and emissions characteristics of an electric generator equipped with a 100 kVA common rail turbocharged diesel engine. The generator was possessing a real time non surfactant emulsion fuel supply system which is an emulsifier free emulsion fuel supply system. They found that nitrogen oxides emissions and smoke opacity were also diminished. Also, Swamy et al. (Ranganatha Swamy et al., 2022) stated in their study that water used diesel emulsified fuel, especially water-diesel emulsion containing 20% water showed better performance in emissions and reduced NOx emissions by 10.8%. Park and Oh (Park & Oh, 2022) stated that water-oil (W/O) emulsion fuels produce 19.6% less NOx emissions compared to diesel.

2.3 Secondary Methods

Secondary methods refer to the NOx gases released after combustion without interfering with the combustion period. The only method currently used is Selective Catalytic Reduction (SCR).

2.3.1 Selective Catalytic Reduction (SCR)

The SCR system, known as the Selective Catalytic Reduction system, was developed to reduce NOx emissions from diesel engines to the environment. The objective in this system is to provide a selective converter for NOx emission after cleaning the particles in the exhaust gas compound in a filter with a catalytic surface coating. The High-Pressure SCR system developed by MAN is illustrated in Fig. 2.

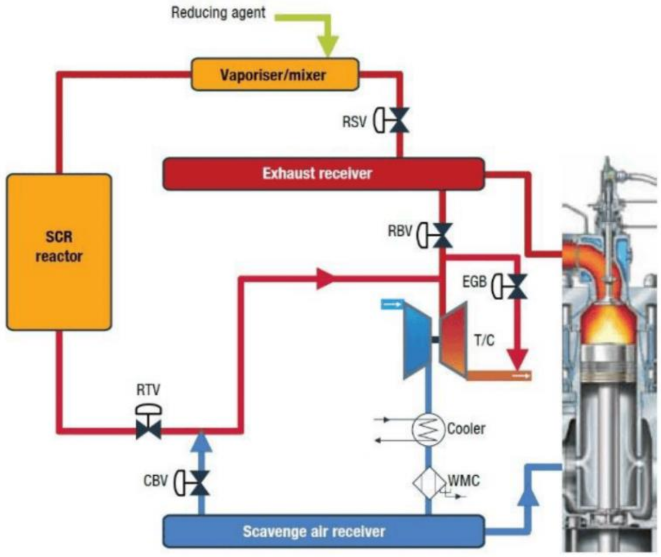

Figure 2: Visualization of the High-Pressure SCR system developed by MAN (Y. Zhu et al., 2022).

The exhaust gases exiting the machine pass through the particulate filter in the first stage and retain up to 70% of the particles. The exhaust gas passing through the particle filter is subjected to oxidation. The oxygen molecules sent on the exhaust gas in the oxidation process react with the incomplete combustion products nitrogen monoxide and carbon monoxide molecules. In addition, the unburned hydrocarbons, which are also present in the exhaust gas, are burned with oxygen there. Then, the blue urea (Ammonia) tank is pumped with a light green dosing pump and sprayed onto the exhaust gas by the injection system. Chemical reactions are allowed here by injection of ammonia. These reactions are as in the red box above. As a result of these reactions, nitrogen molecules and water are produced as products.

Zhang et al. (Zhang et al., 2023) concluded that the high pressure selective catalytic reduction system is particularly well-suited for reducing NOx emissions in high power low-speed marine engines. Their study demonstrated that the weighted specific emission of NOx was measured at 2.09 g/kWh, indicating compliance with Tier III emission regulations.

In another study (Feng et al., 2022) on SCR technology for marine engines, the effects of exhaust components on the catalyst and the improvement of catalyst performance under complex operating conditions were investigated. It was emphasized that there are certain issues that require resolution in order to develop a practically applicable and excellent performance SCR catalyst for marine engines.

3. Conclusion

Consequently, there exist several methods to reduce NOx emissions. The methods examined in this study include common rail, exhaust gas recirculation, Miller cycle, direct water injection, water fumigation from the intake manifold, emulsified fuel, and selective catalytic reduction. Each technology has its own advantages and disadvantages. In addition, certain restrictions and differences may be observed depending on the application areas of these technologies. Therefore, careful consideration must be made against the specific application requirements to determine the most appropriate technology or combination of technologies to reduce NOx emissions.

4. Declarations

4.1 Competing Interests

There is no conflict of interest in this study.

4.2 Author Contribution

Fatih OKUMUŞ: Conceptualization, Methodology, Writing- Original draft preparation, Reviewing, Editing.

Görkem KÖKKÜLÜNK: Conceptualization, Supervision, Writing, Reviewing, Editing.

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