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A Study on Minimizing Potential Accidents in Ship Bunkering Operation Through Use of Failure Mode and Effect Analysis

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ABSTRACT

It is only possible for companies to maintain their position and advance in the competitive environment by preserving their quality and by developing and improving themselves. In this direction, they need to make quality measurements and analyses. For this purpose, more than one quality improvement method has been developed. One of the techniques for enhancing quality is the Failure Mode and Effect Analysis (FMEA) method. FMEA is an operations management and product development method that classifies failures according to similarity, probability, detectability, and severity to analyze potential failure types of a system. It is a technique that focuses on avoiding risks in products and processes during the production phase and documenting these activities. Its purpose is to prevent poor quality, address potential risks that may cause product defects, identify possible types of defects, and determine their consequences and severity. In this study, the bunkering operation between the fuel barge and a ship, the berthing and anchoring of the fuel barge, the fuel transfer process, the unberthing of the fuel barge, and the preparation for the voyage were handled in three stages and the hazards were defined for each stage. Bunkering operation hazards have been identified by using FMEA have been conducted to reduce operational risks, and suggestions have been made.

Keywords: Failure Mode and Effect Analysis, quality improvement, risk, impact, failure

Gemilerde Yakıt İkmali Operasyonunda Gerçekleşmesi Muhtemel Kazaların Hata Türü ve Etkileri Analizi ile Azaltılma Çalışması

ÖZ

Firmaların rekabet ortamında yerlerini koruyabilmeleri ve ilerleyebilmeleri ancak kalitelerini koruyarak, kendilerini geliştirip iyileştirerek mümkündür. Bu doğrultuda kalite ölçümü ve analizi yapmaları gerekmektedir. Bu amaçla da birden fazla kalite iyileştirme yöntemi geliştirilmiştir. Hata Türü ve Etki Analizi (HTEA) yöntemi de kalite iyileştirme yöntemlerinden biridir. HTEA, bir sistemin potansiyel hata çeşitlerini analiz etmek için benzerliğe, olasılığa, saptanabilirlik ve şiddet derecelerine göre hataları sınıflandıran bir operasyon yönetimi ve ürün geliştirme yöntemidir. Üretim aşamasında ürünlerde ve süreçlerde risklerden kaçınılmasına ve bu faaliyetlerin belgelenmesine odaklanan bir tekniktir. Amacı kalitesizliği önlemek, ürün kusurlarına neden olabilecek potansiyel riskleri ele almak, olası hata türlerini belirleyip sonuçlarını ve önem derecelerini saptamaktır. Bu çalışmada yakıt barcı ve yakıt alan gemi arasında gerçekleşen yakıt ikmali operasyonu, yakıt barcının yanaşması ve demirleme, yakıt transferi süreci ile yakıt barcının

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ayrılması ve seyre hazırlık olarak üç aşamada ele alınmış ve her bir aşama için tehlikeler tanımlanmıştır. Tanımlanan tehlikeler HTEA kullanılarak operasyon risklerinin azaltılması konusunda çalışmalar yapılmış ve önerilerde bulunulmuştur.

Anahtar Kelimeler: Hata Türü ve Etkileri Analizi, kalite iyileştirme, risk, etki, hata

1 Introduction

Maritime transport is a significant part of global trade, with many activities involving large-scale vessels. The ship bunker operation is one of these operations. However, bunker operations contain possible hazards and variables that could lead to an accident. This accident can have major repercussions, including pollution, loss of life, economic losses, and ship damage. As a result, reducing potential incidents in bunker procedures is critical. This study investigates how the FMEA method can be used to reduce the risk of accidents in ship bunker operations.

Failure Mode and Effect Analysis (FMEA) is an analysis and evaluation method that systematically investigates the causes and effects of failures that may influence the system's parts (Usug, 2002). The using of the FMEA approach illustrates that good results can be obtained by systematic risk assessment and the deployment of remedial measures to improve the incident's safety and quality. The application of FMEA contributes to the ongoing improvement of the incident regarding safety and quality by assisting in the implementation of risk management measures (Kardos et al., 2021). The FMEA approach can be used to detect, analyze, and minimize probable accidents in ship bunker operations.

This article aims to increase awareness of potential setbacks in ship refueling operations and improve safety through risk assessment using the FMEA approach. By reading this article, stakeholders in the shipping industry can become aware of the potential risks in ship bunker operations and take appropriate procedures to ensure safety.

FMEA is a risk assessment method commonly used in maritime and other industries. To better comprehend the benefits of the FMEA approach and to apply it in this study, it is necessary to first analyze how it is utilized in other industries and what results are obtained. For example, Arabian-Hoseynabadi, H., et al. (2010), investigated the reliability of a wind turbine system utilizing the FMEA method in their study. The FMEA method is applied to a wind turbine system using a proprietary software reliability analysis tool. FMEA quantitative conclusions are compared to confidence field data from real-world wind turbine systems. The unreliability of assemblies, subassemblies, and parts was ranked using FMEA data. This can be used to assist designers in identifying weak points. According to the paper, FMEA has the potential to increase the reliability of offshore wind turbine systems and can play a significant role in the development of maintenance-free or low-maintenance turbines. Finally, this study investigates the applicability and potential of FMEA. In his study, Ceber, Y. (2010) examined the application of FMEA in the manufacturing sector. According to the report, organizations focus on providing higher-quality, more inexpensive, and faster products to meet the challenges of a competitive climate and to remain stable by maintaining consumer happiness. Failure Mode and Effects Analysis (FMEA) is a technique used to avoid existing faults and eliminate potential errors at their source so that their consequences do not occur. FMEA is preferable among other quality procedures since it is simple to implement and can be utilized in various industries. Kaya and Alaykran (2019) estimate the potential error types, causes, and effects that may occur in the production and assembly stages using the Process FMEA method, and the error types that will have the most significant impact on the overall system are prioritized and the risk priority number is determined. It was thus attempted to prevent the incidence of errors and to aid in the planning of activities to minimize the consequences on the client. Asadi, F., et al. (2020) describe a technique for remote monitoring of high voltage transformers in their paper. Based on FMEA, the script functions provided in the study define alert and warning circumstances. This approach detects transformer states early on, allowing errors to be avoided. Tafur, H. D., et al. (2021) investigate the development of reliable control software against hardware failures using an FMEA-based technique, and their findings are promising. Ramere, M. D., and Laseinde, O. T. (2021) provide a novel strategy for using FMEA in the development of care strategies in their study. The performance of engine production equipment must be optimal in the automotive sector. At this point, the FMEA technique aids in the development of a dependable maintenance strategy by identifying potential failure modes and controlling their consequences. A least-cost conflict risk reduction process was integrated into FMEA in a study by Du, Z., et al (2022) to eliminate variations in individual risk estimates in minimum adjustment cost. Using probabilistic linguistic term sets, the suggested FMEA model deals with ambiguity and fuzziness. Risk evaluations can thus be carried out more effectively in complex and uncertain contexts. As a result, risk evaluations can be carried out more thoroughly and sensitively. Hassan, S., et al. (2022) create a modified FMEA model to compensate for a lack of historical data and detect pipeline system hazards more precisely.

These studies in diverse industries show that the FMEA (Failure Modes and Effects Analysis) method has a wide range of applications. These studies demonstrate that FMEA is a successful method for recognizing and mitigating possible accidents in a variety of industries. In addition to FMEA applications in other industries, this method is frequently employed in the marine industry to detect and reduce possible accidents. Cicek, K., and Celik, M. (2013) demonstrate in their studies that FMEA is an effective risk management technique in the maritime industry, providing flexibility to complicated situations such as crankcase explosions. It confronts this difficult maritime engineering problem head on by using FMEA to propose remedies to complex faults such as crankcase explosions. In another study, Zaman, M. B., et al (2014) demonstrate that the fuzzy FMEA method may be employed well for risk assessment of ship collisions in the Malacca Strait. This type of analysis can help improve maritime safety measures and increase maritime transportation safety. Shipyards, another part of marine, are fraught with danger. Ozkok, M. (2014) investigated the shipyard's hull structure fabrication process in a related study. Fault statistics were gathered, faults were classified, and their probability and severity were calculated. This study reveals that FMEA is a useful risk assessment technique in the ship hull structure manufacturing process and offers shipyard strategies to reduce failures and enhance production processes. According to Emovon (2016), a novel FMEA tool incorporating Dempster Shafer Theory and the ELECTRE method is presented to solve the constraints of the FMEA method. The proposed method's practicality is illustrated using a case study of a marine diesel engine. Mentes, A., and Yigit, M. (2020) evaluate the field operations of a ship recycling company in Izmir Aliaga and analyze potential risks using the FMEA approach. The risk priority number (RPN) is calculated for each prospective risk, and conclusions about the prevention or reduction of critical risks are drawn based on the RPN values. Goksu, S. (2021) sought to identify dynamic risk variables in ship operations and to devise a system for assessing the potential consequences of these risks. The FMEA method was used to determine the influence of dynamic risk factors on potential error types. As a consequence of the study, it is suggested that control measures be implemented by identifying the highest priority error kinds. Chang, C. H. et al. (2021) developed a method for assessing the risk levels of major hazards related to Maritime Autonomous Surface Ships (MASS) operation. The FMEA method has made major contributions to hazard classification and risk assessment. Ceylan's (2023) goal is to give a thorough risk evaluation of the ship compressor system. To identify potential failure modes of the ship compressor system, the FMEA method was employed. It ranks risks based on the severity, likelihood, and detectability of each failure mode. Ceylan et al. (2023) provide an enhanced FMEA method for risk analysis of MARPOL Annex-VI ship-related air pollution deficiencies. RPN values are used to list the risk priority of MARPOL Annex-VI deficiencies. The highest risk flaws were discovered in this manner, and the measures that could be performed to mitigate the risks were determined.

According to several research in the literature, the FMEA method has been successfully utilized in various sectors, including the maritime sector. Taking into account all of the benefits of FMEA, this study investigates how the FMEA method might be utilized to reduce potential accidents in ship bunker operations. The fundamental ideas and application methodology of the FMEA approach will be described first. The numerous sorts of faults that can occur in ship bunker operations and the potential consequences of these errors will be explored next. Finally, the outcomes of the FMEA approach will be addressed, as will the measures that can be done to minimize prospective accidents.

2 Method: Failure Mode and Effects Analysis (FMEA)

Once a process is ready for production or is in the production process, it is substantial to ensure the trustworthiness of the process or product. Trustworthiness is an important property of products or processes. It is also a factor that significantly affects customer satisfaction. Customers want the product they use to be long-lasting and at the same time to be a hassle-free process. Therefore, in order to ensure the reliability of a product or process, a risk analysis should be made that can be used to identify possible types of failures and their effects on the product or process and to control its reliability (Yılmaz, 2000).

Issues such as developing sustainable products, increasing the quality of the developed product, production, and logistics are among the challenges faced by manufacturing enterprises today (Kleindorfer et al., 2005). For many years, besides the life cycle evaluation of products, checklists and product guides (Pinheiro et al., 2018) have been used to develop sustainable products. Additionally, various techniques are used to modify the widely used quality management tools to satisfy customer demands and achieve sustainability goals (Luttropp and Lagerstedt, 2006). Failure Mode Effects Analysis is a quality management tool that examines how likely it is for products or processes to fail and how seriously consumers consider the effects of such a failure (Ahsen et al., 2022).

It allows to carry out improvement studies in line with the FMEA result. Thus, improvements can be made on many criteria such as safety, cost, performance, quality, reliability, and environmental standards (Prajapati, 2012).

FMEA has a variety of applications such as System, Design, Process, and Service and covers products and services in sectors. System Failure Mode Effects Analysis is used to analyze a system and its sub-components and to determine the types of failures that may arise from the deficiencies of the system. System FMEA aims to increase the quality and reliability of the system. Design Failure Mode Effects Analysis is used to determine the types of failures that may arise from design failures before production. Design FMEA aims to improve design quality and reliability. Process FMEA is used to prevent failures originating from the production and assembly process. Finally, Service FMEA is used to detect problems that may arise in the organization beforehand. Service FMEA ensures that the failures that occur in the process are taken under control by analyzing the workflow and the process (Özkılıç, 2012).

The Risk Priority Number (RPN) can be determined using the FMEA method. RPN is acquired by multiplying Probability (P), Severity (S), and Detectability (D) values (Ahsen, 2022). The probability degrees in Table 1 indicate the probability of failure (Özfirat, 2021).

Table 1: *The probability and degree of the failure (Özfirat M., and Özfirat P., 2021)*

Probability of failure occurrence	Probability Failure (O)	Rating
Very high: failure is almost inevitable	1/2 or more	10
High: repeated failures	1/3	9
	1/8	8
Moderate: occasional failures	1/20	7
	1/80	6
	1/400	5
Low: comparatively few failures	1/2000	4
	1/15000	3
Remote: failure is unlikely	1/150000	2
	1/1000000 or lower	1

After determining the probability of the failure and the rating corresponding to this probability, the severity value of the effects that may occur as a result of the failure is shown in Table 2.

Table 2: *The Impact and Severity of the Failure (Özfirat M., and Özfirat P., 2021)*

Failure Effect	Severity of Failure (S)	Rating
High hazard without warning	Possible unwarned failure with highly hazardous effects	10
Hazard without warning	Possible unwarned failure with high damage and mass fatality impact	9
Very High	Possible failure with the effect of causing complete damage to the system	8
High	Possible failure causing damage to system components	7
Moderate	Possible failure that adversely affects system performance	6
Low	Possible failure with effects such as broken, permanent minor incapacity, 2nd degree burns etc.	5
Very Low	Possible failure causing injuries such as bruises, minor cuts and scrapes, crushes etc.	4
Minor	Possible failure that slows down the operation of the system	3
Very minor	Possible disturbance to the operation of the system	2
None	No effect	1

After determining the effect and severity of the failure, the detectability of the failure is determined. Detectability refers to the level of detectability of the hazard, and if it is not detected, it refers to the extent of its impact. Its detectability and probability are indicated in Table 3.

Table 3: *Detectability and probability (Özfirat M., ve Özfirat P., 2021)*

Detectability	Detectability Probability	Rating
Absolutely impossible	It is not possible to detect the cause of the possible failure	10
Very remote	Detectability of possible failure is very remote	9
Remote	Detectability of possible failure is remote	8
Very low	Detectability of possible failure is very low	7
Low	Detectability of possible failure is low	6
Moderate	The detectability of the cause of the possible failure is moderate	5
Moderately high	The detectability of the cause of the possible fault is moderate high	4
High	The detectability of the cause of the possible fault is high	3
Very high	The detectability of the cause of the possible fault is very high	2
Almost certain	The detectability of the cause of the possible fault is almost certain	1

A value is obtained by multiplying these numbers with the probability of the error's occurrence, the failure's severity and the detectability numbers for which the Risk Priority Number should be calculated. The RPN Assessment over the calculated value is shown in Table 4.

Table 4: *The Risk Priority Number Assessment (Özfirat M., ve Özfirat P., 2021)*

The Risk Priority Number (RPN)	Precaution to be taken
RPN <40	Existing measures are sufficient.
40 ≤ RPN ≥ 100	It is recommended to take measures in addition to the existing measures.
RPN >100	It is imperative to take measures in addition to the existing measures.

3 Bunker Operation on Ships

Ships refuel in order to use them in the main engine, generators, and boiler and thus continue their course. Although the bunkering operation is routine, it is defined as risky (Kumal, B., and Kutay, Ş., 2021). Although high security measures and procedures have been established for bunkering operations, even the slightest mistake can result in serious problems such as loss of life and marine pollution (Akyüz E., et al., 2018).

The bunker operation stages are shown in Figure 1. The bunker operation begins with the anchoring the ship prepared for the bunker and the berthing of the fuel barge to the ship. When the ship is ready for the bunker operation, the fuel transfer starts by making the appropriate connections with the fuel barge. The bunker operation ends with the disconnection of the fuel supply line after the fuel transfer is completed, the separation of the fuel barge, and the ship's preparations for navigation.

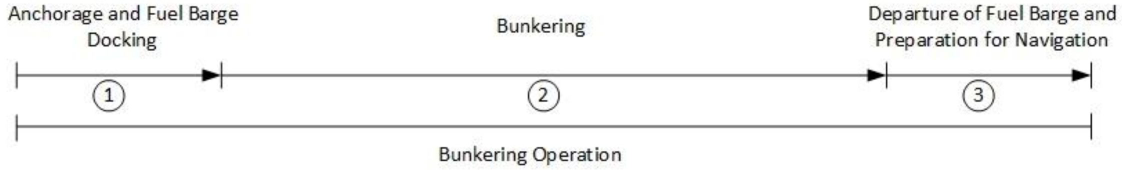

Figure 1: Bunker Operation Steps

The tasks performed during the bunker operation were carried out in three stages: pre-fuel, during, and after the bunker, and are detailed in Section 4.2.

In order for the bunker operation to be carried out safely, it is necessary to have a good command of the current operation steps (Akyüz, E., et al., 2018):

Steps to be taken before the Bunker Operation:

- Conducting the safety meeting
- Taking and recording sounding values from fuel tanks
- Checking the personal protective equipment to be used on the deck
- Checking that all deck brakes are closed
- Making sure the overflow tank is empty
- Checking that the smoking warning is placed
- Ensure that warning signs required for bunkering are placed
- Checking the bunker manifolds
- Checking that Ship Oil Pollution Emergency Plan (SOPEP) equipment to be used in case of fuel leakage into the sea is in suitable places

- Ensure that the fuel barge is safely berthed
- Ensuring correct communication with the fuel barge
- Discussing all the details of the operation with the bunker ship for the bunkering procedure
- Verification of bunkering flowrate.
- Connecting the fuel supply hose to the manifold.

Steps to be taken during bunker operation:

- Opening the manifold valve and starting the supply
- Making sure the flow is kept low during the start of bunkering
- Continuous control of the bunker operation
- Continuous measurement of tank sounders
- Continuous measurement of fuel temperature
- Taking the fuel sample during the bunkering period
- Checking trim and draft
- Closing the manifold valve

Steps to be followed after bunker operation:

- Taking the sounding values of all fuel tanks
- Calculation of the amount of fuel received finally
- Signing the fuel purchase receipt
- Removing the bunkering hose
- Safe separation of the bunker vessel

Table 5: *Failures and definitions*

Failures	Definitions
Personnel Fatigue	The ship's crew may have been out of a busy day before the bunker operation took place. Fatigue may be seen in personnel due to maneuvering, various ship operations, and insomnia before the bunker operation. These reasons can lead to failures.
Insufficient Personnel	The personnel in the bunker operation may not have sufficient knowledge or the ship's crew may have just changed and they may not have operated a bunker on this ship before. The lack of knowledge of the personnel about the operation can lead to failures.
Workload of Personnel	An unexpected problem may arise before or during an operation on board. The crew may be busy with other work other than bunker operation. This situation increases the crew's workload in the bunker operation and can cause failures.
Familiarity	Before the bunker operation, the relevant personnel should be informed about the operation. Bunker operation may take longer than expected and personnel may need to change shifts. The personnel who will change the shift should also be informed about the bunker operation in order not to cause mistakes.
High Level Alarms	High level alarms of fuel tanks should be tested before bunker operation. In case of malfunction, it may cause failures.
Tank Level Sensor	Fuel tank level sensors should be maintained regularly and tested before operation. In case of malfunction during bunker operation, it may not show the level correctly depending on the temperature and density of the fuel taken.
Overconfidence	In the bunker operation, sounding must be taken from the tanks at certain intervals. Many failures can occur when the crew does not care about this situation.

Potential failures in bunker operation steps and their definitions are also shown in Table 5 (Kumal and Kutay, 2021).

It may not follow the chief engineer's instructions or act slowly, which can lead to errors in monitoring.

- Preparing the Bunkering Circuit: The bunkering circuit may have been prepared incorrectly before bunkering. A transfer to a full tank may be initiated due to the opening of the wrong valve, or it may cause overflow on the deck due to a valve not opening.
- Planning: It is of great importance to prepare the bunker operation plan before the bunker operation. Before the operation, how much fuel will be taken into which tank should be calculated correctly. This plan should be known to all personnel. Otherwise, the absence of the plan may lead to failures.
- Communication Between Ship and Fuel Barge: Communication with fuel barge personnel should be established properly. Before starting the bunker operation, how to establish communication should be discussed. Communication with the fuel barge is usually provided by hand signals. For this reason, signs for starting and stopping the operation should be understood before starting the bunker operation. For this reason, personnel should always be assigned to ensure communication on board. It should be checked beforehand that the emergency stop button is also in working condition.
- Onboard Communication: Communication within the ship can be done by radio. Disputes may occur in communication due to environmental effects and weather conditions. This may also cause failures.
- Manifold Connection: The fuel supply line connections should be checked before the bunker operation. The condition of the connection hose is extremely important for the safety of the operation.
- Connection Hose Damaged: The condition of the fuel hose is important, otherwise the damaged hose may cause fuel leakage. This causes major failures.
- Location of the Tank: The location of the ship tanks can negatively affect the bunker operation. If the pumping capacity of the fuel barge is very high and the tank capacity is low, there may be problems during the bunker operation.
- Sea Condition: If the weather conditions are very bad, bunker operation should not be done. Bunker operation may take place when necessary, but bad weather conditions may cause failures.
- Connection hose ruptured: If the fuel connection hose is torn during the bunker operation, it will cause pollution.

4 Bunker Operation Considering the Application Failure Modes and Effects Analysis

When the literature is examined, most studies on the bunker operation have focused on reducing the cost. In addition, some studies analyze the human-induced failures of the bunker operation with various methods (Akyüz et al., 2018). This study analyzed the bunker operation with FMEA and the Risk Priority Number (RPN) was calculated. Additional measures were expressed depending on the RPN and residual risk calculation was made after the additional measures were taken. In this context, the failures to be encountered in the bunker operation are grouped into three stages; the docking of the fuel barge, during the bunkering, and the separation of the fuel barge.

Hazards During Berthing and Mooring of Fuel Barge:

- Conflict Caused by Engine or Rudder Failure (F1)
- Man Overboard During Maneuvering (F2)
- Conflict Due to Bad Weather Conditions (F3)

Hazards During Bunkering:

- Marine Fuel Leakage Due to Incorrect Manifold Connection (F4)
- Fuel Leakage Due to Insufficient Condition of the Connection Hose (F5)
- Fuel Overflows Due to Level Sensor Failure of Fuel Tanks (F6)
- Failure to Properly Conduct the Operation Due to The Inability to Establish Proper Communication Between the Ship and Fuel Barge (F7) [Unable to Adjust the Correct Flowrate, Failure to Stop the Operation in an Emergency Situation, etc.]

Disconnection of Fuel Barge and Hazards During Preparation for Sailing:

- Leakage of Fuel Remaining Inside the Hose While Removing the Hose Connection (F8)
- Man Overboard During Leaving Maneuver (F9)

The probability of occurrence of the hazards described above, the severity that will occur when they occur, the detectability of the hazard, and the risk priority coefficient are expressed in Table 6. Additively, the measures to reduce the hazard are defined in the same table.

Table 6: *Situation Before Taking Action*

Failure	P	S	D	RPN	Precautions to take
F1	5	8	8	320	Performing main engine and rudder checks before maneuvering
F2	5	10	9	450	Ensuring the minimum number of personnel required to be on deck during the maneuver and wearing personal protective equipment of this personnel
F3	3	8	7	168	Considering the weather and sea conditions while scheduling fuel purchase
F4	7	7	7	343	Before the operation, determining the tanks to be fueled and the circuits to be used, making and checking the marking marks on the fuel intake manifold before the operation
F5	5	7	9	315	Periodic checks of hoses and fittings used in the operation
F6	8	7	10	560	Periodic checks of level sensors used in fuel tanks and pre-operation sounding measurements
F7	4	6	9	216	Control of the communication tools before the operation, determination of the hand signals to be used with the bunker barge personnel, placing the emergency stop buttons on the bunker barge and ship side
F8	5	4	6	120	Draining the remaining fuel in the hose circuit to the tank by giving compressed air to the lines after the operation and placing a leak pan under the hose during the removal of the hose.
F9	5	10	9	450	Ensuring the minimum number of personnel required to be on deck during the maneuver and wearing personal protective equipment of this personnel

Table 7: *Situation After Precaution is Taken*

Failure	P	S	D	RPN	Advices
F1	2	8	4	64	In addition to the precautions stated in Table 5, it is recommended to take precautions to reduce severity.
F2	3	5	3	45	It is recommended to take additional precautions to the precautions stated in Table 5.
F3	3	8	2	48	In addition to the precautions stated in Table 5, it is recommended to take precautions to reduce severity.
F4	2	7	3	42	In addition to the precautions stated in Table 5, it is recommended to take precautions to reduce severity.
F5	3	7	2	42	In addition to the precautions stated in Table 5, it is recommended to take precautions to reduce severity.
F6	2	6	2	24	The precautions stated in Table 5 are sufficient and the operation can be carried out by providing safety with continuous monitoring and control.
F7	1	6	2	12	The precautions stated in Table 5 are sufficient and the operation can be carried out by providing safety with continuous monitoring and control.
F8	3	2	2	12	The precautions stated in Table 5 are sufficient and the operation can be carried out by providing safety with continuous monitoring and control.
F9	3	5	3	45	It is recommended to take additional measures to the measures stated in Table 5.

5 Conclusions

Although bunkering operations are routinely performed on ships, they contain serious dangers. Errors that will occur before, during, or after the operation may result in serious marine pollution. In this context, it is important work to reduce the risks in bunkering operations and to carry out a safer operation. The FMEA method is used in this study to reduce the possibility of accidents in ship bunker operations. The FMEA approach was employed for this goal, and the method's benefits and challenges were assessed. Considering the literature research, FMEA has many positive effects. To begin with, FMEA provides a systematic approach for identifying and analysing probable failures in ship bunker operation. This assists in anticipating potential dangers and preventing accidents through preventive actions. Furthermore, FMEA is a method that encourages collaboration and stakeholder participation. This allows multiple viewpoints to be brought together, allowing for a more comprehensive examination. FMEA also aids in resource allocation by getting to the root of problems and focusing on preventative action. FMEA has numerous advantages as well as disadvantages. FMEA attempts to forecast future failures using just available knowledge, however, it is difficult to anticipate all conceivable scenarios. Some FMEA procedures are based on people's subjective assessments. This means that various experts or teams may assess the same fault differently. There may be inconsistency between the outcomes of the evaluation in this scenario.

In the study, the bunkering operation was handled in three stages as the berthing and anchoring of the fuel barge, the fuel transfer process, and the separation of the fuel barge and preparation for the sailing. A total of nine hazards/possible errors belonging to these stages are discussed. The Risk Priority Coefficients of the considered hazards were calculated and the precautions to be taken for each hazard were determined. With the implementation of the measures to be taken, the residual risk score for each hazard has been calculated and recommendations have been added to ensure that the operation can be continued safely.

The bunkering operation usually takes place on the open sea between the bunker and the vessel. The dangers that may arise in the execution of the operation are affected by many parameters such as personnel adequacy, personnel fatigue, sea and weather conditions. Since the bunkering operation takes place in the open sea and is affected by many parameters, small mistakes that cause the realization of hazards have a large impact on the environment and sea pollution.

In this study, it has been found that the measures presented for each hazard reduce the probability and detectability coefficients of the hazards, but do not reduce the severity coefficient as much as the probability and detectability coefficients. It has been found that the measures to be taken in order to reduce the severity coefficients of the hazards considered should be more detailed and comprehensive. In this manuscript, in order to reduce the severity of the hazards in the bunkering operation, a detailed study should be carried out, especially considering the cost/benefit analysis.

Based on the study's findings, we can infer that FMEA is a helpful tool for decreasing the risk of accidents in ship bunker operations. FMEA provides a systematic strategy for identifying and analysing risks and taking preventive measures. However, drawbacks such as subjective judgments and a lack of data should be considered. This study gives ship operators and other stakeholders a vital tool for increasing safety standards in ship bunker operations through the use of FMEA.

6 Declarations

6.1 Competing Interests

There is no conflict of interest in this study.

6.2 Authors' Contributions

Begum DOGANAY: Contribute to the development of the idea of the article, literature review, writing and review of the article

Burak ÇAVUSOGLU: Contribute to the development of the idea for the article, organizing and interpreting the data.

Çagrı Berk GULER: Contribute to the development of the idea for the article, organizing and interpreting the data.

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Cultural Diversity Onboard: A Study About Crew Characteristics

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ABSTRACT

Cultural diversity became a significant factor in seafarers' operational performance onboard. Since ships are operated by multinational crew members, socializing, and understanding foreign cultures became crucial for seafarers working onboard multicultural ships. Diversity management is essential for achieving an effective workforce, as well as making these benefits visible and allowing the organization to leverage them as a competitive advantage. However, apart from its advantages, diversity brought some challenges such as communication errors and cultural misunderstandings. Considering the human element is the primary factor among the maritime accident causations, challenges caused by cultural diversity has the potential to cause a raise in maritime accidents. Crew management onboard multicultural ships should be rigorously carried out to limit unwanted impacts. Our study aims to have a better view on optimal seafarer profile suitable to work onboard ships having multicultural crew members. The prepared questionnaire was administered to interns and officers worked aboard multicultural ships for this purpose, and the findings were evaluated using independent t-test analysis.

Anahtar kavramlar: Cultural diversity, maritime safety, teamwork, multicultural ships

Gemilerde Kültür Çeşitliliği: Personel Özelliklerine Yönelik Bir Çalışma

ÖZ

Kültürel çeşitlilik, denizcilerin gemideki operasyonel performanslarında önemli bir faktör haline gelmiştir. Gemiler çok uluslu mürettebat üyeleri tarafından işletildiğinden, çok kültürlü gemilerde çalışan denizciler için sosyalleşmek ve yabancı kültürleri anlamak çok önemli bir hal almıştır. Gemide kültürel çeşitlilik yönetimi, etkili bir iş gücüne ulaşmanın yanı sıra bu faydaları görünür kılmak ve kuruluşun bunları bir rekabet avantajı olarak kullanmasına izin vermek açısından oldukça önemlidir. Ancak kültürel çeşitlilik, avantajlarının yanı sıra iletişim hataları ve kültürel yanlış anlamalar gibi bazı zorlukları da beraberinde getirmektedir. Deniz kazalarının sebeplerinin başında insan unsurunun geldiği düşünüldüğünde, kültürel çeşitliliğin yarattığı zorluklar deniz kazalarında artışa neden olma potansiyeline sahiptir. Çok kültürlü gemilerde mürettebat yönetimi, istenmeyen etkileri sınırlamak için titizlikle yürütülmelidir. Çalışmamız, çok kültürlü mürettebata sahip

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gemilerde çalışmaya en uygun gemiadamı profili hakkında daha iyi bir görüş ortaya koymayı amaçlamaktadır. Hazırlanan anket bu amaçla çok kültürlü gemilerde görev yapan stajyer ve zabitlere uygulanmış ve bulgular bağımsız t-testi analizi ile değerlendirilmiştir.

Keywords: Kültürel çeşitlilik, Denizde emniyet, Takım çalışması, Çok kültürlü gemiler.

1 Introduction

With the expanding maritime industry, there is a greater demand for seafarers in all positions onboard. Growing world fleet led ship owners donate their ships with multinational crew members. This need brought both positive and negative features together (Daniels, 2017). Seaway transportation is among the most global, multicultural and technological industries in the world as well as the main transportation mode within global trade (Berg et al, 2013). Considering the rate of shipping within world trade, maritime transportation issues have the potential to disrupt global trade. According to studies conducted about maritime accidents, vast majority of the maritime transportation issues occur due to human element. Cultural diversity onboard is commonly considered as a weakness (Theotokas & Progoulaki, 2007). As the cultural diversity has potential negative impacts on human element such as communication errors and cultural misunderstandings, crew management should be carried out elaborately (Yorulmaz & Yanık, 2021). Our study aims to obtain the optimum crew specifications which works onboard multinational ships from the eye of the seafarers. Our study will contribute to the maritime domain in reducing maritime accidents by improving the safety culture and teamwork efficiency onboard multinational ships.

Effects of multinational crew donation on maritime safety is a hot topic in maritime field in recent years. The Seafarers International Research Centre et. al published a report named "The Impact of Multicultural and Multilingual Crews on MARitime COMmunication" in 1999. Multinational crew effects on maritime safety were studied in 2 main categories; language conflict and cultural differences. Same report indicates that over the past 25 years 80% of the world fleet became multinational in crewing. In such environments suspicions and misunderstandings can lead to human errors and cause dangers in maritime operations (The Seafarers International Research Centre, 1999).

Pilot-master cultural diversity effect was studied in previous researches from the perspective of maritime safety. Tuncel et al. (2022) stated that communication errors between pilots and masters have a considerable impact on maritime accidents which occur during pilot embarkation and disembarkation. Horck (2008) mentioned that communication challenges may lead to maritime accidents in ports not only by seafarer errors but also by VTS (Vessel Traffic Service) operator and pilot errors. Horck (2008) also argues that in case cultural awareness courses don't become compulsory, ISM (International Ship Management) Code will lose its efficiency.

2 Methodology

A survey containing 16 questions about seafarer specifications was prepared with the help of an expert group. To obtain opinion of the seafarers on optimum seafarer specifications onboard multinational ships, the prepared and electronically delivered survey was applied to 394 seafarers. A glance at respondents data indicates that respondents mostly consist of students who completed their internship onboard ships. In accordance with gender seafarer statistics, significant part of the respondents are men.

Answers of the respondents were analyzed in Statistical Package for Social Science (SPSS-25). The data was processed by independent t-test.

Prepared survey consists of 4 grouping variables and 16 test variables. Grouping variables examines whether there is significant difference between the answers given for each question by group members where test variables examine the importance of each item according to the respondents. Grouping variables and test variables are as presented in Table 1.

Table 1. *Grouping and test variables*

Code	Testing Variables
Q1	Good knowledge of daily English
Q2	Good knowledge of vocational English
Q3	Socialization skills
Q4	Respecting other religions/beliefs
Q5	Respecting cultural differences
Q6	Respecting gender equality
Q7	Being open-minded about food consumption
Q8	Being prone to teamwork
Q9	Effective usage of body language
Q10	Being understanding
Q11	Being fair
Q12	Being creative
Q13	Being prescriptive
Q14	Being friendly
Q15	Having experience at multinational ships
Q16	Having experience at current position
Code	**Grouping Variables**
G1	Gender (male/female)
G2	Department (deck/engine)
G3	Position (officer/cadet)
G4	Place of origin (coastal/terrestrial)

After forming the survey, respondents are asked to answer the testing questions with the scale mentioned in table 2.

Table 2. *Linguistic terms of the testing answers.*

Value	Linguistic term
1	Not important
2	Little important
3	Neutral
4	Important
5	Very important

3 Results and discussion

According to the t-test analysis, Q5 has the highest mean value in general with 4.51. Respondents highly believe that seafarers who will work onboard multicultural ships must respect cultural differences. Q5 is closely followed by Q4 in general with 4.50 mean value. Respondents believe that seafarers with no respect to other beliefs or religions other than theirs should not be working onboard multicultural ships. Q11, Q8 and Q10 are the next most important specifications for seafarers in this case with 4.48, 4.43 and 4.40 mean values, respectively. Being fair, understanding and prone to teamwork are considered as significantly important for seafarers working onboard ships with cultural diversity. Reliability analysis was carried out in SPSS and Cronbach's Alpha value was found to be 0.819 which proves reliability of the analysis.

Table 3. *Mean values*

Code	Mean	Male	Female	Deck	Engine	Officer	Cadet	Coastal	Terrestrial
Q1	3.54	3.53	3.58	3.54	3.53	3.29	3.57	3.66	3.33
Q2	3.21	3.20	3.32	3.18	3.50	3.85	3.12	3.16	3.29
Q3	3.98	4.01	3.66	3.99	3.88	3.52	4.04	4.04	3.87
Q4	4.50	4.51	4.42	4.52	4.28	4.40	4.51	4.58	4.36
Q5	4.51	4.51	4.58	4.55	4.15	4.27	4.55	4.61	4.34
Q6	4.23	4.23	4.18	4.26	3.93	3.81	4.29	4.21	4.26
Q7	4.09	4.11	3.87	4.16	3.45	4.23	4.07	4.19	3.91
Q8	4.43	4.44	4.32	4.45	4.20	4.13	4.47	4.44	4.41
Q9	4.09	4.10	4.03	4.08	4.18	3.65	4.16	4.16	3.98
Q10	4.40	4.44	4.03	4.41	4.25	3.63	4.50	4.46	4.28
Q11	4.48	4.51	4.21	4.50	4.35	4.17	4.53	4.53	4.40
Q12	4.07	4.10	3.79	4.10	3.83	3.50	4.15	4.15	3.94
Q13	4.07	4.09	3.84	4.10	3.75	4.23	4.04	4.02	4.14
Q14	4.14	4.17	3.92	4.18	3.85	3.56	4.23	4.15	4.14
Q15	2.95	2.94	3.08	2.99	2.60	3.33	2.90	2.84	3.14
Q16	3.27	3.26	3.37	3.28	3.18	3.40	3.25	3.26	3.29

356 of the respondents were male where 38 were female. The biggest difference in mean value between this group members is observed in Q10. Male respondents' mean value is 4.44 where females' mean value is 4.03. This result indicates that male seafarers expect more understanding coworkers onboard a multicultural ship. Also, according to significance (sig.) value, male and female respondent answers are significantly different for Q10 as well as Q11. Being fair has mean value of 4.51 for men and 4.21 for women. This result indicates that men respondents attribute more importance to this personal value as a need at multicultural ships.

Within the departments, 354 respondents are from deck department and 40 from the engine. In this comparison, answers to test variables Q5, Q7, Q13 and Q14 are significantly different according to sig value. Seafarers from deck department attribute more importance for mentioned variables comparing to seafarers from engine department. Results indicate that remaining test variables don't have significant difference between deck and engine department seafarer answers.

Respondents consist 48 officers and 346 cadets. Answers are noted to be significantly different for Q2, Q3, Q5, Q6, Q8, Q9, Q10, Q11, Q12, Q14 and Q15. Officers attribute more importance to Q2 and Q15 comparing to cadets where cadets attribute more importance to Q3, Q5, Q6, Q8, Q9, Q10, Q11, Q12 and Q14. Experience factor between these 2 groups is considered to be the main reason for having so many significant differences in answers.

251 respondents are from coastal area in origin where 143 from terrestrial area. This group variable is involved in our study as culture between these regions are different. According to the sig values Q1, Q4, Q5, Q7 and Q12 has significantly different answers from the group members. All mentioned variables are considered to be more important by respondents from coastal area in origin.

A recent research about sailors' mental health and wellbeing indicates that people onboard feel more isolated and lonely (Sampson & Ellis, 2019). This information is closely related to seafarers socialization skills which has 3.98 mean value in our study. With this value, respondents clearly show that socialization skills are important for seafarers. In order to overcome problems of gender, belief and culture diversity, many researches advised maritime diversity training programs (Appanah et al., 2017; Phillips et al, 2016). This suggestion could have positive impact especially on Q4, Q5 and Q6. Seafarers with diversity awareness, with knowledge of their rewards and challenges can achieve such difficulties easier and become more suitable to work in a culturally diverse ship environment. Smith et al. (2013) declared that superiors' acknowledgment and social support can help strengthen communication and relationships in multicultural working groups. Q9, Q10, Q11 and Q14 are closely related to this point. Friendly, fair and understanding approach to the seafarers by their superiors can help break down the barriers. All these test variables have mean value over 4.00 which is an indication about their importance. Sampson et al. (2020) made a research about effect of belief diversity on cargo ships. Thus, living the religious beliefs in private is a good way to prevent conflicts which may arise from this aspect. Gilliat-Ray et al. (2022) mentions that discussing religious beliefs onboard may offend other seafarers in multicultural ships. Q4 variable in our study is asking the respondents about importance of respecting other religions and beliefs which has a mean value of 4.50, indicating critical importance.

4 Conclusion

In this study, analysis about important personal characteristics for seafarers working onboard multicultural ships were carried out. Importance levels of the variables which were obtained by maritime experts were measured by independent t-test. Answers of respondents were analyzed separately as well according to their gender, department, position and place of origin and results were evaluated. It is observed that importance level of the variables may change according to these grouping variables. It is a fact that cultural diversity will widely spread in shipping industry and weak spots it cause needs to be seen and crew management should be carried out considering these points. Hiring seafarers who are not suitable to work onboard multicultural ship environment may cause extra dangers for maritime operations. So choosing the right group to hire will reduce the dangers. Our study has the potential to give an idea about what seafarers expect from their coworkers while working onboard with people from different cultures. For a healthy work environment onboard and effective teamwork, seafarer perspective needs to be considered in this subject. Results indicate that respecting cultural differences, respecting other religion/beliefs, being fair, being prone to teamwork and being understanding are really important specifications to be possessed by seafarers onboard vessels having cultural diversity. In our study, majority of the survey participants were cadets with experience onboard multinational ships. A research evaluating the same subject from deck and engine officer perspective would be useful in order to understand opinions of more experienced seafarers and discuss the differences of the results obtained in this study.

5 Declarations

5.1 Competing Interests

There is no conflict of interest in this study.

5.2 Author Contribution

Refik CANIMOĞLU: Conceptualization, Methodology, Software, Data curation, Writing- Original draft preparation

Umut YILDIRIM: Conceptualization, Supervision, Writing, Reviewing, Editing.

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Evaluation of Decarbonization Methods on Ships

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ABSTRACT

Reducing CO_2 emissions from ships is regulated by the IMO due to global warming. The regulations aim to reduce carbon emissions gradually. This paper highlights the most recent developments for reducing carbon emissions from ships in compliance with the applicable regulations. Basically, three different techniques are used to reduce carbon emissions. These are the use of clean alternative fuels that do not contain carbon atoms, such as hydrogen and ammonia; the other is the use of ship propulsion systems that can be propelled by electricity; and finally, the use of carbon capture systems. As a result of the study, the potential, advantages, and disadvantages of the techniques used are mentioned. As a result of the study, it was found that carbon capture systems reduce carbon emissions by up to 90%. One of the findings is that CO2 emissions can be significantly reduced with appropriate storage practices.

Keywords: CO_2 reduction techniques, Sustainability, Alternative marine fuels, Marine diesel engines, Carbon capture

Gemilerde Karbonsuzlaştırma Tekniklerinin Değerlendirilmesi

ÖZ

Gemilerden kaynaklanan CO_2 emisyonlarının, küresel ısınma nedeniyle IMO tarafından getirilen düzenlemeler ile azaltması amaçlanmaktadır. Bu düzenlemeler, karbon salımını kademeli olarak azaltmayı hedeflemektedir. Bu çalışma, getirilen düzenlemelere uygun olarak gemilerden kaynaklanan karbon emisyonlarının azaltılmasına yönelik en son gelişmeleri ortaya koymaktadır. Karbon salınımını azaltmak için temel olarak üç farklı teknik kullanılmaktadır. Bunlar hidrojen ve amonyak gibi karbon atomu içermeyen temiz alternatif yakıtların kullanılması, diğeri ise elektrikli gemi sevk sistemlerinin kullanılması ve son olarak karbon yakalama sistemlerinin kullanılmasıdır. Çalışma içerisinde kullanılan tekniklerin potansiyelleri, avantaj ve dezavantajlarından bahsedilmiştir. Çalışma sonucunda karbon yakalama sistemlerinin karbon salımını %90 seviyelerine kadar azalttığı görülmüştür. Uygun depolama uygulamaları ile CO_2 emisyonlarının önemli ölçüde azaltılabileceği ortaya konulmuştur.

Anahtar Kelimeler: CO_2 azaltma teknikleri, Sürdürülebilirlik, Alternatif deniz yakıtları, Gemi dizel motorları, Karbon yakalama

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1. Introduction

The climate crisis, which has arisen due to global warming, is among the most crucial sources of concern today. The main reason for this situation is the high anthropogenic greenhouse gas emissions (GHG) released into the atmosphere. When the general greenhouse gas emissions are examined, the growth rate in greenhouse gas emissions between 2010 and 2019 is around 1.3%, and between 2000 and 2009, it is around 2.3%. Although the rate has been low in recent years, the situation is at alarming levels due to its incremental progress (Cachola et al., 2023).

When anthropogenic GHG emissions are examined between 1990 and 2019, the largest share is undoubtedly CO2. While its ratio among total anthropogenic GHG emissions was approximately 72% in 1990, this ratio increased to approximately 75% in 2019 (IPCC, 2022). Figure 1 represents anthropogenic greenhouse gas emissions between 1990 and 2019.

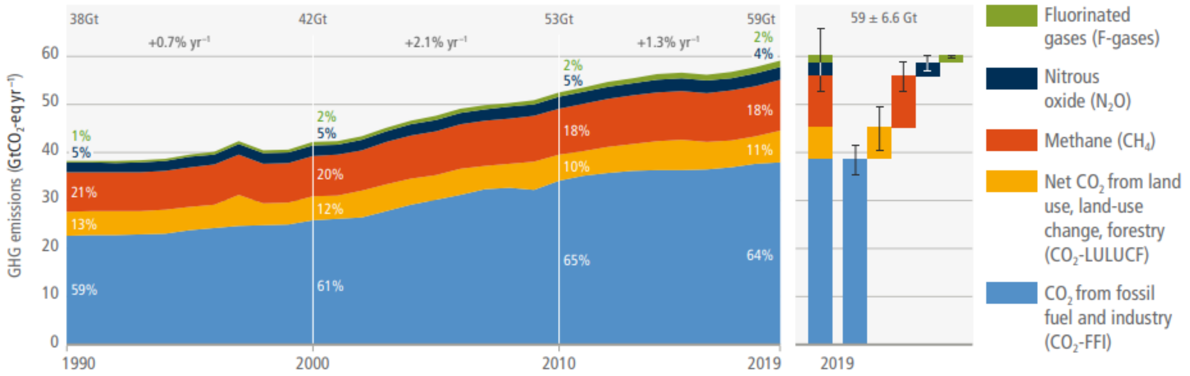

Figure 1: Anthropogenic greenhouse gas emissions (IPCC, 2022).

The fact that approximately 90% of the world's transportation is carried out by sea and the construction of ships with high power requirements in transportation shows that the role of ships in carbon emissions is high (Woodcock et al., 2007). It is thought that the annual CO_2 emissions in the world originating from maritime transport are approximately 940 million tons and this value constitutes 2.5% of the total CO_2 emissions (Eu, 2022).

To address difficulties with maritime pollution brought on by the shipping industry, the IMO established the maritime Environment Protection Committee (MEPC) in 1973. Similarly, in order to prevent environmental pollution from ships, the International Maritime Organization (IMO) adopted the MARPOL Convention in 1973. The MARPOL convention addresses a wide range of marine pollution issues arising from the shipping sector, including oil spills, the transit of poisonous liquids and other hazardous chemicals, sewage, rubbish, and ship air pollution. As a result, it has a considerable impact on the control of marine pollution associated with maritime transport and covers 99% of global commerce tonnage (IMO, 2005, 2022; Perera & Mo, 2016).

The regulations for reducing greenhouse gases, which have been in effect since 2011 within the scope of MARPOL, are generally related to energy efficiency. The arrangements given are generally carried out according to the flow chart given Figure 2.

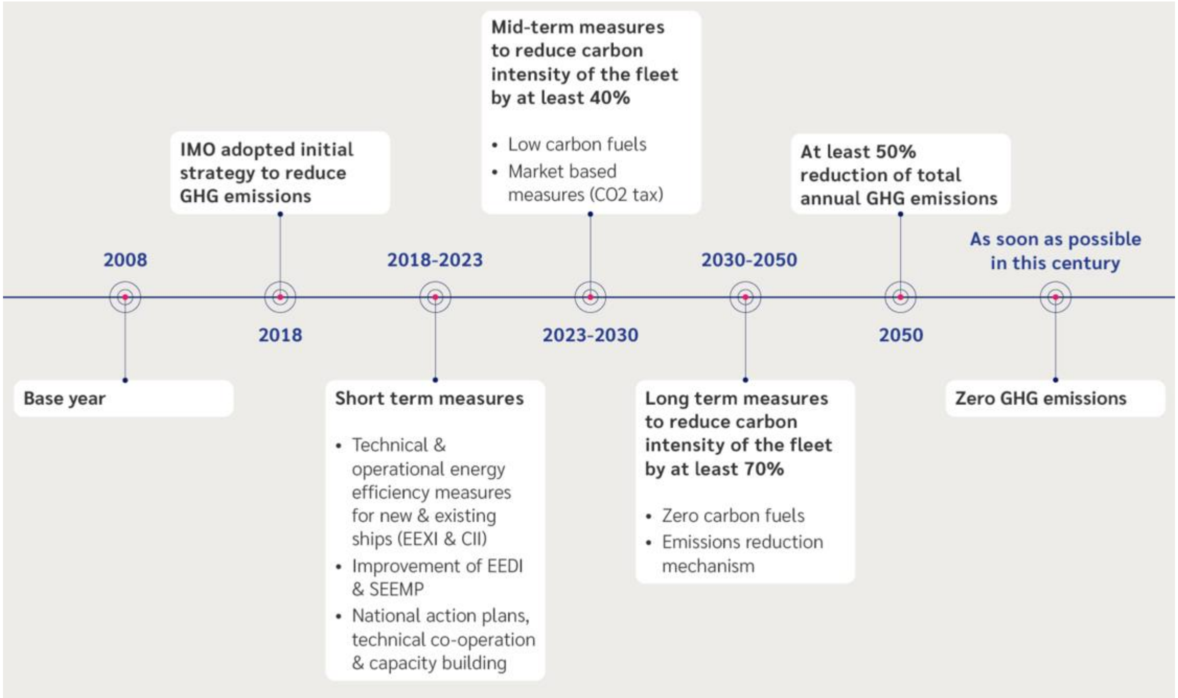

Figure 2: IMO CO_2 regulation (IMO, 2014).

In this context, carbon emissions from ships technically include the following regulations.

Energy Efficiency Design Index (EEDI): EEDI was implemented in 2011 with the goal of lowering CO_2 emissions from ships. It is basically a value related to ship design and expresses the amount of CO_2 that can be released per unit load carrying capacity. The EEDI value, which calls for a significant change in how new ships emit CO2, must be assessed during the design phase and then confirmed through navigational testing. Figure 3 represents the EEDI reference value until 2025 (Eyring et al., 2010).

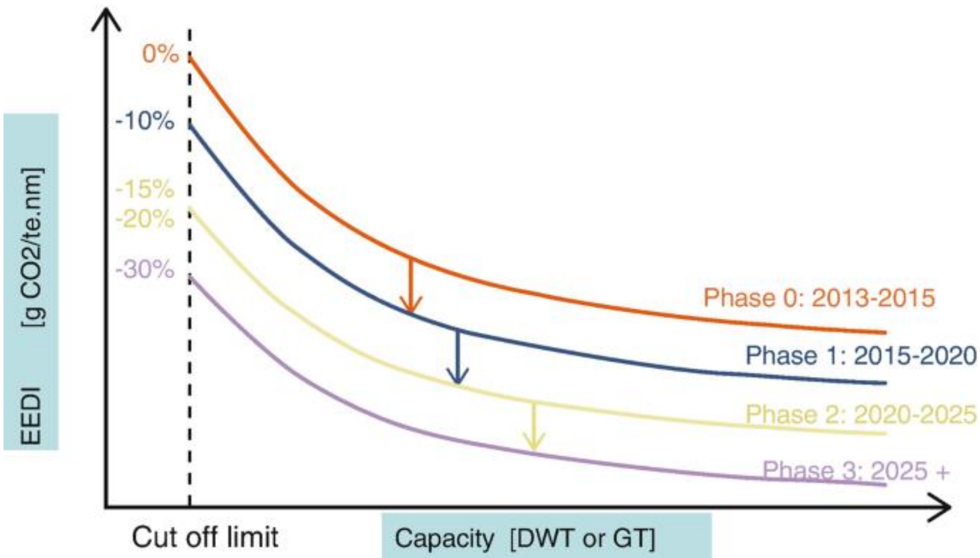

Figure 3: EEDI values (Zheng et al., 2013).

The EEDI was developed for various ship types and must be equal to or less than the reference line. IMO aims to reduce CO_2 emissions by 10% compared to the first phase and 30% by 2025, starting in 2015. For this reason, the development of more efficient ships will be encouraged by applying various technologies to meet the specified EEDI value (Polakis et al., 2019).

Energy Efficiency Existing Ship Index (EEXI): IMO introduced EEXI in its revision approved in 2020 under MARPOL Annex IV on the prevention of air pollution from ships. As of 2023, EEXI is valid for ships larger than 400 GT and regulates the calculation of the standardized CO_2 emissions based on installed engine power, payload, and ship speed (DNV GL, 2022; Rutherford et al., 2020).

Energy Efficiency Operational Index (EEOI): The Energy Efficiency Operational Index (EEOI), an important IMO metric of ship energy efficiency, came into effect in 2011 (Hou et al., 2019). Ship speed, resistance, specific consumption of fuel, operational effectiveness, and further energy efficiency are all directly related to operational operating parameters. Consequently, speed optimization and research of engine speed on ships is the most important of reducing EEOI, energy saving and emission reduction.

SEEMP: SEEMP is an operating strategy that creates a framework to increase the efficiency of energy on board by tracking the performance of the ship and installing energy-efficiency solutions. Since 2013, the plan for management, which includes four phases: planning, implementation, tracking, self-evaluation and enhancements, has included an important mechanism that encourages ship owners to take various measures that promote economical in fuel operation (MEPC.213(63), 2012; Nuchturee et al., 2020).

Basically, these regulations play an important role in reaching the carbon-zero target to prevent global warming by 2050. To decrease the release of CO_2 from ships, the amount of carbon that is aimed to being reduced by different energy efficiency applications is given in Figure 4.

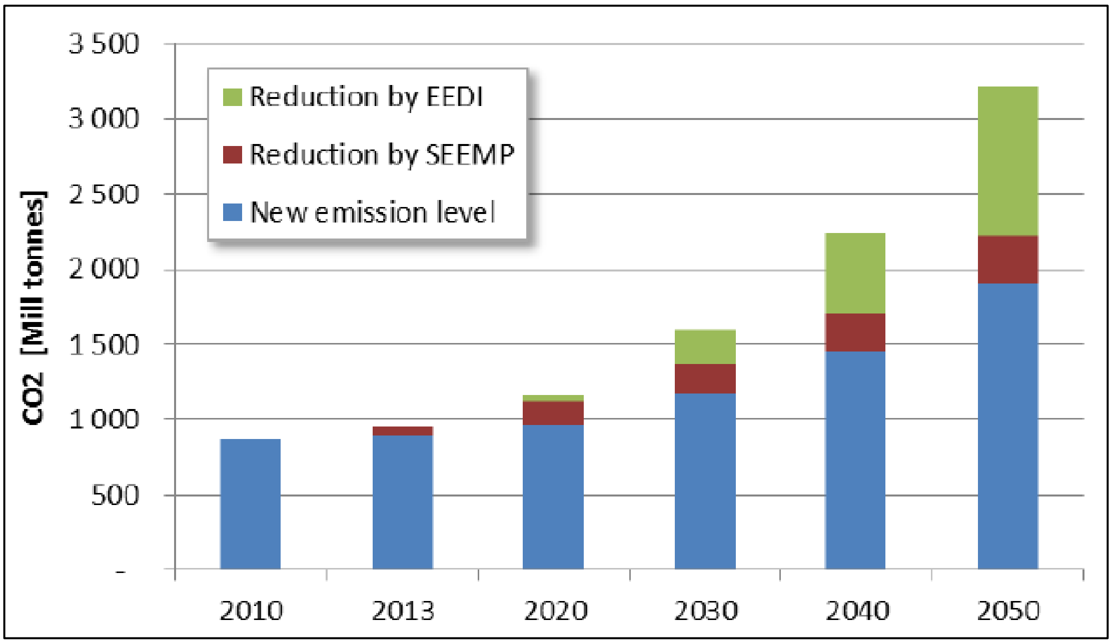

Figure 4: Rates of CO_2 emitted from maritime transport per million tons per year (IMO, 2020).

In this study, approaches that can be used to reduce carbon emissions that cause global warming, especially from ships, and emission reduction amounts will be evaluated comparatively.”

2. Techniques of CO_2 Emission Reduction

To achieve the carbon zero target until 2050 to reduce CO_2 emissions from ships, different technologies are used that can meet the regulations within the scope of MARPOL Annex IV. These methods include the utilization of alternative fuels and renewable energy sources, ship energy-efficient technologies, and the use of carbon capture devices (Hoang et al., 2022).

2.1 Using Alternative Fuels

Alternative fuels used to reduce CO_2 emissions from ships can basically be grouped into two main groups. The first is conventional ship fuels with low carbon content, and the second is fuels that do not contain carbon atoms in their structure. In this study, mainly hydrogen and ammonia will be examined for carbon zero purposes.

Ammonia: Because it excludes carbon atoms in its structure, ammonia is one of the most likely fuels to be employed in the objective of reducing greenhouse gases by approximately 50% and CO2 emissions by 70% by 2050 in order to avert global warming. (Yapicioglu & Dincer, 2018). Liquid ammonia storage, transportation, and distribution are easier and less dangerous than hydrogen. Ammonia is easily liquefied and held at ambient temperature at comparatively low pressure (1030 kPa) or at ambient pressure at a low temperature (240 K). Hydrogen, on the other hand, must be held at greater temperatures (Dimitriou & Javaid, 2020). Ammonia is traded globally and is mostly produced in China, India, Russia, and the United States. Consisting of 17.6% hydrogen and 82.4% nitrogen components by weight, ammonia also undertakes the task of carrying hydrogen (Machaj et al., 2022).

Hydrogen: One of the most important fuels foreseen to be used in ship diesel engines is Hydrogen. Because of its abundance, cleanliness, and high efficiency, hydrogen is a promising future fuel. It can be electrochemically turned into electricity via fuel cells or burned in internal combustion engines. Despite the fact that fuel cells represent a potential future technology, the usage of hydrogen in internal combustion engines remains critical, primarily for power production or heavy-duty applications. Various investigations on the feasibility and advantages of hydrogen as a form of fuel for internal combustion engines have been done in this direction (Bayramoğlu & Yılmaz, 2021; Dimitriou et al., 2018). It has become vital to use alternative carbon-free fuels in combustion systems in order to reduce carbon emissions and achieve the zero-carbon emission target. Since fuel cannot be lost during burning, it is also the most efficient strategy. Due to its lack of carbon, hydrogen is one of the most widely used carbonless fuels (Chai et al., 2021). Since hydrogen cannot be obtained naturally and must be created to be used, it cannot be used widely. The costly equipment required to liquefy hydrogen and transport it as liquid are additional factor (Kojima, 2019). Table 1 shows the thermodynamic properties of alternative fuels (Dotto et al., 2023).

***Table 1**:Specifications of alternative fuel* (Dinesh & Kumar, 2022; Song et al., 2022).

Property	H_2	CH_3OH	NH_3	LNG
Density [kg/m^3]	71.1	805	683	422.6
Calorific value [MJ/kg]	120	20	19	50
air-to-fuel ratio	34	6.5	6	17.2
Storage temperature [°C]	−253	25	−34	−162
pressure of storage [bar]	1	1	1	1
h_{vap}[kJ/kg]	450	1199	1371	512

2.2 Using Renewable Energy Sources

The usage of alternative energy sources on ships means the elimination of all harmful gases released into the atmosphere. There are basically two types of green energy sources, solar and wind. According to the statistics made in 2021, by the end of 2020, the renewable energy generation capacity will have reached a level of approximately 2799 GW (Huang et al., 2021). The share of solar and wind among the renewable energy sources produced is 25.5% (714 GW) and 26.1% (733 GW), respectively. (Jathar et al., 2022). However, although renewable energy sources are used alone in small-sized vessels today, they are mostly used as hybrid energy sources with solar and wind. Hybrid systems are widely used on naval vessels, tugboats, offshore vessels, research vessels and yachts. Figure 5(a) depicts the "Greenline 33 Hybrid Yacht" built together with Slovenia and Italy in January 2010. The boat is powered by a battery package, solar and diesel power, and it can run in both diesel and electricity configurations. Feadship, a Dutch constructor, constructed the 274-foot (83.5 m) boat "Savannah" in 2015, as seen in Figure 5(b). This yacht's power system consists of a four-stroke diesel engine, three electricity producers and a bank of 1 MW lithium-ion batteries. There are three operating modes for the boat's power system: diesel-powered, hybrid diesel-electric, and power-only. A system that uses hybrid power has benefits such as long-term dependable performance at high speed and power levels and long-term stable operation at low speed and power levels.

Combination diesel-electric power technology has advanced in tandem with the advancement of power electronics technology. Using this kind of technology, all power generating and storage devices for energy have primarily been utilized in the design of propulsion systems onboard tugboats, yachts, ferryboats, research vessels, navy and offshore ships. The watercraft depicted in Figure 5(c) became operational in November 2017 as the world's first 2000-tonne new energy electric ship. The ship used two electric motors to operate the flat-bladed omnidirectional propellers as the control and power system, which was powered by a hybrid energy storage system (a supercapacitor and a lithium-based battery). The California Air Resources Board (CARB) announced in June 2018 the production of a 70-foot aluminum catamaran ferry called the "Water-Go-Round" in the Bay Area, as depicted in Figure 5(d). This vessel is powered by a hybrid of hydrogen fuel cells and lithium-ion batteries. It was the world's first ship to use ~~a~~ hybrid fuel cell technology. Furthermore, this ship is the world's first to use fuel cells (Jathar et al., 2022).

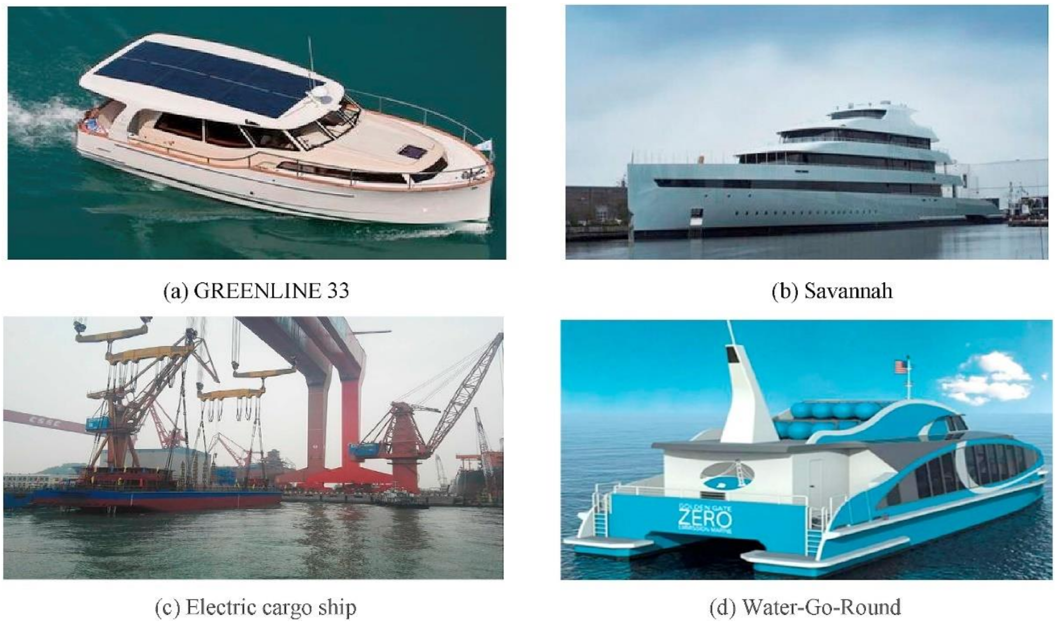

Figure 5: Hybrid ships (Yuan et al., 2020).

2.3 Carbon Capture and Storage Systems

Carbon capture and storage (CCS) systems on ships can be considered as a technology used to achieve standards related to decarbonisation, in the case of using conventional fuels. CCS can be used in ships to treat all carbon-containing fossil, electrical and biofuels, which can have a medium- to long-term impact on ship decarbonization. However, the viability of CCS is dependent on a number of variables, such as the advancement of CCS technology, commercial feasibility, the cost and accessibility of alternative fuels, and future emission-related policies (Howell et al., 2022).

There are primarily three different types of carbon capture techniques. These are pre-combustion carbon capture, post-combustion carbon capture and oxygen combustion and carbon capture systems. A post-combustion carbon capture system has been proposed by Pi-Innovation, where water acts as a physical mass transfer solvent. This CO_2 Capture may be utilized on land or at sea. Decarbonization that is largely complete of flue gases provides low cost and ease of usage in numerous different flue gas sources with partial CO_2 content. Also, The fact that post-combustion CO_2 capture produces a solubility difference between CO_2 and N_2 at lower temperatures and higher pressures is a significant benefit (Blount et al., 2017; Malekli & Aslani, 2022) . Figure 6 represents the post-combustion carbon capture process.

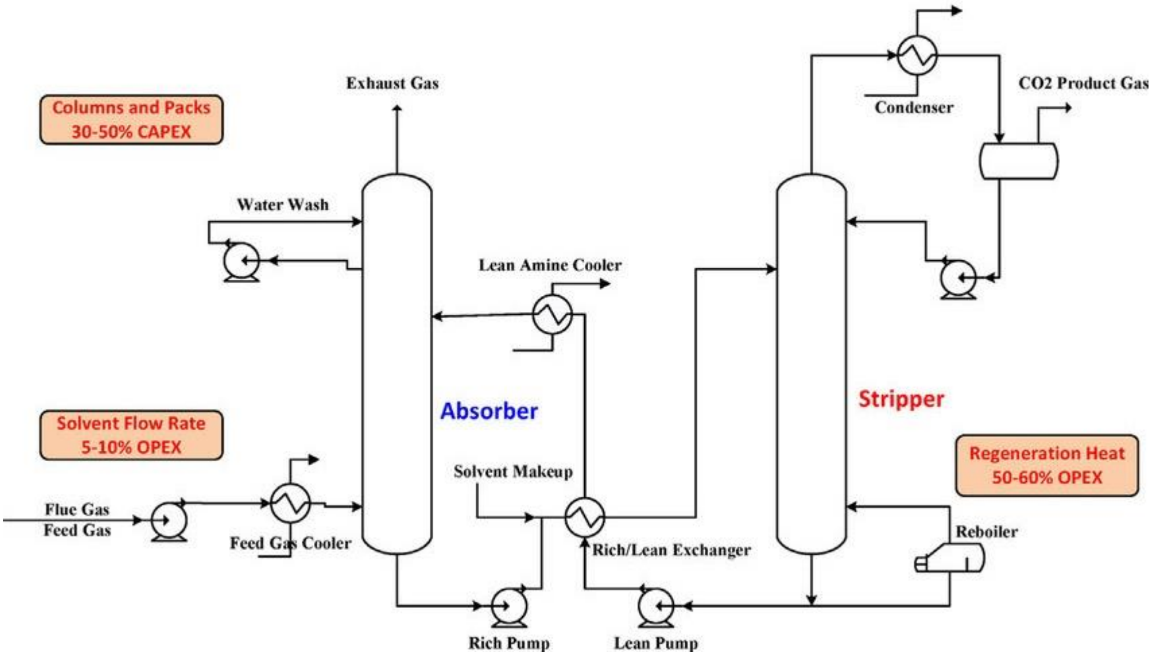

Figure 6: Post-combustion carbon capture process (Liang et al., 2015)

Pre-combustion carbon capture involves the process of removing carbon dioxide from a fossil fuel or biomass fuel before the combustion process is complete. It is mainly based on the gasification process of fuels in the form of biomass, natural gas, and coal (Theo et al., 2016). To reduce the CO_2 components formed as a result of the combustion of fossil fuels such as natural gas, the CO_2 and H_2 components in its structure are separated with the help of a membrane. As a result, the CO_2 components in its structure will be separated without requiring gasoline to be sent to the ship's diesel engines. The purified gas, which the mixture is made up of about 40% CO_2 and 60% H_2 separated from natural gas prior to combustion, will undergo CO_2 separation treatment to produce pure H_2, which will then be fed to gas turbines for the purpose of generating electricity. The methods used to remove CO_2 from a fuel gas mixture include absorption, adsorption, membrane separation, and cryogenic separation (Babu et al., 2016). Figure 7 represents the pre combustion carbon capture process.

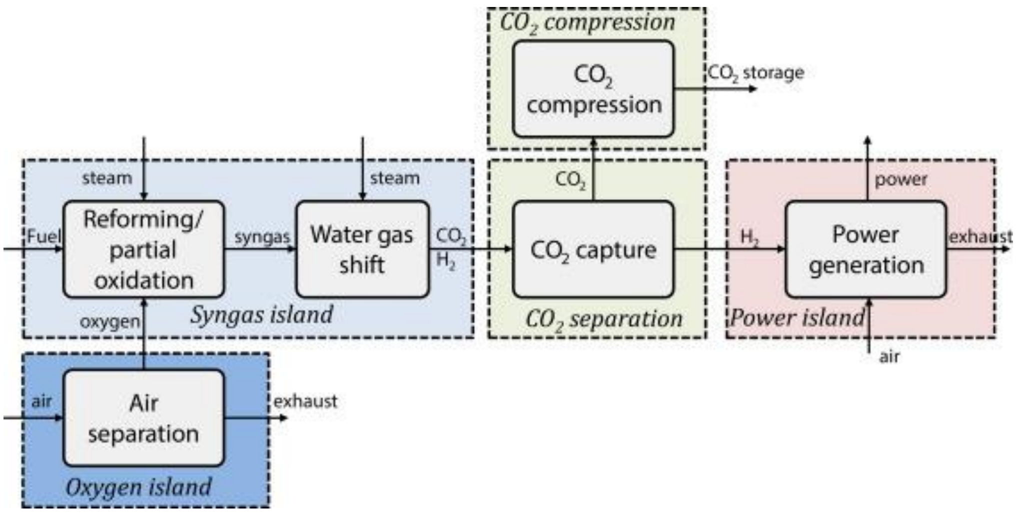

Figure 7: Carbon capture process pre-combustion (Jansen et al., 2015)

As a result of pure oxygen combustion, combustion takes place by using pure oxygen instead of air in the carbon capture process. After combustion, the exhaust gas consists of CO_2 and H_2O vapor. The flue gas is cooled so that the water turns into liquid and is separated from the carbon dioxide. Combustion with pure oxygen produces very high temperatures. This process simplifies carbon dioxide capture as it contains no nitrogen. This process can compete with the post-combustion capture process, but experience with this process is limited (Albazzaz, 2020). Figure 8 represents the oxy-combustion carbon capture process.

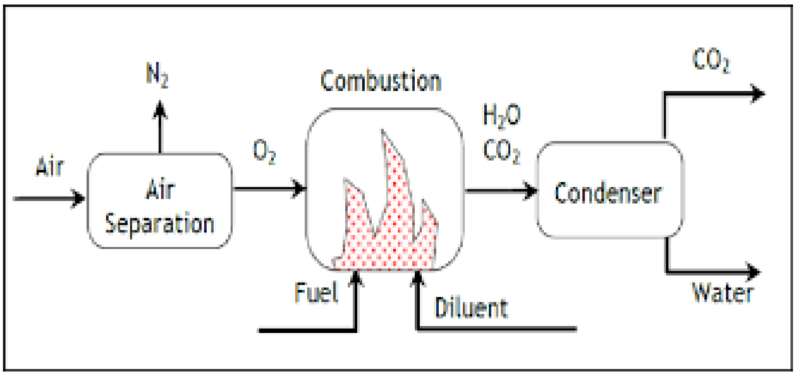

Figure 8: oxy-combustion carbon capture systems (Albazzaz, 2020)

3. Comparison of Carbon Reduction Systems on Ships

Different methods are used to reduce the CO_2 gases that cause global warming from ships. These technologies, in addition to lowering CO_2 emissions, have a significant influence on the performance of engines and other emissions.

In the study conducted by Seddiek and Ammar (Seddiek & Ammar, 2023), the effect of ammonia use on CO_2 emissions in diesel engines versus conventional ship fuel was evaluated. As a result of the study, 1052 tons of CO_2-eq. Against the emission of ammonia, this rate was determined as 202.8 tons CO_2-eq. Likewise, in the case of diesel fuel combustion, the percentage ratio of CO_2, CH_4 and N_2O components is determined as 96.3%, 2.7% and 1%, while only CO_2 components are formed in the use of ammonia. The chemical process used to produce ammonia is the primary cause of the synthesis of carbon compounds. The determined EEDI and EEOI in the case of diesel fuel use were 20.32 gCO_2/ton·nm and 39.68 gCO_2/ton·nm, respectively, while the EEDI and EEOI were determined as approximately 1 gCO_2/ton·nm in the case of ammonia usage.

Although hydrogen as a fuel combines with different gases, it is not found alone in nature. Therefore, it is necessary to separate the structures in the form of compounds with different techniques (Bayramoğlu et al., 2022). Even though it does not create a CO_2 component as a result of combustion in diesel engines, it causes CO_2 formation in the chemical processes during its production. Wang et al. (Wang et al., 2023) intended to investigate the full maritime hydrogen fuel technology chain. Figure 9 represents six different technologies of hydrogen production.

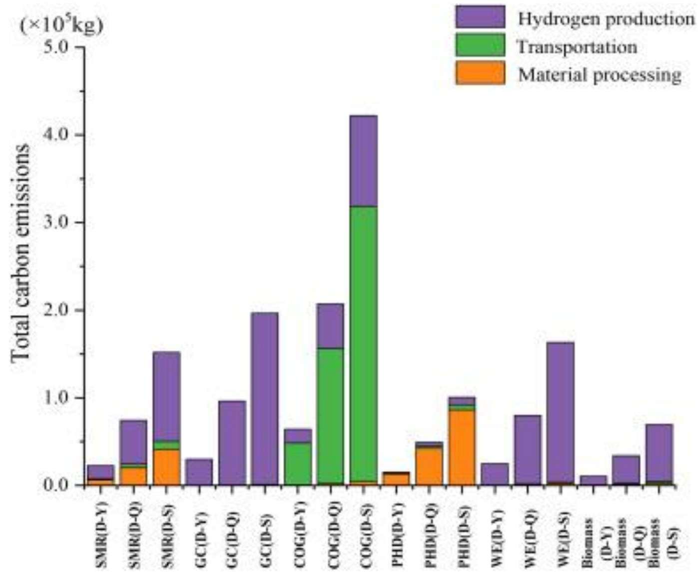

Figure 9: Carbon emissions of six types of hydrogen production (Wang et al., 2023)

Different techniques applied in hydrogen production are defined as steam methane reformer (SMR), gasification of coal (GC), coke oven gas (COG), propane dehydrogenation (PDH), water electrolysis (WE), and biomass gasification. According to the findings, the use of the biomass for hydrogen supply technique has a substantial benefit with regard to of CO_2 emissions.

Renewable energy sources are systems that are sensitive to both human health and the environment. However, the fact that a large part of maritime transport is carried out by ships has made it necessary to optimize higher carrying capacity and lower costs. Therefore, renewable energy sources can be used either in small marine vehicles that require less energy or with hybrid systems in addition to diesel engines (Caliskan et al., 2013; Jeong et al., 2022). Furthermore, clean energy is critical to effectively meeting energy-saving targets and lowering emissions. However, due to the very nature and functioning of ships, utilizing one energy source or one energy form simultaneously has some limitations has restrictions, particularly for ships with high power capacities. Solar energy, for example, is affected by ship structure, operational circumstances, and meteorological variables, making it unsuitable for all ship types (Diab et al., 2016; Nasirudin et al., 2017).

Stec et al. (2021) evaluated the impact of post-combustion carbon capture systems on CO_2 and EEDI reductions in marine applications. Reducing CO_2 components in ships directly leads to a decrease in the EEDI value (Stec et al., 2021). In parametric studies, it has been determined that CO_2 emissions have been reduced by approximately 90%. The study mainly investigates the potential of reducing the EEDI of a 47,000 DWT intermediate tanker (Handymax class tanker) using HFO. In addition, Feenstra et al. (2019) demonstrated the Ship-Based Carbon Capture idea as a transitional solution to notably reduce CO_2 emissions on ships. The concept of Ship-Based Carbon Capture has been shown to be technically feasible. Theoretical design ideas for two sample instances, an inland ship and a cargo ship, are presented. Balances of mass and energy reveal the probability of ships aptitudes of up to 90% of their pollutions. In addition, it emerged that the dimensions as well as the weight of the equipment were suitable for the cargo ship's design and did not impair its stability's.

Comparisons between the EEDI values of a ship currently in operation and those in which three different carbon reduction techniques are applied are given in Figure 10. The results obtained basically reveal that the EEDI values of the ships that are shipped with hydrogen fuel, carbon capture and storage systems, and electrical power, which do not contain carbon in their structure, are close to zero. In addition, basic parameters such as CAR, Es and CS used in EEDI calculations were also investigated in the study (Law & Othman, 2022).

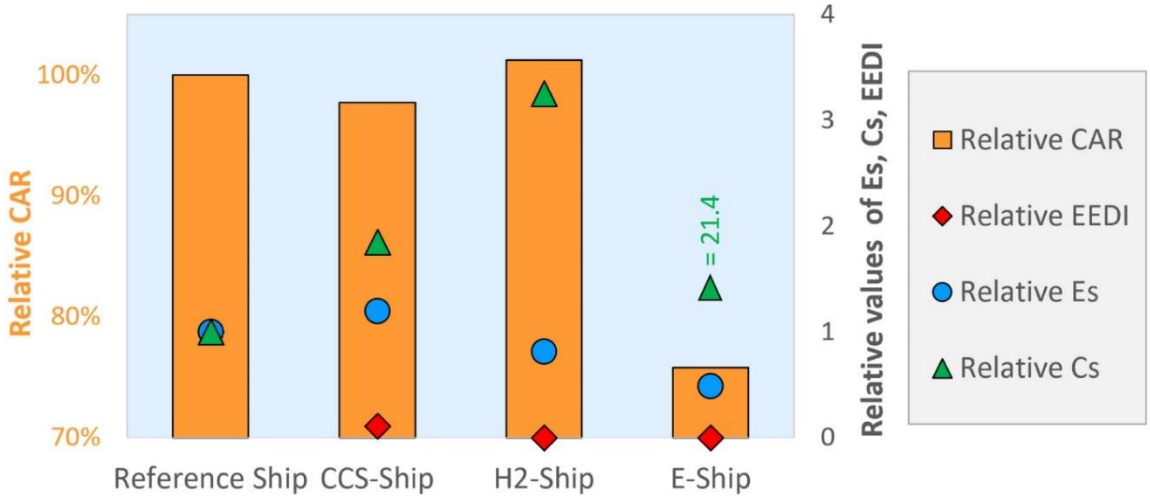

Figure 10: EEDI for variable configurations (Law & Othman, 2022)

4. Conclusion

For the first time in 2011, the IPCC was implemented to reduce carbon emissions from ships. Implementations will be carried out gradually until 2070, ultimately aiming to achieve carbon zero by reducing carbon emissions from ships by approximately 70%. With the introduced regulations, it is aimed to apply alternative fuels with a low carbon ratio, which allows carbon emissions to be reduced by 25%, such as LNG, until 2030 in the first place.

In the second stage, it is necessary to apply clean fuels such as ammonia and hydrogen, which do not contain carbon atoms in their structure, to reduce it by approximately 50% until 2040. However, some difficulties arise due to the low calorific energy of ammonia and the release of carbon emissions during its production. If hydrogen is used as a diesel fuel, engine modifications are also required if it is used directly as a stand-alone fuel due to its high energy value and rapid flammability. In addition, although hydrogen is the lightest metal and makes compounds with most metals, it is not found alone in nature. This makes it necessary to obtain hydrogen with different techniques. In addition, it prevents the usage of H_2 as a energy sources in the storage and transportation problems of hydrogen obtained by chemical means.

In the third stage, in reducing carbon emissions by 70%, it removes the obstacles to carbon zero in carbon capture and storage systems, as well as clean fuels. Carbon capture and storage systems only remove the Barriers to fuel prices and reduce emissions from the usage of fossil sources. However, the initial installation and operating costs also raise questions about the use of these systems on ships.

5. Declarations

5.1. Competing Interests

There is no conflict of interest in this study.

5.2. Author Contribution

Kubilay BAYRAMOĞLU: Conceptualization, Writing- Original draft preparation, Writing - Review & Editing.

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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.

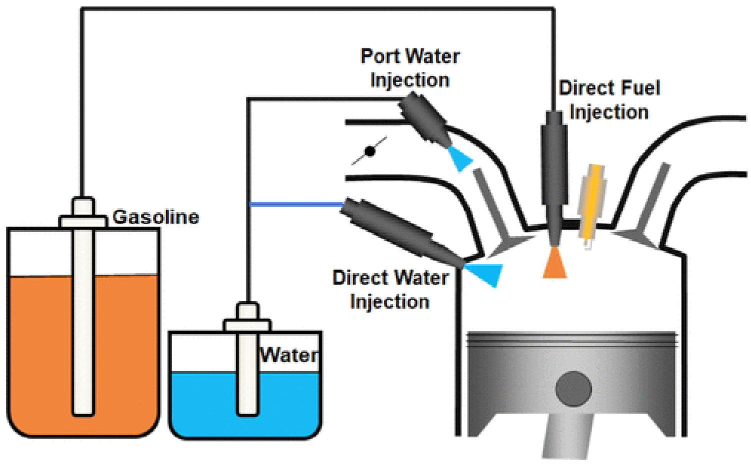

Figure 1: The schematic drawing of DWI unit (Singh et al., 2020).

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.

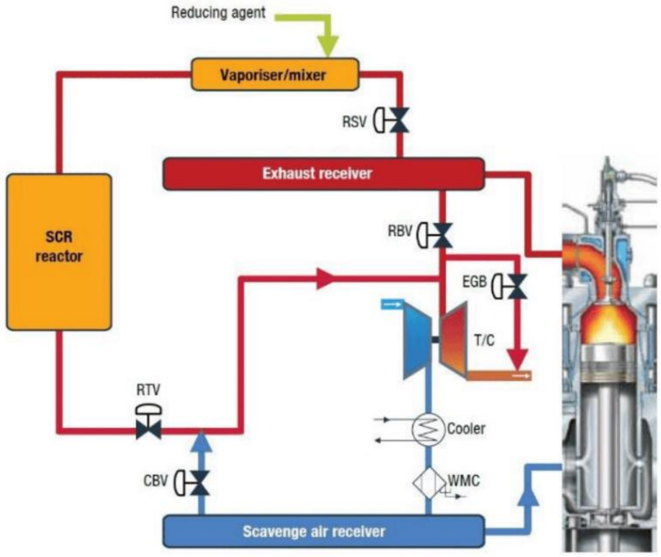

Figure 2: Visualization of the High-Pressure SCR system developed by MAN (Y. Zhu et al., 2022).

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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