JOURNAL OF MARITIME RESEARCH

Vol XXII. No. I (2025) pp 324–331

ISSN: 1697-4840, www.jmr.unican.es

The Environmental Impact of Anaerobic Digestion for Methane Generation on Cruise Ships

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ARTICLE INFO

Article history:
Received 05 Aug 2024;
in revised from 20 Aug 2024;
accepted 17 Sep 2024.

Keywords:
Anaerobic Digestion; CFD;
Greenhouse Gases (GHG); IMO;
Nitrogen Oxides.

ABSTRACT

Many studies verify that fossil fuels are the main factor responsible for climate change and other environmental issues. The combustion of fossil fuels produces a major portion of the greenhouse gases (GHG) that blanket the Earth and trap the sun's heat. The transportation sector, especially the shipping industry, accounts for a large share of the world's rising energy consumption. This study highlights the IMO regulations and the technological methods to develop environmental sustainability in seafaring. One of the primary components of shipping exhaust emissions is nitrogen oxide (NOx). To respond to increased natural demands and environmental concerns, the International Maritime Organization (IMO) established restrictions to reduce NOx emissions. Methane can be utilized as an alternative fuel in a Methane-Diesel Dual Fuel Engine to reduce noxious emissions. Generating methane by onboard anaerobic digestion provides an additional energy source for ship operations. The current study shows that organic waste generated onboard cruise ships can contribute significantly to a more efficient ship energy system through anaerobic digestion. This study also focuses on the environmental effect of using methane as an alternative fuel to reduce the NOx emissions, performed by using the commercial software ANSYS to simulate and model the combustion process.

1. Introduction.

Greenhouse gases have a significant impact on climate change and global warming (Elmallah, 2025a; Elmallah, 2025b). These gases, such as carbon dioxide, methane, and nitrous oxide, trap heat in the earth's atmosphere, creating a warming effect that can lead to rising global temperatures (Elmallah, 2025c; Elmallah, 2025d; Elmallah, 2025e). As humans continue to burn fossil fuels and engage in other activities that release these gases into the atmosphere, the concentration of greenhouse gases has been steadily increasing over the past few decades (Elmallah, 2025f; Elmallah, 2025g). This increase is causing the Earth's temperature to rise, leading to a range of negative impacts such as melting glaciers, rising sea levels, and more frequent and severe weather events. Due to growing worries about the environmental impact and cost of fossil fuels, the investigations for alternative renewable energy sources have become more urgent (Elmallah, Elgohary, Shouman, 2023). To combat the effects of greenhouse gases, it's important to reduce emissions and convert to cleaner sources of energy (Elmallah et al., 2024a; Elmallah et al., 2024b). This can include things like investing in renewable energy, improving energy efficiency, and reducing reliance on fossil fuels (Elmallah et al., 2024c; Elmallah, 2024). Doing so will slow the rate of climate change and protect the planet for future generations. Reducing greenhouse gases has

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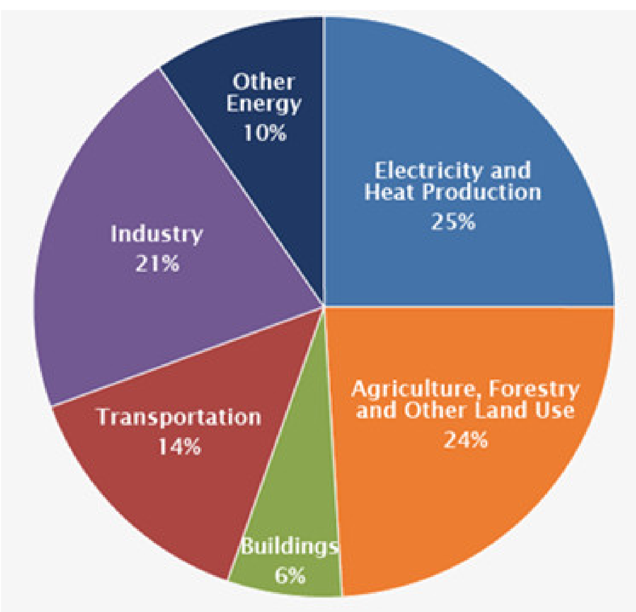
become a priority in government policies and research committees due to the growing international collaboration regarding the adverse effects of climate change. It is crucial to comprehend the factors that affect the GHG emissions and to develop up suitable methods to decrease these emissions.

In 2015, the concentrations of greenhouse gases, such as CO_2, methane (CH_4), and nitrous oxide (N_2O) in the atmosphere increased by 44%, 156%, and 21%, respectively, compared with these concentrations in 1750 (EPA, 2016).

According to commonly used economic sector categories, greenhouse gas emissions are distributed among major economic sectors (EPA, 2016). The largest source of greenhouse gas emissions from human activity goes to electricity and heat production. However, the transportation sector is crucial to economic and social development and also has one of the world's fastest-rising rates of energy consumption and emissions. Figure 1 illustrates the greenhouse gas emissions by economic sectors.

Figure 1: Greenhouse gas emissions by economic sectors.



Source: US EPA, 2016.

International shipping is one of the greatest GHG emitting industries in the world economy, and it is also predicted to have one of the quickest GHG growth rates (Gibbs et al., 2014).

According to the International Maritime Organization (IMO), shipping is estimated to be responsible for 2.2% of the world's greenhouse gas emissions in 2018, although this number is expected to rise sharply in the future. The IMO has put out regulations to reduce emissions from shipping, including the use of low-sulphur fuels, the use of energy-saving technologies, and the implementation of emissions monitoring and reporting requirements. Despite these attempts, the shipping sector still has a way to go in terms of decreasing its emissions, but it is still possible to minimize the consequences of climate change with the correct regulations and technologies. The maritime sector is responsible for 6.6%, 4% and 2.6% of Nitrogen Oxide (NOx), Sulfur dioxide (SOx) and Carbon dioxide (CO_2) emissions, respectively (El-Gohary, 2012)

The emission of nitrogen oxides (NOx) from shipping has a significant impact on the global environment and contributes to air pollution, health concerns, acid rain, and global warming. the IMO has set a target of reducing NOx emissions from shipping by at least 80% by 2050 compared to 2008 levels, by establishing emission control areas (ECAs) in designated regions, such as the Baltic Sea and the North Sea by implementing a three-tier system in NECAs (NOx Emission Control Areas). This study focuses on the technological methods to decrease noxious emissions and to develop environmental sustainability in seafaring. Table 1 shows a summary of emission mitigation methods for ships.

Table 1: Summary of Emission Mitigation Options for Ships.

Measure Types	Measure	Description	Examples
Technological strategies	Lower sulfur fuel	- Marine residual or bunker with sulfur content at 1.5%, or below (44% Sox reduction, 18% PM reduction) - Marine distillate and gas oil with sulfur content at 0.1% or below (> 90% Sox, > 80% PM reduction)	- EU (and IMO) Sulfur Emission Control Area: Baltic Sea (2006), English Channel, and North Sea (2007) - San Pedro Harbor Maersk voluntary agreement (0.2% sulfur fuel, 2006)-California auxiliary engine rule (2007)
	Selective catalytic reduction (SCR)	- exhaust after-treatment technology providing over 90% reduction in NOx, PM, CO, and HC reduction can be obtained when SCR is combined with a PM filter and oxidation catalyst	- Units in service starting in early 1990s in applications ranging from ferry, cruise ship, to roll-on roll-off vessels
Operational strategies	Vessel speed reduction	- speed within harbors is reduced to reduce engine load and NOx production (4%-8% reduction)	Voluntary program in the Los Angeles/Long Beach harbor since 2001
	Shore-side power	- Land based power for docked ships (100% reduction in at-port emission)	- Facilities operating in the Baltic and North Seas, Juneau (Alaska), and Port of Los Angeles
Market-based strategies	Environmentally differentiated fee	- Fee reductions based on vessel environmental performance - Emissions benefits depend on level of participation and implemented technologies	- Voluntary Environmentally Differentiated Fairway Dues Program in Sweden since 1998
	Cap and trade system	- A government or regulatory body first sets a limit or (cap) on the amount of environmental degradation or pollution permitted in a given area and then allows firms or individual to trade permits or credits in order to meet the cap.	

Source: Authors.

Methane, also known as natural gas, has been considered as a potential alternative fuel for engines in ships due to its low emissions and cost-effectiveness. The use of methane as a fuel can significantly reduce emissions of carbon dioxide (CO_2), nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter (PM). Reducing methane emissions from organic wastes is essential for mitigating climate change, as it is 28 times more potent than carbon dioxide in terms of its impact on global warming. Organic wastes, particularly from human activities, are significant sources of methane emissions. However, recent researches have shown that a good environment can effectively pull methane from organic wastes and turn it into a useful energy source. The production of methane on land occurs through a process known as anaerobic digestion (AD), where microorganisms break down organic matter in the absence of oxygen. This process is commonly used to treat wastewater, landfill waste, and animal manure.

The production of methane on land not only generates biogas for energy but also reduces waste and greenhouse gases emissions. On the other hand, methane generation on ships occurs through the natural decomposition of organic matter, such as food waste, sewage, and other biodegradable waste. The methane produced on ships can be captured and used as a renewable energy source, reducing the use of traditional fossil fuels. This paper provides an in-depth study of onboard organic waste that can be converted into biogas, with a focus on food waste and sewage sludge. This paper also focuses on the environmental effect of using methane as an alternative fuel to reduce the NOx emissions.

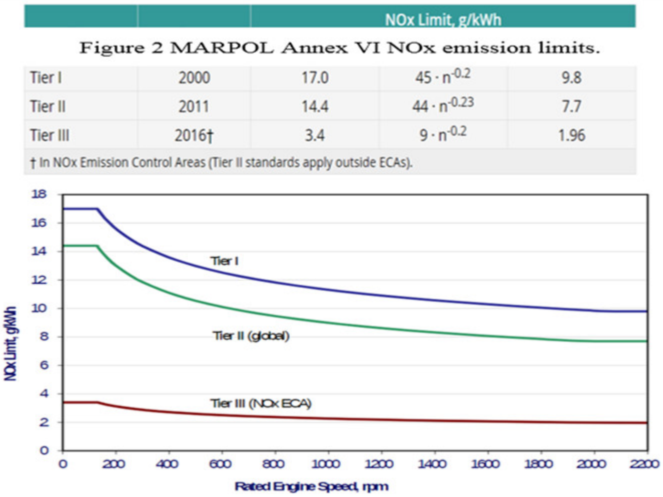
2. Overview of NO_x emissions.

Nitric oxide (NO) and nitrogen dioxide (NO2) are the two most prevalent oxides that nitrogen can produce, despite the fact that nitrogen can also form eight additional oxides. Almost 80% of the nitrogen (N2) in regular air is oxidized to NOx (NO, NO2, and N2O) during combustion. Colorless gas NO has certain negative health effects, these effects are significantly less severe than those of an equivalent dose of NO2. NO2 is created when NO combines with O2 in the atmosphere and in industrial devices. This brown gas is a significant respiratory irritant. NO and NO2 are frequently viewed as a single issue and written NOx. The majority of NOx emission rules rely their numerical figures on the supposition that all NO is transformed to NO2. NO will continue to be converted to NO2 in the atmosphere. Rain will wash away NO2, and over time, acid rain will enhance the soil's acidity. Large combustion sources like fossil fuel-fired power plants and diesel engines that burn oil mostly produce NOx into the environment. Together with acid rains, NOx is known to contribute to ozone depletion, which negatively impacts human health. All emission reduction techniques seek to reduce the thermal NOx component, which is crucial for overall emission. The temperature and oxygen concentration possess the greatest influence on the generation of NOx in the combustion chamber: the higher the temperature and the longer the temperature residence time are the more thermal NOx will be produced (Nam Dong, 2000). Thermal NOx, prompt NOx, and fuel NOx are three sources for NOx formation. NOx formation occurs by reaction between nitrogen and oxygen in the combustion air (thermal NOx), by reaction between exhaust gas hydrocarbons and combustion air oxygen (prompt NOx) and by the reaction between nitrogen bindings in fuel (fuel NOx). By implementing a three-tier system in NECAs (NOx Emission Control Areas), the goal is to cut NOx emissions from shipping by 80% since January 2021 (IMO 2017). TIER 2 was implemented in 2011 with a 20% decrease in NOx emissions from shipping compared to TIER 1, while TIER 1 went into effect in 2005 (IMO 2008). The maximum operating speed of diesel engines determines the NOx emission limits, as indicated in Table 2 and in Figure 2. While Tier III rules only apply in NOx Emission Control Zones, Tier I and Tier II restrictions are global.

3. Overall NOx mitigation strategies.

(Nam Dong, 2000), thermal efficiency and reliability have been the two main technologies used to build the diesel engine. The environment is currently a prominent theme in the development of diesel engines, and the majority of technological efforts

Figure 2: MARPOL Annex VI NOx emission limits.



Source: Authors.

are currently focused on this issue. In addition to focusing on improving engine performance and reliability, engine builders have to tackle environmental concerns.

There are two categories of practical NOx reduction techniques for marine diesel engines: primary techniques and secondary techniques. In primary methods, reduced NOx formation during combustion is the primary goal of primary techniques. Most of these procedures have been implemented primarily to reduce the cylinder's maximum temperature. In secondary methods, NOx removal from exhaust gas is implemented by downstream treatment, The Selective Catalytic Reduction (SCR) is the most used exhaust gas treatment technique.

Table 2: Primary methods categories.

Modification of fuel injection	Addition of water	Combustion air treatment	Change of engine process
Modification of the fuel nozzle Delayed fuel injection High pressure fuel injection	Direct water injection Water emulsified fuel Stratified water injection Intake air Humidification	Exhaust gas recirculation Adjustment of inlet /exhaust valve	Compression ratio

Source: Authors.

4. The effect of AD plant on cruise ships.

This paper focuses on an effective method to decrease the noxious emissions through using methane as an alternative fuel in Methane - Diesel Dual Fuel Engine. The environment is harmed when methane is released into the air before it is burned. Methane affects climate change by trapping heat in the atmosphere. Methane is more effective at trapping heat than other greenhouse gases, even though its lifetime in the atmosphere is shorter than that of those gases. reducing methane emissions from organic wastes is crucial for mitigating climate change.

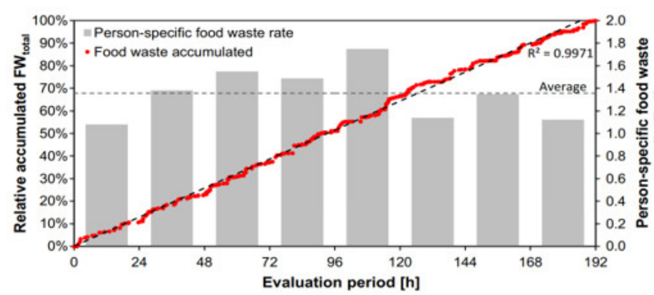
The Intergovernmental Panel on Climate Change (IPCC) estimates that methane is 28 times more potent than carbon dioxide in terms of its impact on global warming. Although there are natural mechanisms in soil and chemical reactions in the atmosphere that help remove methane from the environment, it is crucial that all human activities that release methane into the atmosphere should be carried out in a manner that minimizes their methane emissions. This includes developing procedures to trap methane that would otherwise be emitted into the atmosphere and use it as a fuel. Methane can act as a clean renewable source of energy that complies with the IMO restrictions to decrease greenhouse emissions, despite the constraints that require special modifications in the engines. Cruises have been a popular industry for 20 years, with 19.1 million passengers in 2010 and 28.5 million in 2018 (Clia,2019). As a result of this expanding industry, the environmental effect increased with the number of cruise ships and passengers.

Some studies provide a collaborative assessment of the recent challenge with cruise ship solid waste (Sanchez, 2020). However, no specific information on organic waste was provided. Studies discussed the optimization of waste management onboard cruise ships for glass, paper, and cellulosic waste, as well as the recovery of energy embedded in paper and cellulosic waste through the use of incinerator exhaust flue gas (Toneatti 2020). A demonstration of the best management practices for ship-generated food waste and sewage in the Baltic Sea region was shown in a case study (Vaneeckhaute 2020). On shore, the anaerobic digestion (AD) technology utilized for biogas generation is mature because it has been deeply studied and used over decades. In contrast, no effective implementation onboard ships have been noted to date. Several cruise lines are currently working to improve environmental protection on their ships. For example, all new cruise ships will be equipped with "advanced wastewater treatment systems" (Clia 2019), despite the fact that the performance of these on-board systems has not yet reached advanced onshore treatment standards. Improved environmental protection onboard can provide benefits if efficiency is raised, fossil fuels are substituted, and organic and nutrient loads from waste streams are reduced. A recent study aimed to display the advantage of implementing an (AD) onboard ships to generate biogas (Schumüller, Weichgrebe, Köster 2021). However, since no anaerobic digestion plants exist onboard cruise ships currently, establishing a large-scale biogas plant is challenging, considering the absence of prior experience with system integration or operation. However, Organic waste generated onboard cruise ships can contribute significantly to a more efficient ship energy system through anaerobic digestion. Furthermore, direct onboard energy conversion prevents ships from discharging untreated organic waste into the marine environment. Potentially, 159 L of methane can be produced per passenger per day, resulting in 66 Watt per person and 198 kW per cruise ship with an average passenger capacity of 3000 persons, while about 76% of the Chemical Oxygen Demand (COD) load of organic waste will be diminished if AD technology is applied. (Schumüller, Weichgrebe, Köster 2021).

5. Methodolgy.

This section will illustrate the quantity and substrate characteristics of the organic wastes onboard ships. The effect of methane addition to diesel fuel will be illustrated from the perspective of NOx emissions, performed by using the commercial software ANSYS to simulate and model the combustion process. This research paper adopted the investigation of Schumüller et al. for the AD implementation on cruise ships (Schumüller, Weichgrebe, Köster 2021). It is also crucial to state the main substrates on board that are beneficial for the AD, such as screening solids, galley grease and black water, food wastes FW, and sewage sludge SS with a daily rate of 8.8 kg per person. Figure 3 represents the daily fluctuations in accruing food wastes FW during the 8-day evaluation period onboard cruise ship, Considering different day types like cruise, port and changeover days. The first 4 days included port stays with a duration of 7 to 11 h, with the lowest FW amount on day one. A high-FW day on day 5 (cruise) is followed by a below-average day (change over), followed by a cruise day with an average FW generation.

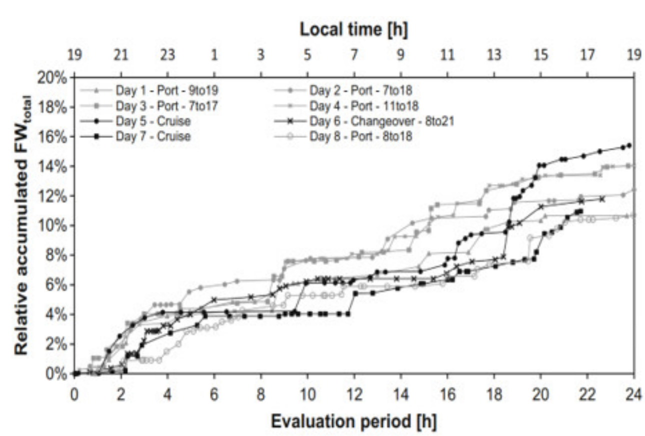
Figure 3: Trend of accumulated food waste during the evaluation period and corresponding person specific food waste rates onboard.



Source: Authors.

Figure 4 shows 24-h trends of onboard-generated food wastes FW, with Significant peaks are at breakfast 7:00–11:00 and dinner 20:00–23:00 (Schumüller, Weichgrebe, Köster 2021).

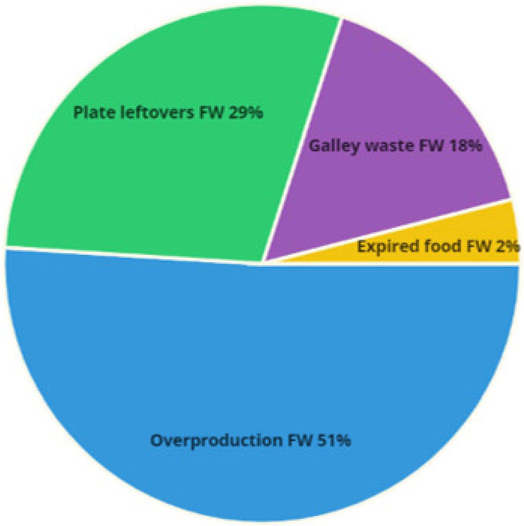
Figure 4: Separated diurnal flow of accumulated food waste during the evaluation period of 8 days onboard cruise ship.



Source: Authors.

Investigations show that 51% of FW is due to overproduction, while 29%, 18%, and 2% are due to plate leftovers, galley waste, and expired food, respectively (TUI Cruises & Futouris, 2019). Figure 8 shows the food wastes distribution on cruise ships.

Figure 5: Food wastes distribution on cruise ships.



Source: Authors.

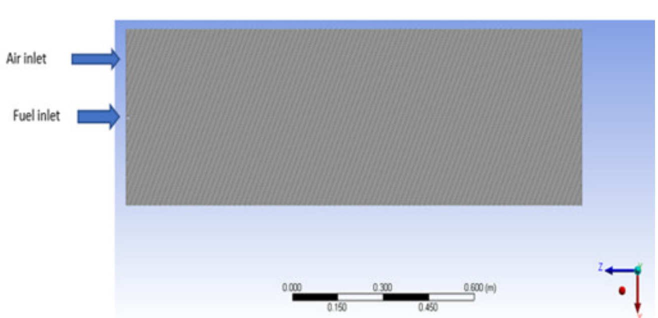
In this paper, a model of a combustion chamber is modelled using commercial CFD fluid flow (fluent) to evaluate NOX emissions from adding methane to diesel fuel. Table 4 shows the main dimensions of the combustion chamber, while Figure 6 shows the primary features of the combustion chamber.

Table 3: Main dimensions of the combustion chamber.

Chamber dimensions	
Length (chamber)	1400 mm
Diameter (chamber)	540 mm
Dimeter (nozzle)	8 mm
Length (nozzle)	12 mm

Source: Authors.

Figure 6: Primary features of the combustion chamber and the fine mesh of the model.



Source: Authors.

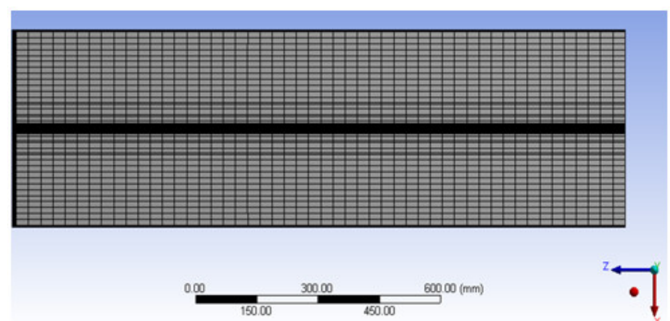
It is crucial to use mesh metrics to evaluate the mesh's quality, which depends in part on the mesh's skewness, aspect ratio, and softness (change in cell size). Table 5 shows the Mesh metric for skewness and aspect ratio. The fine mesh for the model is shown in figure 7.

Table 4: Mesh metric for skewness and aspect ratio.

Mesh Metric	**skewness**
Min skewness	3.3561e-003
Max skewness	0.51228
Mesh Metric	**Aspect Ratio**
Min	2.3279
Max	371.63
Smoothing	High

Source: Authors.

Figure 7: Fine mesh for the model.

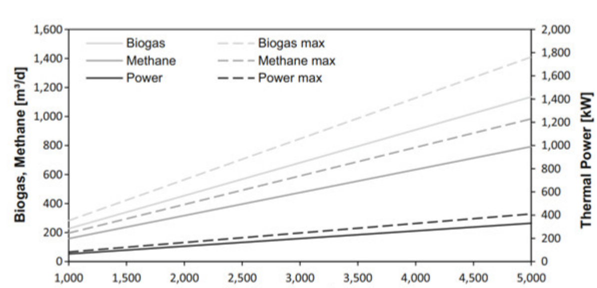


Source: Authors.

6. Results and Discussions.

The available power through AD of all available substrates can potentially produce 159 L of methane per passenger per day, generating thermal power of 66 Watt per person and 198 kW per cruise ship with an average passenger capacity of 3000 persons, while AD technology can reduce 76% of the Chemical Oxygen Demand (COD) load of organic waste. The available thermal power through AD of all available substrates onboard according to the actual number of persons onboard can be seen in figure 8.

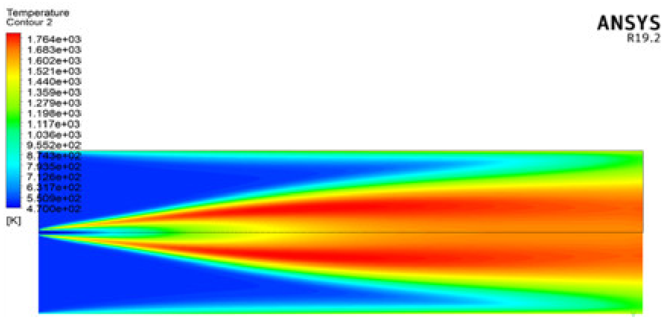
Figure 8: Available thermal power through AD of all substrates.



Source: Authors.

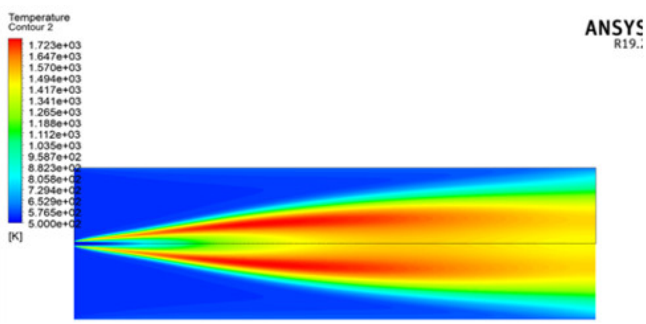
The results of methane addition to diesel fuel on NOx emissions are demonstrated using the commercial software ANSYS. Figure 9 shows the CFD results of 0% methane addition, figure 10 shows the CFD results of 10% methane addition, and figure 11 shows the CFD results of 30% methane addition.

Figure 9: (0%) methane addition.



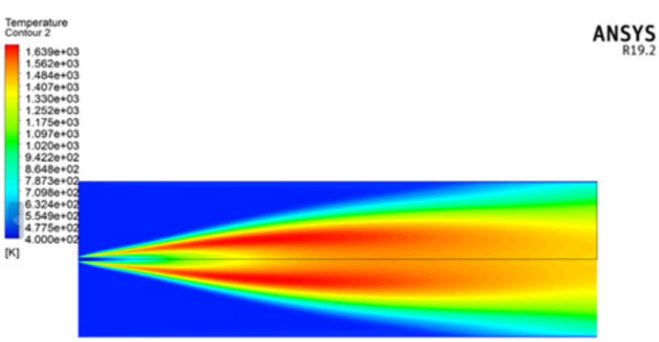
Source: Authors.

Figure 10: (10%) methane addition.



Source: Authors.

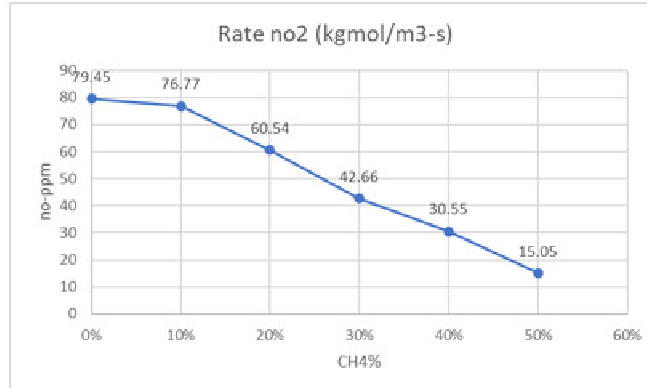
Figure 11: (30%) methane addition.



Source: Authors.

Figure 12 shows NOx ppm for methane addition. The results show that 0% of methane addition leads to a NOx emission of 79.45 ppm, 10% of methane addition leads to a NOx emission of 76.77 ppm, and 30% of methane addition leads to a NOx emission of 42.66 ppm.

Figure 12: NOx ppm for methane addition.



Source: Authors.

Conclusions.

The methane produced on cruise ships can be captured and used as a renewable energy source, reducing the use of traditional fossil fuels. Onboard organic waste can be converted into biogas, with a focus on food waste and sewage sludge. Anaerobic digestion onboard cruise ships can produce 159 L of methane per passenger per day with thermal power of 66 Watt per person and 198 kW per cruise ship with an average passenger capacity of 3000 persons. Anaerobic digestion onboard cruise ships can reduce 76% of the COD load of organic waste. Methane can act as a clean renewable source of energy that complies with the IMO restrictions to decrease greenhouse emissions, despite the constraints that require special modifications in the engines. Due to the significant environmental effects of using methane as an alternative fuel, methane is a promising marine alternative fuel for meeting current NOx regulations. This study focuses on the environmental effect of using methane as an alternative fuel to reduce the NOx emissions, performed by using the commercial software ANSYS to simulate and model the combustion process. the study shows that 10% of methane addition has decreased NOx emissions by 3.3%, 20% of methane addition has decreased NOx emissions by 23.9%, and 30% of methane addition has decreased NOx emissions by 46.3%.

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