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# Exploring Eco-Friendly Paths: A Comparative Study of Emissions in Medium Speed Diesel Engines Utilizing Alternative Fuels through Simulation Analysis

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**ABSTRACT**

In the ship industry, emissions from marine activities have been shown to influence air quality and climate, with pollutants such as sulphur dioxide ($SO_2$), nitrogen oxides ($NO_x$), and Carbon Dioxide ($CO_2$). the International Maritime Organization (IMO) has implemented MARPOL Annex VI to reduce emissions from maritime activities, one of which is using alternative fuels. With the need of sustainable energy source of reducing emissions, the evaluation of alternative fuels becomes crucial. This study presents a comparative analysis of performance and environmental emissions from medium speed diesel engines utilizing different fuels, namely Biodiesel (B10-100), Heavy Fuel Oil (HFO), and Ultra Low Sulphur Fuel Oil (ULSFO) under various engine speed. the research was carried out using the Diesel-RK application with Internal Combustion Engine simulation that integrates thermodynamics and emission prediction algorithms to accurately represent the combustion process and subsequent pollutant formation. Parameters such as engine load, injection timing, and fuel properties are systematically varied to assess their impact on emissions of nitrogen oxides ($NO_x$), sulfur dioxides ($SO_2$), and carbon dioxide ($CO_2$). Results indicate distinct performance and emission profiles for each fuel type in various engine speed. All Biodiesel and ULSFO demonstrates increasing $NO_x$ emissions compared to HFO with an average of 51.4%. However, they exhibit lower $CO_2$ and $SO_2$ compared to HFO with average of 3% for $CO_2$ and 98.8% for $SO_2$, this is due to higher oxygen content that can promote more efficient combustion, and both Biodiesel and ULSFO contains lower sulphur content.

## 1. Introduction

In recent years, regulations have been implemented to reduce emissions in the environment based on MARPOL regulations, prompting governments and shipping companies to seek solutions for using more environmentally friendly fuels in ship operations [1].

Many efforts stated by various authors are being made to significantly impact environmental emissions in the shipping industry [2,3]. One of these efforts is the implementation of Renewable energy such as biodiesel in the industry. According to research on hydrokinetic energy, renewable

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energy (RE) indicates that marine and other renewable sources may eventually replace or supplement fossil fuels. By using locally accessible biomass or other renewable resources, incorporating bio-based fuels into diesel engines could help reduce emissions while also supporting national and worldwide energy sustainability projects [4]. In Indonesia, Biodiesel policies are based on Minister of Energy and Mineral Resources Regulation No. 12 of 2015 and continue to be updated. In September 2018, the Biodiesel that were used was changed to Biodiesel B20, then transitioning to B30 in 2020. By the end of 2020, the target was to shift to B50 [5]. With the implementation of biodiesel as a fuel, the government aims to make biodiesel one of the sustainable and environmentally friendly alternatives to fossil fuels, stated by Fazal *et al.,* [6]. However, with the use of this new fuel, questions arise about whether biodiesel can be a solution to reduce environmental emissions and whether it can be advantageous as an alternative fuel without significant negative impacts for the ship owners.

From the literature study that were conducted, combustion characteristics of biodiesel-fueled engines differ from diesel-fueled engines. Most research by various authors indicates that compared to diesel, using biodiesel can help improve the efficiency of ship engines and lowering [7-9]. Stated by Biodiesel have higher cetane number, contains almost no sulphur, and naturally oxygenated fuel [10]. Diesel-biodiesel blends provide a shorter ignition delay and lower heat release rates stated by Kass *et al.,* [11] and Khani *et al.,* [12]. It is also stated that Biodiesel also produces lower smoke emissions than diesel, and on average, the use of biodiesel can reduce carbon monoxide (CO) emissions [13].

Using biodiesel for ship engine has several benefits. Biodiesel is domestically produced, which can help increase energy security and reduce transportation energy costs, Biodiesel has energy density levels close to traditional diesel fuel, making it a viable alternative for medium speed engines in ship vessels.

While biodiesel shows promise in reducing CO and $SO_2$ emissions, there is a need for further research for each Biodiesel blend percentage and a comparison with Heavy Fuel Oil. Additionally, more studies are needed to assess the long-term impacts of biodiesel on engine performance and emissions.

This study aims to evaluate the overall effectiveness of alternative fuel Biodiesel and ULSFO for medium-speed marine diesel engines by focusing on emission reductions ($CO_2$, $NO_x$, and $SO_2$) and assessing the long-term implications of its use on engine components and operational efficiency. The objective is to identify which of these alternative fuels can be a sustainable, eco-friendly alternative in maritime applications while minimizing operational drawbacks.

### *1.1 Biodiesel*

Biodiesel is produced through the conversion of vegetable oils and animal fats with alcohol into fatty acid methyl esters (FAME). When methanol is used as the alcohol, it results in the production of fatty acid methyl esters (FAME). Biodiesel can be used as a motor diesel fuel in pure form or blended with diesel oil at varying percentages, as stated by Palani *et al.,* [13].

#### *1.1.1 FAME (Fatty Acid Methyl Ester)*

FAME (Fatty Acid Methyl Ester) is derived from vegetable oils or animal fats. The characteristics of FAME are closer to fossil diesel fuel than pure vegetable oil, but its properties depend on the type of vegetable oil used. FAME has physical properties similar to conventional diesel, is non-toxic, and biodegradable, as stated by Lin [14].

### *1.2 ULSFO (Ultra Low Sulphur Fuel Oil)*

Ultra Low Sulfur Fuel Oil (ULSFO) has become increasingly important in maritime fuel usage, primarily due to regulations set forth by the International Maritime Organization (IMO) since 2020, requiring a significant reduction in sulfur content in ship bunker fuel. ULSFO is typically created through blending high-sulfur fuel oil (HSFO) with lower sulfur components to adhere to these strict sulfur limits. Its composition can vary depending on the region, often including hydrodesulfurized atmospheric residues (AR), catalytic cracker heavy cycle oil (HCO), and hydrotreated vacuum gas oil. Quality concerns related to ULSFO, such as cold flow properties and sulfur content, have prompted research into methods like ultrasonication to enhance its chemical makeup and stability. Overall, ULSFO is crucial for maritime operations, meeting ISO standards, yet it presents technical and operational hurdles necessitating careful management and maintenance.

### *1.3 Fuel Characteristic*

The fuel characteristic influenced by some aspects of the fuel compositions such as sulphur content, heating value, density, and ignition quality.

### *1.4 Mass Composition of Fuel*

Mass Composition of Fuel refers to the quantity of various substances present in a fuel mixture. As stated by Lin [14], it describes the fuel composition in terms of mass or the percentage of its individual components. The mass composition of fuel can significantly affect its properties, performance, and emissions when used in ship engines [15].

### *1.5 Sulphur Fraction*

Sulphur fraction in fuel is the amount of sulphur present in a fuel sample as stated by Khani *et al.,* [12]. When this fuel is burned, sulphur compounds in the fuel are released as sulphur dioxide ($SO_2$), which can contribute to air pollution.

Low heating value (also known as Net Calorific Value) is the amount of heat released per unit of fuel when it undergoes complete combustion, and all combustion products are cooled to a reference temperature as stated by Nishio *et al.,* [16].

The ignition quality of any fuel is determined based on its cetane number under specific conditions [17]. Biodiesel fuels have a higher cetane number compared to diesel. A higher cetane number is desirable for smooth and noiseless engine operation, improving engine performance, and reducing emissions, as stated by Khani *et al.,* [12].

## **2. Methodology**

In Figure 1, This flowchart outlines a detailed methodology for assessing the environmental emissions of biodiesel in ship engines. The process begins with a Literature Review and Problem Identification, focusing on biodiesel and ship engine emissions. Following this, Data Collection is conducted, including engine specification data for a 1000 RPM engine and various fuel types, such as HFO, VLSFO, and biodiesel blends like B10, B20, B40, B60, B80, and B100.

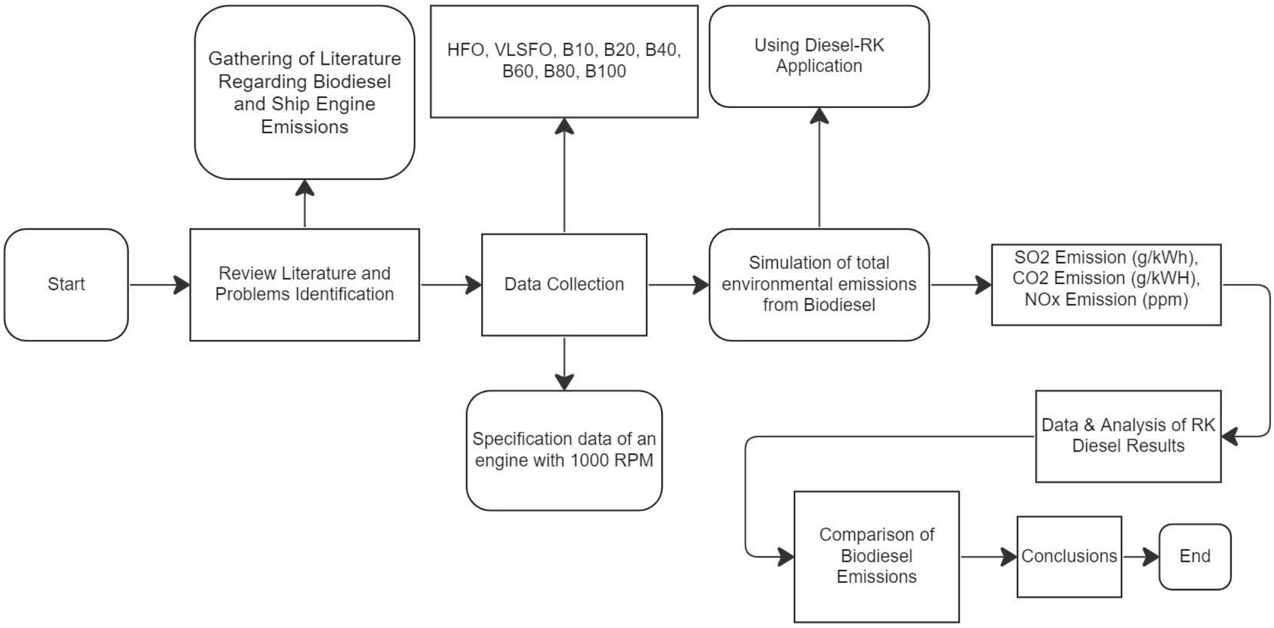


**Fig. 1.** Flowchart research method

The next phase involves using the Diesel-RK Application to simulate the total environmental emissions from biodiesel, specifically analyzing emissions such as $SO_2$ (g/kWh), $CO_2$ (g/kWh), and $NO_x$ (ppm). Afterward, the Data and Analysis of RK Diesel Results is carried out, followed by a Comparison of Biodiesel Emissions to evaluate how biodiesel performs relative to other fuels. Finally, the process concludes with drawing Conclusions based on the analysis, leading to the end of the methodology.

This approach integrates literature review, data collection, and simulations to compare the environmental impact of various biodiesel blends, making it a comprehensive assessment of biodiesel emissions in marine engines.

In this phase, an elaboration on the data required for the research is carried out. The data needed to be collected includes the specifications of the engine and the physical properties of the fuels used, namely HFO, ULSFO, B10, B20, B40, B60, B80, and B100.

The research involves utilizing the Diesel-RK software to simulate data, incorporating variables such as fuel physical properties and engine specifications. The software was improved to serve as a more effective tool for simulating and optimizing internal combustion engines with engine parameters.

Over the years, ongoing efforts have been dedicated to collaborating with internal combustion engine engineers and computational researchers, addressing the requirements of various manufacturers in the field. The software's robustness has been tested for compatibility with multiple engines of different types and applications. Various computational processes and options have been incorporated into the software to align with the needs of industrial enterprises.

Continuous advancements in the Diesel-RK software involve the integration of sophisticated mathematical models to accurately depict the combustion process in diesel engines. the software meets the diesel injection characteristics and precision of fuel atomizing, development of fuel sprays dynamics. Accounting the emissions of NO is achieved by the Zeldovich mechanism. The diesel-RK contains visualization of the fuel spray code. This code permits the servant to analyze the animation picture of development the sprays of fuel, their interaction with combustion chamber. The code is helpful to design the shape of piston bowl and in producing a proper option of diameter, number of injector nozzles and directions for a specific fuel supply characteristic.

### *2.1 Fuel Physical Properties*

Certain physical properties of the various fuel types are summarized in Table 1 below.

**Table 1**
Fuel Characteristics

| Fuel Type | HFO | B10 | B20 | B40 | B60 | B80 | B100 | ULSFO |
|---|---|---|---|---|---|---|---|---|
| Mass Composition of fuel | | | | | | | | |
| C | 0.87 | 0.859 | 0.8496 | 0.8297 | 0.8104 | 0.7915 | 0.7731 | 0.862 |
| H | 0.13 | 0.12525 | 0.1245 | 0.123 | 0.1216 | 0.1202 | 0.0118 | 0.136 |
| O | 0 | 0.0152 | 0.0259 | 0.0473 | 0.068 | 0.0883 | 0.1081 | 0.002 |
| Sulphur fraction in fuel | 0.5 | 0.00054 | 0.00105 | 0.00208 | 0.00308 | 0.00405 | 0.005 | 0.001 |
| Low Heating Value (MJ/kg) | 40.6 | 41.825 | 41.18 | 39.89 | 38.64 | 37.41 | 36.22 | 42.8 |
| Cetane Number | 48 | 48.35 | 48 | 49.37 | 50.03 | 50.67 | 51.3 | 47 |
| Fuel Density ($kg/m^3$) | 981 | 835.5 | 841 | 852 | 963 | 874 | 876 | 889.85 |
| Surface Tension (N/m) | 0.028 | 0.02963 | 0.03122 | 0.0344 | 0.03741 | 0.0404 | 0.0433 | 0.028 |
| Dynamic Viscosity (Pa.s) | 0.003 | 0.00317 | 0.00334 | 0.00368 | 0.004 | 0.00432 | 0.00463 | 0.003 |
| Molar Mass (kg/mol) | 190 | 201 | 211.5 | 232.5 | 252.9 | 272.8 | 292.2 | 190 |
| Vapor Pressure at 480 K | 0.0477 | 0.06304 | 0.0433 | 0.00382 | 0.03241 | 0.02567 | 0.01 | 0.0477 |
| Critical Temperature (K) | 710 | 714.8 | 721.2 | 734 | 748.6 | 765.9 | 786 | 718 |

Table 1 outlines the specific characteristics of various biodiesel blends used in diesel engines, which are critical for understanding fuel performance and environmental impact. The blends range from HFO (Heavy Fuel Oil), VLSFO (Very Low Sulfur Fuel Oil), to various biodiesel mixes like B10, B20, B40, B60, B80, and B100, representing the percentage of biodiesel in the mix. Each of these blends has distinct properties such as viscosity, density, calorific value, and sulfur content.

As the percentage of biodiesel increases, the fuel properties tend to change, influencing engine efficiency and emissions. Higher biodiesel blends (like B60, B80, B100) generally result in lower sulfur emissions compared to conventional fossil fuels like HFO and VLSFO. However, the performance characteristics such as calorific value might decrease as biodiesel content rises, potentially affecting fuel consumption and power output.

This table is essential for comparing how different biodiesel blends perform in terms of engine efficiency and environmental sustainability, enabling a deeper understanding of the trade-offs between emissions reduction and engine performance.

### *2.2 Engine Data Specifications*

The engine used is CAT 3608 and the Table 2 below are the engine specifications for this research.

**Table 2**
Engine Specifications

| Engine | CAT 3608 |
|---|---|
| RPM | 1000 |
| Bore (mm) | 280 |
| Stroke (mm) | 300 |
| Compression Ratio | 13:1 |
| 4 Stroke Cycle | |
| 8 Cylinder | |
| Cooling system | Water |

### *2.3 Research Approach*

The experiments that will be performed for each Biodiesel-Diesel with an engine speed of, 300 RPM, 400 RPM, 500 RPM, 600 RPM, 700 RPM, 800 RPM, 900 RPM, and 1000 RPM.

### *2.4 Analysis Process of Diesel-RK*

Diesel-RK software have its own database for simulating engine performance and emissions. with inputting engine's data, the software can generate necessary data to complete the engine specification from its database, whereas to generate $NO_x$, $CO_2$, and $SO_2$ emissions, they generate data with empirical equations that are similar to thermodynamics equations, here is how Diesel-RK works starting from the input then the output of the application.

In Figure 2, flowchart represents the process of simulating the emissions and performance of a diesel engine based on specific inputs. It begins with two key data: Engine Specifications and Fuel Characteristics. These data then can be put into a series of simulations in Diesel-RK Software, including Diesel Cycle Thermodynamics, Chemical Reactions of $NO_x$, Brake Power Simulation, and Specific Fuel Consumption (SFC) Simulation. The environmental impact is further analyzed through simulations of emissions like $SO_2$, $NO_x$, and $CO_2$. Once all the necessary calculations and simulations are completed, the results are categorized into two primary outputs: Emissions to the Environment and Engine Performance. These outputs provide critical insights into how the engine behaves and its environmental impact based on the fuel and engine characteristics.

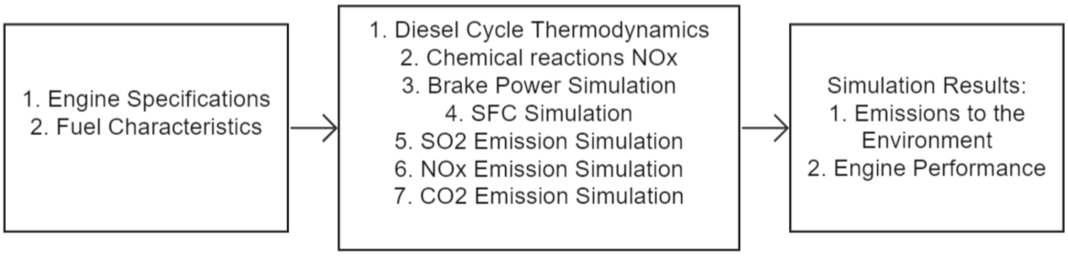
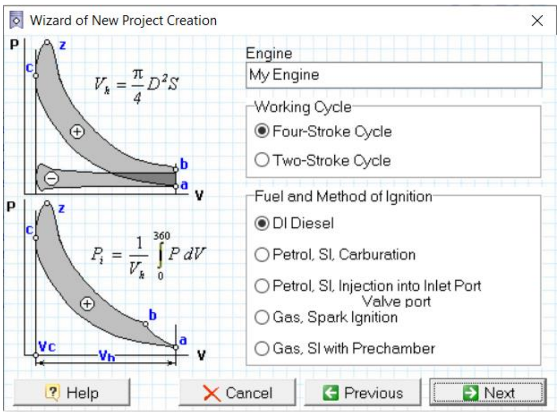


**Fig. 2.** Flowchart of Diesel-RK working system

After collecting the ship engine specification data, it is then inputted into the data section "Wizard of New Project Creation" as shown in the following image, User just has to answer the questions in the windows interface as shown in Figure 3 and Figure 4.

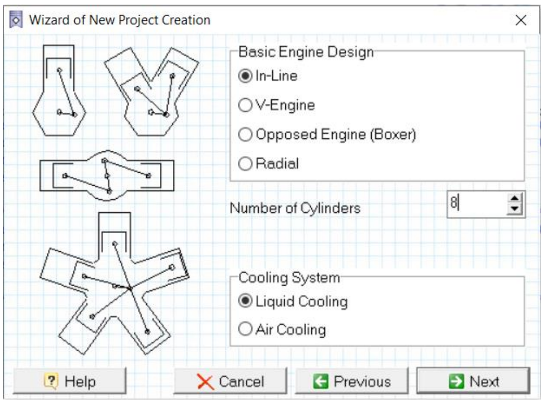


Engine: My Engine

Working Cycle
● Four-Stroke Cycle
○ Two-Stroke Cycle

Fuel and Method of Ignition
● DI Diesel
○ Petrol, SI, Carburation
○ Petrol, SI, Injection into Inlet Port Valve port
○ Gas, Spark Ignition
○ Gas, SI with Prechamber

**Fig. 3.** Selection of engine cycle, fuel and method of ignition menu



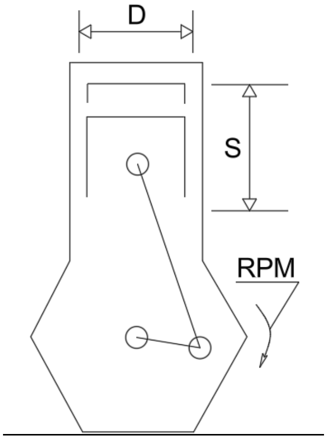
Basic Engine Design
● In-Line
○ V-Engine
○ Opposed Engine (Boxer)
○ Radial

Number of Cylinders: 8

Cooling System
● Liquid Cooling
○ Air Cooling

**Fig. 4.** Engine geometrical dimensions cylinder bore, stroke, engine speed and compression ratio

With the engine cycle and basic design already inputted from Figure 3 and Figure 4 above, the user has to input the engine bore, stroke, and RPM into the design as shown in Figure 5 below.



| Engine | CAT 3608 |
|---|---|
| RPM | 1000 |
| Bore, **D** (mm) | 280 |
| Stroke, **S** (mm) | 300 |

**Fig. 5.** Engine geometrical dimensions cylinder bore, stroke, engine speed and compression ratio

The "Wizard of New Project Creation" will generate input files, set the necessary coefficients, calculate and establish basic dimensions for air and fuel intakes based on statistical data and experience in engine design accepted in the industry.

After filling in the data in the previous section, then enter the Fuel Physical Characteristic data according to the fuel used, then the results of the simulation can be seen from Diesel-RK.

## 3. Results

### *3.1 Brake Power*

One of the main factors influencing energy content is the calorific value of the fuel. Biodiesel has a higher calorific value than Heavy Fuel Oil (HFO). Calorific value represents the amount of energy produced by the combustion of a fuel. The higher the calorific value, the more energy can be generated by burning that fuel, stated by Gautam *et al.,* [8], as shown in Figure 6.

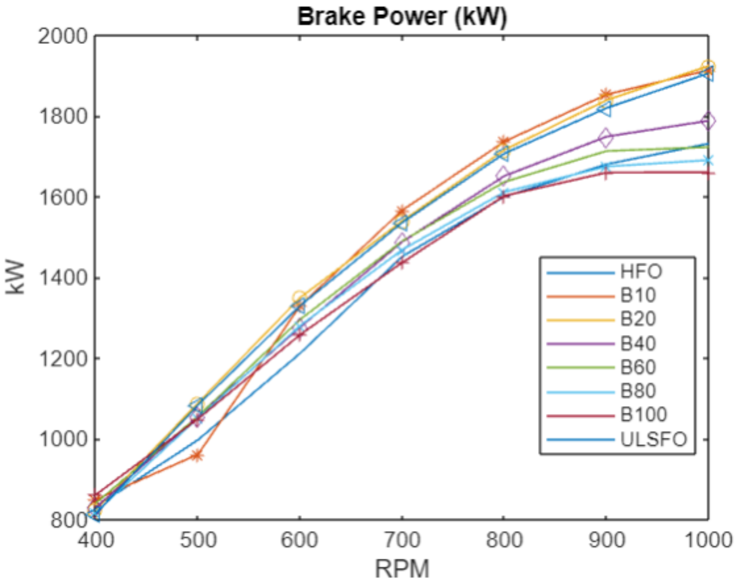


**Fig. 6.** Brake Power (kW) of HFO, ULSFO, B10, B20, B40, B60, B80, B100

### 3.2 Specific Fuel Consumption (SFC)

The reason Biodiesel ULSFO, B40, B60, B80, and B100 have higher Specific Fuel Consumption (SFC) compared to HFO is due to the Lower Heating Value of the Biodiesel compared to HFO stated by Limratana *et al.,* [18]. The lower heating value results in higher SFC during combustion compared to HFO, as stated by Firdaus *et al.,* [7], as shown in Figure 7.

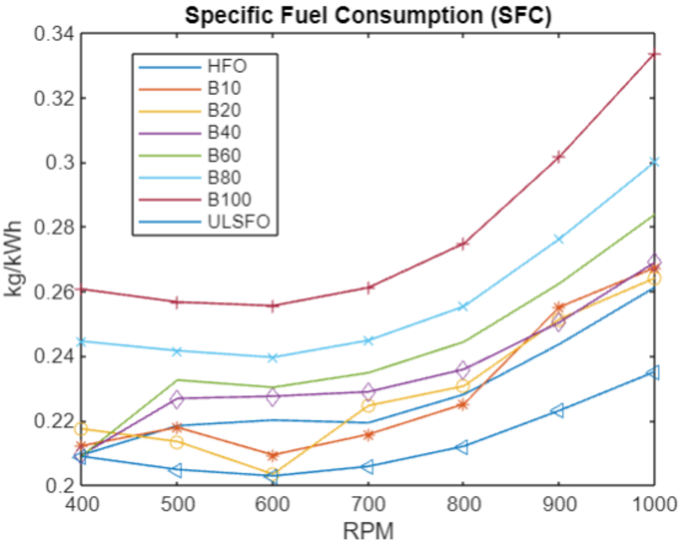


**Fig. 7.** Specific Fuel Consumption (kg/kWh) of HFO, ULSFO, B10, B20, B40, B60, B80, B100

### 3.3 $NO_x$ Emission

Results for $NO_x$ Emissions shows that all of these alternative fuels compared to Heavy Fuel OIL (HFO) have a huge increase in $NO_x$ emissions. the highest promotion from these alternative fuels is from Biodiesel B10 with an increase of 62.7% and the lowest promotion are ULSFO with an increase of 95%c ompared to Heavy Fuel Oil (HFO).

Related to the oxygen content in fuel characteristics, Biodiesel contains more oxygen, which leads to more complete and efficient combustion. This increased combustion efficiency raises the combustion temperature, which in turn promotes the formation of nitrogen oxides ($NO_x$), The additional oxygen present in biodiesel facilitates the formation of $NO_x$. When the fuel has more oxygen, the nitrogen in the air can more readily combine with this oxygen at high temperatures, increasing $NO_x$ emissions. Stated by an author, early combustion initiation leads to higher cylinder pressure and higher combustion temperature, resulting in higher $NO_x$ emissions, as shown in Figure 8 [19].

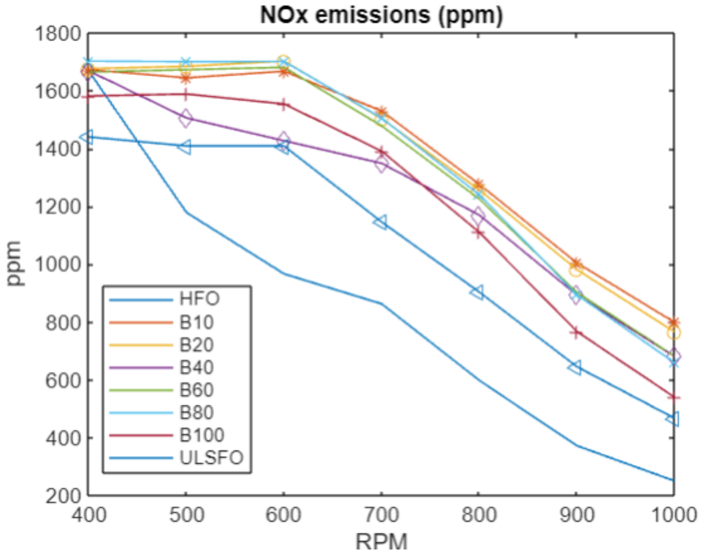


**Fig. 8.** $NO_x$ Emission (ppm) of HFO, ULSFO, B10, B20, B40, B60, B80, B100

### *3.4 $SO_2$ Emission*

Results for $SO_2$ Emissions shows that the highest reduction from these alternative fuels are from Biodiesel B10 decreased by 99.8% and the lowest reduction are ULSFO decreased by 95% compared to Heavy Fuel Oil (HFO).

The Sulphur Fraction in the fuel sample have a major impact on the emission. The higher the sulphur content, the more sulphur emissions are present in the engine. The sulfur content in biodiesel is often less than 0.001%, while HFO can contain up to 3.5% sulfur by weight, stated by Kass *et al.,* [11]. This significant difference means that when biodiesel is burned, it releases far less sulfur into the atmosphere, leading to significantly higher $SO_2$ emissions compared to biodiesel and ULSFO. Also, Biodiesel having a higher oxygen content than HFO enhances more efficient combustion, resulting in lower $SO_2$ emissions, as shown in Figure 9. For the detailed $SO_2$ reduction line chart for B10-B100 and ULSFO, see Figure 10.

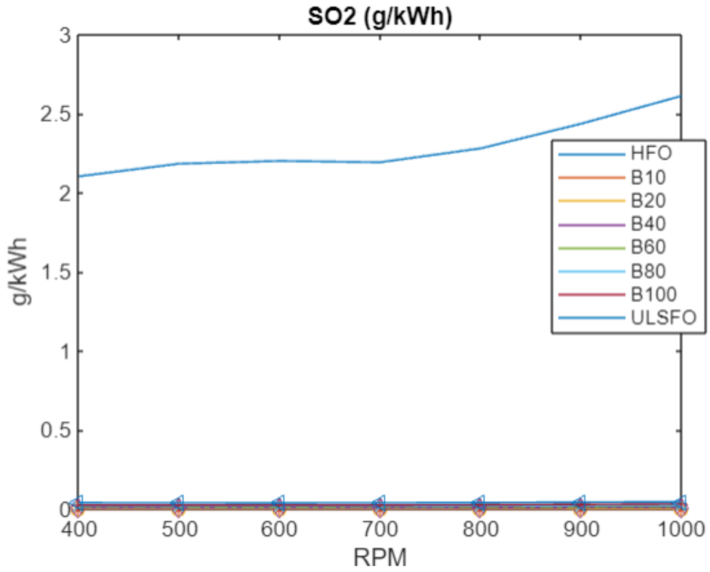


**Fig. 9.** $SO_2$ Emission (g/kWh) of HFO, ULSFO, B10, B20, B40, B60, B80, B100

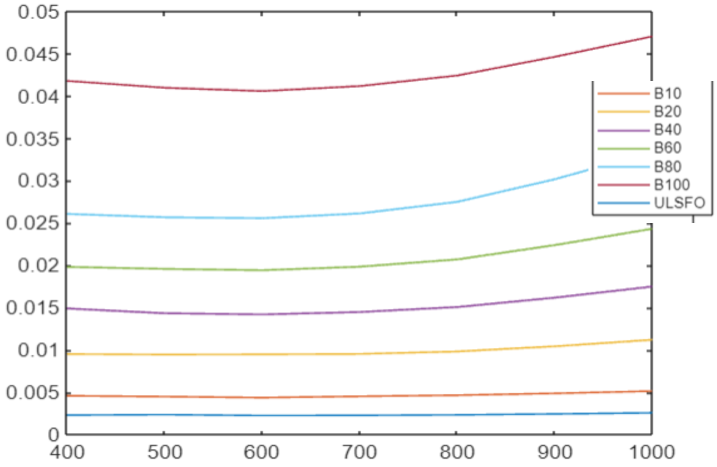


**Fig. 10.** $SO_2$ Emission (g/kWh) of ULSFO, B10, B20, B40, B60, B80, B100

### *3.5 $CO_2$ Emission*

Results for $CO_2$ Emissions shows that the highest reduction from these alternative fuels are from B20 decreased by 5.98% and the lowest reduction are B100 decreased by 0.05% compared to Heavy Fuel Oil (HFO).

Biodiesel has a greater oxygen content than HFO and ULSFO. The higher oxygen content available for combustion can promote more efficient combustion, resulting in lower $CO_2$ emissions stated by Abed *et al.,* [1], its renewable nature providing a more carbon-neutral lifecycle, lower sulfur content reducing incomplete combustion, and better combustion characteristics due to a higher cetane number. These factors contribute to the overall reduction in $CO_2$ emissions when using biodiesel as an alternative fuel. as show in Figure 11.

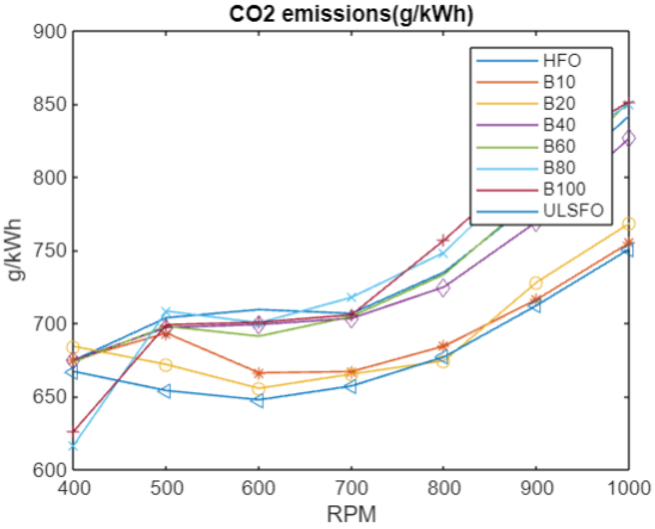


**Fig. 11.** Graphic $CO_2$ Emission (g/kWh) of HFO, ULSFO, B10, B20, B40, B60, B80, B100

### *3.6 Effect on Using Biodiesel in Engine*

Using Biodiesel can speed up the replacement of fuel filtration. With the large changes in properties that occur in biodiesel and its mixtures in line with the increased risk of contaminant formation in the oil, this can increase the possibility of blockages or blockages on the surface of the filter media. And the higher the biodiesel mixing ratio used in engine operation, the greater the potential for filter blockage. The filtration turnover rate becomes faster. From the research that was conducted, the filter surface in contact with the biodiesel is predominantly covered by oil sludge in the form of slime. This shows that the fatty acid content in biodiesel is high and forms polluting compounds that easily gel. This is due to its low oxidation stability so it easily crystallizes and becomes solid as stated by Komariah *et al.,* [20].

It should also be noted that water contamination in biodiesel can cause sludge. As long as the handling of Biodiesel is good and in accordance with the recommended handling procedures, sludge in the biodiesel will not arise.

## 4. Conclusions

Biodiesel demonstrates several advantages and challenges compared to traditional fuels like Heavy Fuel Oil (HFO) and Ultra-Low Sulfur Fuel Oil (ULSFO). In terms of performance, biodiesel exhibits higher brake power due to its greater calorific value, leading to improved engine efficiency. However, its specific fuel consumption (SFC) is higher than HFO and ULSFO, as more biodiesel is required to produce the same amount of energy due to its lower heating value. In terms of emissions, biodiesel significantly reduces $SO_2$ emissions due to its low sulfur content, and it offers lower $CO_2$ emissions as well, thanks to its oxygen-rich composition that supports more efficient combustion. Moreover, biodiesel is derived from renewable sources, which helps it achieve a more carbon-neutral lifecycle compared to fossil fuels.

On the downside, biodiesel results in higher $NO_x$ emissions, primarily due to its higher oxygen content, which increases combustion temperatures, promoting $NO_x$ formation. Biodiesel's higher cetane number also leads to advanced combustion, further increasing in-cylinder temperatures and $NO_x$ emissions. Additionally, biodiesel can impact engine components, particularly by increasing the risk of contaminant formation in the oil, which necessitates more frequent fuel filtration maintenance due to sludge buildup.

To address $NO_x$ emissions, strategies such as the installation of $NO_x$ reduction technologies, like Selective Catalytic Reduction (SCR), are recommended. Further research is also needed to assess the long-term effects of biodiesel use on ship engines. Overall, biodiesel offers significant benefits in reducing $CO_2$ and $SO_2$ emissions, making it an eco-friendlier alternative for the maritime industry. However, its higher $NO_x$ emissions and operational challenges, particularly related to maintenance, highlight the need for mitigation strategies and further technological developments.

In summary, for these alternative fuels, Biodiesel B20 and B10 offers a promising solution for reducing $CO_2$ and $SO_2$ emissions in the maritime sector as an alternative. However, challenges related to $NO_x$ emissions and its impact on engine components need to be addressed through further research and innovation.

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