Universiti Malaysia Terengganu Journal of Undergraduate Research
Volume 7 Number 1, April 2025 16-26

eISSN: 2637-1138

ANALYSING THE IMPACT OF VARIOUS DIESEL TYPES ON THE PERFORMANCE AND EMISSIONS OF MARINE DIESEL ENGINES USING DIESEL-RK SOFTWARE

CHE WAN MOHD NOOR[1,2]* AND MOHD HAFIZUDDIN[1]

[1]*Faculty of Ocean Engineering Technology, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.*
[2]*Fuels and Engine Research Interest Group, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia.*

**Corresponding author: che.wan@umt.edu.my*
https://doi.org/10.46754/umtjur.v7i1.425
Received: 28 August 2023 Revised:22 October 2024 Accepted: 14 November 2024 Published: 15 April 2025

Abstract: Software applications to solve engineering problems and performance issues of marine diesel engines are becoming easier in current trends due to the rapid development of technology and computer science. However, the cost of software kits for users is very high and burdensome, especially for researchers in developing countries. Alternatively, Diesel-RK software is an open-source program created to help researchers in modelling and making predictions on the performance and exhaust emissions of a diesel engine. Therefore, this work presents the results of the Diesel-RK application for simulating performance, emissions, and the capability of use of another type of diesel by marine diesel engines of 4-cycle-inlined 6-cylinder, and suggests the best type of diesel fuel for testing on an actual marine engine. Different types of diesel fuel, such as Light Fuel Oil 1 (LFO-1), Diesel No. 2, EN590, and Heavy Fuel Oil, were tested in this simulation. The engine performance and emission parameters, such as brake power, torque, specific fuel consumption, thermal efficiency, Nitrogen Oxide (NO_x) emissions, and Carbon Dioxide (CO_2) emissions, were analysed. The research indicated that utilising EN590 fuel resulted in enhanced marine diesel engine performance, including improved brake power, torque, thermal efficiency, and fuel consumption. Moreover, EN590 fuel exhibited significantly reduced NO_x and CO_2 emissions compared to Diesel No.2, LFO-1, and Heavy Fuel, offering valuable guidance for both simulation and practical engine studies.

Keywords: Marine diesel engine, diesel-rk, diesel fuel, engine performance, emissions.

Introduction

Marine diesel engines are commonly used in the shipping industry for their power, efficiency, and suitability for large-scale transportation. In recent years, waterway transportation has become the primary mode of international trade due to its ability to handle substantial cargo loads, offer low freight rates, and facilitate long-distance transport (Liu *et al*., 2022; Song *et al*., 2023). However, emissions from international shipping are expected to increase up to 5-fold by 2050, necessitating the development of engine technologies and cleaner energy carriers to address these environmental challenges (Fourth IMO GHG Study 2020, 2020).

Among the efforts to tackle this challenge, global research efforts have increasingly concentrated on engine simulation, particularly in understanding mixture formation and combustion processes in diesel engines. Commercially available software solutions such as Boost (AVL), Wave (Ricardo), and GT-Power (Gamma Technologies), offer advanced features for engine simulation. However, the high cost of these software packages which can be hundreds of thousands of dollars, makes them difficult to afford, especially for researchers in developing countries. Meanwhile, these software packages provide valuable insights but often lack detailed analysis of engine performance and emissions. Computational Fluid Dynamics (CFD) is a technique used to simulate and study the flow of fluids in 3D. It helps solve complex problems by modelling how fluids behave in different situations. However, using CFD can be challenging because it requires very powerful computers to run the simulations. Programs like KIVA, FIRE, STAR-CD, and VECTIS are commonly used for this purpose. Nevertheless, they need a lot of computing power to work effectively (Pham, 2019).

To address these limitations, experts at Bauman Technical University in the Russian Federation developed Diesel-RK, an internal combustion engine simulation program. Diesel-RK has been widely used by research, development, and production facilities. It employs a multi-zone combustion model known as the Razleisev-Kuleshov (RK) model which considers parameters such as fuel supply, combustion chamber shape, spray characteristics, cylinder motion, and spray interaction to accurately simulate diesel engine combustion (Chaurasiya *et al*., 2022). The Diesel-RK software shares core features with well-established thermodynamic software. However, it also stands out with its contemporary and advanced applications, offering capabilities not commonly found in other programs. Notably, Diesel-RK places particular emphasis on optimizing the combustion process in diesel engines and conducting thorough analysis and optimization of internal combustion engines. An example of the Diesel-RK user interface is illustrated in Figure 1.

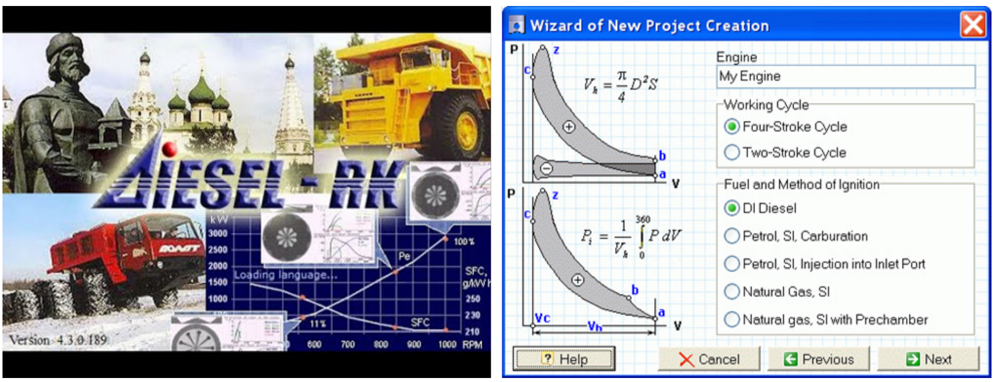


Figure 1: Diesel-RK user interface

Diesel-RK is a comprehensive program that effectively simulates the thermodynamic cycle of engines. It is specifically designed to model and optimise the operational processes of both 2-stroke and 4-stroke turbocharged engines. With its robust capabilities, Diesel-RK empowers researchers and engineers to gain valuable insights into the intricate workings of these engines, facilitating the exploration of various performance and efficiency enhancements. One of the distinguishing aspects of Diesel-RK is its presumption that all cylinders in the engine operate uniformly. Other than that, this tool is user-friendly and capable of designing, simulating, and optimising diesel engine operating parameters with modifications, offering accurate estimations using minimal empirical coefficients (Dhana Raju *et al*., 2022).

This distinctive feature sets Diesel-RK apart, enabling researchers and engineers to achieve more efficient simulations and address intricate challenges associated with diesel engine performance and emissions. Several researchers have utilised Diesel-RK software to validate their experiments. Rajak *et al.* (2023) discovered that Diesel-RK has successfully validated the common rail direct injection engine fuel with spirulina microalgae with acceptable accuracy (Rajak *et al*., 2023). Meanwhile, Gad *et al*. (2021) studied the combustion characteristics of a diesel engine running with Mandarin essential oil-diesel mixtures. They determined another decent agreement in the validation results when using the Diesel-RK model (Gad *et al*., 2021). Various studies have demonstrated that the results obtained from engine simulation software are validated with experimental values for optimised fuels. For example, a study concluded that the Tamarind Seed Methyl Ester (TSME 20) biodiesel blend exhibits superior engine characteristics in both simulation and experimental approaches. The good agreement between the modelling and experimental data confirms the accuracy of the numerical predictions (Raju *et al*., 2020).

This study aims to develop a simulation model for marine diesel engine combustion using Diesel-RK software, determine the performance and emissions of different types of fuels on marine diesel engines, and propose the most suitable fuel for further experimental research on real engines. Other than that, the Diesel-RK software was chosen in this study because it provides detailed simulations that can predict engine behaviour and optimise performance, often offering a cost-effective and faster alternative to actual experiments.

Methodology

The simulation setup involved the utilisation of the Diesel-RK software with a Cummins-NT855 marine diesel engine, a 4-cycle in-line 6-cylinder configuration, and a water-cooled system. The engine was tested with different types of diesel fuels including LFO-1, Diesel No. 2, EN590, and Heavy Fuel. This comprehensive setup allowed for a detailed analysis of the engine's performance and emissions under varying fuel conditions, providing valuable data for comparison and evaluation. Specifically, the engine used in this study is the 14-liter, six-cylinder NTA855 model. Table 1 presents a detailed engine specification as an input engine parameter in the simulation. The schematic diagram of the engine test rig and its components is illustrated in Figure 2.

Table 1: Engine specification

Brands	**Cummins NT-855**
Engine type	4 cycle – In-line – 6 cylinders
Bore x stroke	139mm x 152mm
Displacement	14 litres
Fuel consumption	52.0 litre/hr
Compression ratio	14.5
Maximum torque	1068 Nm
Maximum power	201 Kw
Cooling system	Water Cooling

Source: Mohd Noor *et al*. (2020)

In the simulation model developed for this study, four different types of fuel related to marine engines were chosen for testing. Note that the selected fuels encompass a range of diesel variants commonly used in marine applications. Each fuel type possesses distinct characteristics that can significantly impact marine engine performance and emissions.

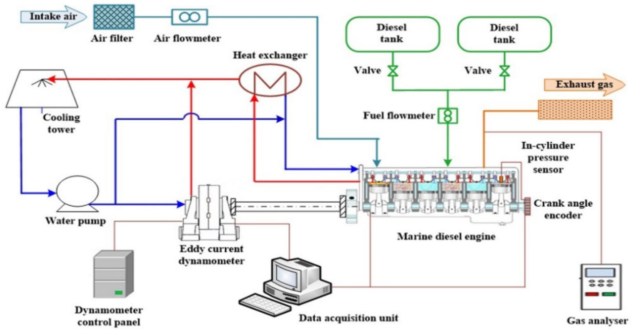


Figure 2: Engine schematic diagram

The evaluation performance of these fuels in the simulation model provides information for decision-making regarding optimising marine engine operations in terms of efficiency and environmental impact. The input parameter of each fuel type is outlined in Table 2 below:

Table 2: Fuel specifications

Fuel	**Cetane Number**	**Density of Fuel, (kg/m3)**	**Dynamic Viscosity, (Pa s)**	**Fuel Temperature, (K)**	**Low Heating Value of Fuel, (MJ/kg)**
LFO-1	46	838.3	0.003	381	42.86
Diesel No.2	48	830	0.003	380	42.5
EN590	53.3	810	0.003	380	43.1
Heavy Fuel	48	981	0.003	423	40.6

Light Fuel Oil 1 (LFO-1) is a type of marine fuel commonly used in diesel engines for ships and other maritime vessels. It is a refined fuel that falls under the category of "distillate fuels" and is often referred to as Marine Gas Oil (MGO) or Marine Diesel Oil (MDO) (Wang *et al*., 2020). Diesel No. 2 is a conventional diesel fuel widely used in various diesel engines, including those in marine applications, which is a middle distillate fuel with a moderate viscosity and sulphur content. Meanwhile, EN590 is a diesel fuel standard specified by the European Union. It is a high-quality fuel with strict limits on sulphur content and other impurities. Furthermore, EN590-compliant diesel is widely used in Europe and other regions, adhering to similar standards. Its low sulphur content makes it an environmentally friendly choice, resulting in reduced emissions and improved air quality (Tomic *et al*., 2014). Heavy Fuel Oil is a residual fuel obtained from crude oil refining processes. It is a thick, viscous fuel with a high energy density, making it an economical choice for marine engines.

However, Heavy Fuel has a high sulphur content and can produce more emissions of Sulphur Dioxide (SO_2) and particulate matter compared to lighter, cleaner fuels like LFO-1 and EN590. Its use is subject to stricter environmental regulations in certain regions. Each fuel type has its advantages and disadvantages, and their selection can significantly impact marine engine performance, emissions, and compliance with environmental regulations. Through the simulation model and testing, the study aims to understand how each fuel type influences the engine's behaviour. This assists in making informed decisions to optimise efficiency and reduce the environmental impact of marine diesel engines.

The engine simulation test was conducted under full load conditions, encompassing a range of engine speeds from 1,000 RPM to 1,600 RPM. This comprehensive approach was adopted to accurately depict the actual operating conditions of a marine engine during its typical usage. Note that testing the engine at full load ensures that it operates under maximum power demand, simulating real-world scenarios where ships and vessels require full propulsion capacity to navigate through challenging conditions or maintain high speeds.

Furthermore, by varying the engine speeds from 1,000 rpm to 1,600 rpm, the study covers a wide spectrum of operational regimes. Lower engine speeds represent slower operations, such as when a vessel is maneuvering in confined spaces or docking, while higher engine speeds correspond to cruising or transiting at sea. This range of engine speeds allows for a detailed examination of the engine's performance and emissions across different operational states. It provides valuable data to understand its behaviour under various practical conditions encountered in marine operations. To ensure accurate and reliable simulation results, the following specific assumptions, boundary conditions, and initial conditions were established within the Diesel-RK software model:

1. Engine configuration: The engine model assumes a four-stroke, turbocharged marine diesel engine with parameters as listed in Table 1.
2. Fuel properties: The fuel properties, including density, viscosity, Lower Heating Value (LHV), and cetane number, were based on Table 2 data.
3. Thermal equilibrium: It was assumed that the engine components reach thermal equilibrium quickly, with negligible effects from transient thermal states.
4. Ambient conditions: Simulations were conducted under standard sea-level ambient conditions, with ambient temperature set at 298 K and pressure at 101.3 kPa.
5. Inlet and exhaust boundaries: The inlet air pressure was adjusted to reflect turbocharged conditions, typically set at 1.5 to 2.0 times the atmospheric pressure. The exhaust boundary was set to atmospheric pressure, assuming no backpressure effects beyond standard exhaust system losses.
6. Cooling and lubrication: Engine cooling and lubrication effects were included by defining boundary conditions for heat transfer from the cylinder walls and friction losses based on empirical models within Diesel-RK.

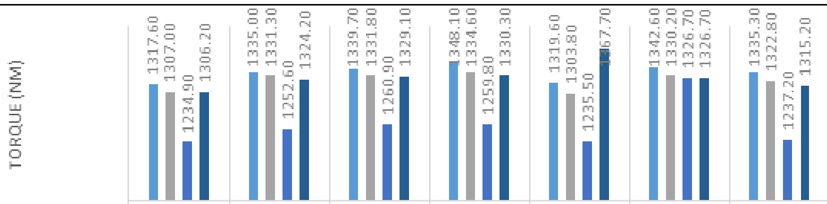
During the engine test, several crucial performance and emission parameters were measured and analysed to gain a comprehensive understanding of the marine diesel engine's behaviour under different fuel types and operating conditions. The key parameters examined in this study include braking power, torque, thermal efficiency, brake-specific fuel consumption, specific Nitrogen Oxide (NO_x) emissions, and Carbon Dioxide (CO_2) emissions.

Hence, analysing these performance and emission parameters under different engine speeds and fuel types provides valuable data on how each fuel type affects the marine engine's efficiency and environmental impact. By comparing the results, researchers can determine which fuel yields the best performance and emission characteristics, aiding in making informed decisions regarding fuel selection for marine operations.

Result and Discussions

Torque

Torque is a rotating force produced by an engine's crankshaft. The more torque an engine produces, the greater its ability to perform work. The trend in Figure 3 illustrates an increasing value of torque when increasing the speeds. However, when it comes to maximum speed, the torque slowly decreases. The reason is that horsepower rises to torque multiplied by rpm and divided by a constant. Since there is generally a limit to how fast an engine can go, having more torque will provide more horsepower at low rpm.



	Torque 1,000 RPM	Torque 1,100 RPM	Torque 1,200 RPM	Torque 1,300 RPM	Torque 1,400 RPM	Torque 1,500 RPM	Torque 1,600 RPM
Diesel No. 2	1317.60	1335.00	1339.70	1348.10	1319.60	1342.60	1335.30
EN590	1307.00	1331.30	1331.80	1334.60	1303.80	1330.20	1322.80
Heavy Fuel	1234.90	1252.60	1260.90	1259.80	1235.50	1326.70	1237.20
LFO-1	1306.20	1324.20	1329.10	1330.30	1367.70	1326.70	1315.20

Figure 3: Torque vs. Speed

According to Figure 2, Diesel No. 2 fuel has the maximum torque, which is 1,348.9 Nm at 1,300 RPM. It is slightly 1% higher than LFO-1. Apparently, Heavy Fuel has the lowest torque compared to other types of fuel, which is 5% lower than LFO-1, 5% lower than EN590, and 6% lower than Diesel No. 2. That is due to it having the lowest low heating value, which is 40.6 MJ/kg.

Conversely, EN590 and Diesel No. 2 present relatively consistent torque values, though EN590 has slightly higher torque at lower RPMs, while Diesel No. 2 leads slightly at higher RPMs. Heavy Fuel demonstrates less variation and generally lags behind the other fuels in torque production, particularly at higher RPMs. The trend indicates that Diesel No. 2 might be more suitable for applications requiring high torque at mid-range RPMs. However, this could come with trade-offs such as efficiency, emissions, or operational costs that are not shown in the data. The figure suggests that the fuel choice significantly impacts engine performance, and the optimal fuel type depends on the specific operational requirements and constraints.

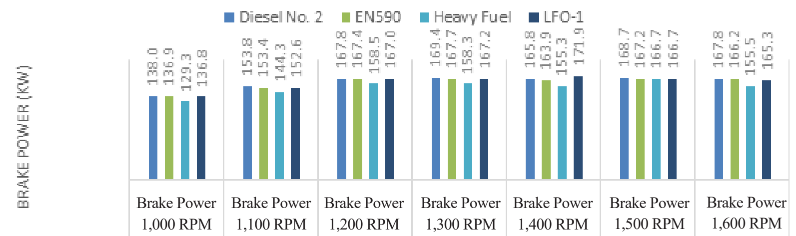
Brake Power

Brake power is the measurement of an engine's horsepower before the loss of power caused by the gearbox, alternator, water pump, and other auxiliary components. A device used to load and hold an engine at a desired engine speed, also known as brakes.

Figure 4 illustrates the differences between four different types of diesel in brake power at variable speeds and constant load. The trend of the graph for all fuel types indicates the increasing values of power when the simulation is running at all speeds. It appears that the brake power performance for LFO-1 produced the maximum power at 1,400 RPM compared to other fuels, which is 171.9 kW, which is 2.5 kW ahead of LFO-1 at 1,300 RPM. Knowing the engine brake drive is the solution to ensure that the output is strong enough to drive both the engine and any auxiliary components. By assessing the horsepower of the brakes, it is possible to decide how much control must be carried out to allow the engine to operate at the highest capacity on the basis.

Heavy Fuel remains the lowest value in brake power compared to the other types of fuel, which is 6% lower than diesel No. 2 and 5% lower than EN590 and LFO-1. This means that Heavy Fuel has the lowest power production. Basically, power is a measure of the rate of work an engine can do. An engine that can do much work quickly is called a very powerful engine.

Therefore, most fast ships use high-powered engines. Diesel No. 2 is the most powerful fuel, and it can manage to maintain a high value in brake power at peak speed. The brake power value for this type of diesel is also the highest compared to EN590, LFO-1, and Heavy Fuel.



	Brake Power 1,000 RPM	Brake Power 1,100 RPM	Brake Power 1,200 RPM	Brake Power 1,300 RPM	Brake Power 1,400 RPM	Brake Power 1,500 RPM	Brake Power 1,600 RPM
Diesel No. 2	138.0	153.8	167.8	169.4	165.8	168.7	167.8
EN590	136.9	153.4	167.4	167.7	163.9	167.2	166.2
Heavy Fuel	129.3	144.3	158.5	158.3	155.3	166.7	155.5
LFO-1	136.8	152.6	167.0	167.2	171.9	166.7	165.3

SPEED (RPM)

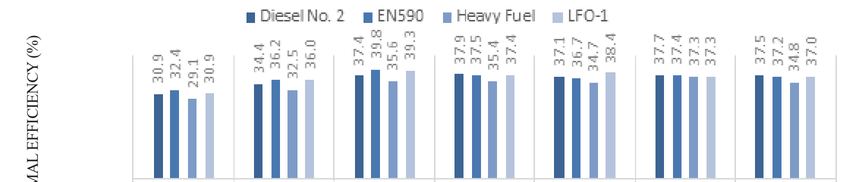
Figure 4: Brake power vs. Speed

Thermal Efficiency

Thermal efficiency is the percentage of heat energy that is transformed into work. The trend of the graph for all fuel types indicates the increasing values of Brake Specific Fuel Consumption (BSFC) at all speeds, as illustrated in Figure 5. It seems EN590 has the maximum value at 1,200 rpm, at 39.8%, approximately 1% higher than LFO-1. The reason is that if the oxygen-to-fuel ratio in EN590 is greater, which means the greater the amount of air in an air-to-fuel ratio, the cleaner the fuel burns and the more energy it produces. Note that EN590 has a higher thermal efficiency value when compared to the other three types of diesel fuel, and Heavy Fuel had the lowest one.

However, at higher speeds (beyond 1,400 RPM), Diesel No. 2 emerges as more efficient, suggesting that it may be more effective under conditions requiring sustained high-speed operation, possibly due to its different combustion characteristics or lower energy losses at these speeds. In contrast, Heavy Fuel consistently indicates the lowest thermal efficiency across all RPM levels, reflecting its lower oxygen content and possibly higher energy losses due to incomplete combustion or other inefficiencies. LFO-1, while trailing EN590 slightly, performs consistently across the range, indicating it might offer a balanced performance without the specific advantages or disadvantages of EN590 and Heavy Fuel.

These observations suggest that fuel selection should be carefully matched to the engine's operating conditions and desired performance outcomes, as each fuel type offers distinct trade-offs regarding efficiency, power output, and potentially emissions.



	Thermal Efficiency 1,000 RPM	Thermal Efficiency 1,100 RPM	Thermal Efficiency 1,200 RPM	Thermal Efficiency 1,300 RPM	Thermal Efficiency 1,400 RPM	Thermal Efficiency 1,500 RPM	Thermal Efficiency 1,600 RPM
Diesel No. 2	30.9	34.4	37.4	37.9	37.1	37.7	37.5
EN590	32.4	36.2	39.8	37.5	36.7	37.4	37.2
Heavy Fuel	29.1	32.5	35.6	35.4	34.7	37.3	34.8
LFO-1	30.9	36.0	39.3	37.4	38.4	37.3	37.0

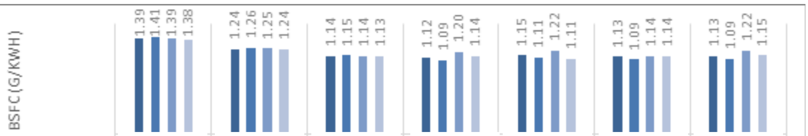
SPEED (RPM)

Figure 5: Thermal efficiency vs. Speed

Brake-Specific Fuel Consumption

The fuel consumption rate divided by its corresponding engine brake power output can best be described as BSFC. The production of the same amount of work with less fuel use means that there is a lower rate of brake-specific fuel consumption. Generally, an increasing speed reduces the BSFC of the engine, as depicted in Figure 6. The increased percentage of required fuel in engine operation is less than the increased percentage of brake power due to a relatively small portion of the heat losses at higher loads. Moreover, it appears that the engine running with all types of fuel indicates the minimum values of BSFC at 1,200 rpm due to an optimal balance between fuel combustion and power output. The difference between each fuel changes by around 2%. Lower BSFC means the engine requires less fuel to generate a given horsepower.

EN590 has reached the lowest end of the BSFC, which is 1.09 g/kWh. It has been proved that EN590 is more efficient compared to other types of fuel. On the other hand, Heavy Fuel consistently determines the highest BSFC values, particularly 6% to 7% higher than the other fuels, highlighting its relative inefficiency. This higher BSFC suggests that more fuel is required to produce the same amount of power, likely due to poorer combustion characteristics and greater heat losses. Diesel No. 2 and LFO-1, while more efficient than Heavy Fuel, do not match the performance of EN590. However, their BSFC values are still competitive, particularly at higher RPMs. The differences in BSFC among the fuels emphasise the importance of selecting the appropriate fuel type based on the specific performance requirements of the engine.



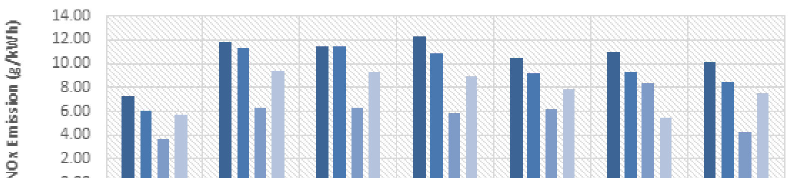
	Brake Specific Fuel Consumption 1,000 RPM	Brake Specific Fuel Consumption 1,100 RPM	Brake Specific Fuel Consumption 1,200 RPM	Brake Specific Fuel Consumption 1,300 RPM	Brake Specific Fuel Consumption 1,400 RPM	Brake Specific Fuel Consumption 1,500 RPM	Brake Specific Fuel Consumption 1,600 RPM
Diesel No. 2	1.39	1.24	1.14	1.12	1.15	1.13	1.13
EN590	1.41	1.26	1.15	1.09	1.11	1.09	1.09
Heavy Fuel	1.39	1.25	1.14	1.20	1.22	1.14	1.22
LFO-1	1.38	1.24	1.13	1.14	1.11	1.14	1.15

Figure 6: BSFC vs. Speed

Specific NO_x Emission

NO_x emissions are seen as an emission polluting the air environment, so the results obtained from the graph are very significant. Note that NO_x is produced from the reaction of nitrogen and oxygen gases in the air during combustion, especially at high speed. EN590 and Diesel No. 2 exhibit significantly higher NO_x emissions across all RPM levels, indicating maximum readings at 1,100 RPM and 1,200 RPM, as shown in Figure 7. This can be attributed to the higher combustion temperatures typically associated with these fuels, which promote the formation of NO_x due to the reaction of nitrogen and oxygen in the air. The elevated NO_x emissions are concerning because they contribute to air pollution, including the formation of smog and acid rain, and pose health risks such as respiratory issues.

On the other hand, Heavy Fuel and LFO-1 produce much lower NO_x emissions, suggesting they burn at lower temperatures or with less complete combustion, which may reduce the formation of NO_x. Nevertheless, while these fuels might be less harmful from a NO_x perspective, they could have other drawbacks, such as higher particulate matter emissions or lower overall efficiency, as seen in the BSFC and thermal efficiency graphs.

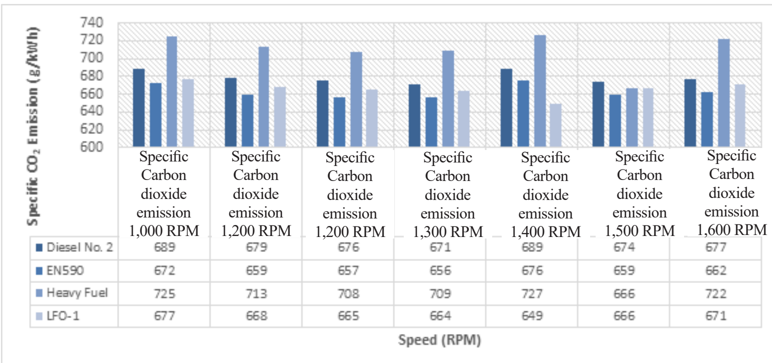


	Specific Nox Emission 1,000 RPM	Specific Nox Emission 1,100 RPM	Specific Nox Emission 1,200 RPM	Specific Nox Emission 1,300 RPM	Specific Nox Emission 1,400 RPM	Specific Nox Emission 1,500 RPM	Specific Nox Emission 1,600 RPM
Diesel No. 2	7.32	11.78	11.44	12.33	10.45	10.96	10.10
EN590	6.11	11.28	11.39	10.90	9.12	9.32	8.40
Heavy Fuel	3.72	6.35	6.29	5.78	6.21	8.36	4.30
LFO-1	5.74	9.41	9.30	8.99	7.81	5.45	7.52

Figure 7: Specific NO_x emission vs. Speed

Specific Carbon Dioxide Emission

CO_2 emissions are the primary driver of climate change. It is widely recognised that the world needs to reduce emissions to avoid the worst impacts of climate change. Furthermore, carbon emissions are one kind of environmental pollution that occurs when CO_2 enters the air as a result of human activity or process. They are vital to this discussion because they are crucial aspects of emission in terms of quantity. Figure 8 illustrates that Heavy Fuel consistently exhibits the highest CO_2 emissions across all RPM levels, with a peak of 727 g/kWh at 1,400 RPM. This high level of emissions is likely due to the higher carbon content of Heavy Fuel and the incomplete combustion that often occurs with such dense fuels, leading to greater CO_2 output per unit of energy produced. The higher CO_2 emissions also align with the fuel's lower efficiency, as previously discussed, indicating that more fuel is required to produce the same amount of power, further contributing to its larger carbon footprint.



	Specific Carbon dioxide emission 1,000 RPM	Specific Carbon dioxide emission 1,200 RPM	Specific Carbon dioxide emission 1,200 RPM	Specific Carbon dioxide emission 1,300 RPM	Specific Carbon dioxide emission 1,400 RPM	Specific Carbon dioxide emission 1,500 RPM	Specific Carbon dioxide emission 1,600 RPM
Diesel No. 2	689	679	676	671	689	674	677
EN590	672	659	657	656	676	659	662
Heavy Fuel	725	713	708	709	727	666	722
LFO-1	677	668	665	664	649	666	671

Figure 8: Specific carbon dioxide emission vs. Speed

In contrast, EN590 and LFO-1 demonstrate significantly lower CO_2 emissions, suggesting that these fuels burn more efficiently and with a better air-to-fuel ratio, resulting in more complete combustion and lower CO_2 output. EN590, in particular, examines the lowest CO_2 emissions, reinforcing its position as a more environmentally friendly option among the tested fuels. Diesel No. 2 falls between Heavy Fuel and the lower-emitting fuels, indicating that while it is more efficient than Heavy Fuel, it still produces a considerable amount of CO_2, especially at higher RPMs.

Conclusions

This study successfully developed a simulation model for marine diesel engine combustion using Diesel-RK software, which enabled a comprehensive evaluation of the performance and emissions of different fuel types on a marine diesel engine. The simulation results demonstrate that EN590 is the most stable and suitable fuel among those tested, significantly enhancing engine performance regarding brake power, torque, thermal efficiency, and brake-specific fuel consumption. Moreover, EN590 results in substantially lower NO_x and CO_2 emissions compared to Diesel No. 2, LFO-1, and Heavy Fuel, making it a more environmentally friendly option that aligns with IMO emission regulations, particularly within emission control areas.

However, the study has certain limitations. The findings are based on a simulation model, which, while successfully developed and valuable, may not fully capture the complexities of real-world engine operations. Although robust, the accuracy of the Diesel-RK software is limited by the quality of input data and the assumptions made during the modelling process. Additionally, the study did not explore the long-term effects of using different fuels on engine wear and maintenance, which could be significant in real-world applications. In the future, the authors recommend conducting experimental research on real marine diesel engines using EN590 to validate the simulation results.

Acknowledgments

The authors would like to thank all reviewers for their comments and suggestions for improving this manuscript.

Conflict of Interest Statement

The authors declare that they have no conflict of interest.

References

Chaurasiya, P. K., Rajak, U., Veza, I., Verma, T. N., & Ağbulut, Ü. (2022). Influence of injection timing on performance, combustion and emission characteristics of a diesel engine running on hydrogen-diethyl ether, n-butanol and biodiesel blends. *International Journal of Hydrogen Energy*, *47*(41), 18182-18193.

Raju, V. D., Soudagar, M. E. M., Venu, H., Nair, J. N., Reddy, M. S., Reddy, J. S., Rao, T. S., Khan, T. Y., Ismail, K. A., & Elfasakhany, A. (2022). Experimental assessment of diverse diesel engine characteristics fueled with an oxygenated fuel added lemon peel biodiesel blends. *Fuel*, *324*, Article 124529. https://doi.org/10.1016/j.fuel.2022.124529

Fourth Greenhouse Gas Study 2020. (2020). https://www.imo.org/en/ourwork/Environment/Pages/Fourth-IMO-Greenhouse-Gas-Study-2020.aspx

Gad, He, Z., El-Shafay, A., & El-Seesy, A. I. (2021). Combustion characteristics of a diesel engine running with Mandarin essential oil -diesel mixtures and propanol additive under different exhaust gas recirculation: Experimental investigation and numerical simulation. *Case Studies in Thermal Engineering*, *26*, Article 101100.

Liu, Z., Zheng, X., Zhang, H., Li, W., Jiang, R., & Zhou, X. (2022). Review on formation of biofouling in the marine environment and functionalization of new marine antifouling coatings. *Journal of Materials Science*, *57*(39), 18221-18242.

Noor, C. W. M., Mamat, R., Ali, O., Najafi, G., & Mansor, W. N. D. (2020). Cyclic Variation Analysis of Palm biodiesel fuel in low compression marine diesel engine. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences*, *75*(2), 43-58.

Pham, V. V. (2019). Research on the application of diesel-RK in the calculation and evaluation of technical and economic criteria of marine diesel engines using the unified ULSD and biodiesel blended fuel. *Journal of Mechanical Engineering Research and Developments*, *42*(2), 87-97.

Rajak, U., Panchal, M., Nashine, P., Verma, T. N., Kumar, R., & Pugazhendhi, A. (2023). Sustainability evaluation of green microalgae biofuel production and reducing the engine emissions in a common rail direct engine. *Fuel*, *350*, Article 128687.

Raju, V. D., Venu, H., Subramani, L., Kishore, P., Prasanna, P., & Kumar, D. V. (2020). An experimental assessment of prospective oxygenated additives on the diverse characteristics of diesel engine powered with waste tamarind biodiesel. *Energy*, *203*, Article 117821.

Song, J., Xu, C., & Wang, C. (2023). Impacts of the carbon tax on green shipping supply chain under the port competition. *Expert Systems*, *41*(5), e13229. https://doi.org/10.1111/exsy.13229

Tomic, M., Savin, L., Micic, R., Simikic, M., & Furman, T. (2014). Possibility of using biodiesel from sunflower oil as an additive for the improvement of lubrication properties of low-sulfur diesel fuel. *Energy*, *65*, 101-108.

Wang, Z., Paulauskiene, T., Uebe, J., & Bucas, M. (2020). Characterization of Biomethanol–Biodiesel–Diesel blends as alternative fuel for marine applications. *Journal of Marine Science and Engineering*, *8*(9), Article 730.