Thermal Science and Engineering 2024, 7(2), 8821.
https://doi.org/10.24294/tse.v7i2.8821

Article

Performance and emissions of water-emulsified diesel fuel in an IDI diesel engine under varying engine load

Pedro Oliveira[1,*], Francisco Brójo[2]

[1] Centre for Mechanical and Aerospace Sciences and Technologies (C-MAST), University of Beira Interior, 6200-358 Covilhã, Portugal
[2] Department of Aerospace Sciences, University of Beira Interior, 6200-358 Covilhã, Portugal
*** Corresponding author:** Pedro Oliveira, p.m.penafiel@gmail.com

CITATION

Oliveira P, Brójo F. Performance and emissions of water-emulsified diesel fuel in an IDI diesel engine under varying engine load. Thermal Science and Engineering. 2024; 7(2): 8821. https://doi.org/10.24294/tse.v7i2.8821

ARTICLE INFO

Received: 14 April 2024
Accepted: 3 May 2024
Available online: 12 May 2024

Abstract: This paper aims to verify the possibility of utilising water-in-diesel emulsions (WiDE) as an alternative drop-in fuel for diesel engines. An 8% WiDE was produced to be tested in a four-stroke, indirect injection (IDI) diesel engine and compared to EN590 diesel fuel. An eddy current brake and an exhaust gas analyser were utilised to measure different engine parameters such as torque, fuel consumption, and emissions at different engine loads. The results show that the engine running on emulsified fuel leads to a reduction in torque and power, an increase in the specific fuel consumption, and slightly better thermal efficiency. The highest percentual increment of thermal efficiency for WiDE is obtained at 100% engine load, 5.68% higher compared to diesel. The emissions of nitric oxide (NO) and carbon dioxide (CO_2) are reduced, but carbon monoxide (CO) and hydrocarbons (HC) emissions are increased, compared to traditional diesel fuel. The most substantial decrease in NO and CO_2 levels was achieved at 75% engine load with 33.86% and 25.08% respectively, compared to diesel.

Keywords: water-in-diesel emulsion; IDI diesel engine; performance; emissions; micro-explosion

1. Introduction

For numerous years, governments worldwide have regrettably overlooked pollution and its detrimental impact on the environment, despite its standing as a chief contributor to both health issues and the planet's decline in recent decades. Among the most severe manifestations of pollution is air pollution, a grave concern highlighted by the World Health Organization, attributing over 4.2 million fatalities annually [1]. Fossil fuels are one of the main responsibles for these emissions of pollutants into the air, accounting for over 84.3% of all primary energy sources [2]. The transport sector represents over 15.0% of the fossil fuels emissions, and in Europe, oil represents over 93% of the total energy consumption in the sector, followed by low amounts of biofuels and natural gas [3,4].

Internal combustion engines represent the big share of fossil fuels' consumption, being responsible for the high concentrations of greenhouse gases in the atmosphere [5]. Until now, diesel engines stood out as one of the most efficient and dependable mechanisms for converting energy, boasting superior fuel-to-power conversion efficiency. This inherent efficiency translates into improved fuel economy [6]. Hence, they reign as the predominant category of engines across a diverse spectrum of applications, including power generation, on-road transportation, agriculture, military usage, and marine operations [7]. However, on a less positive note, diesel engines constitute the primary source of the most concerning exhaust emissions, notably nitrogen oxides [8].

With the upcoming emissions restrictions scheduled for 2025, known in Europe as the European Emission Standards (Euro 7) [9], plentiful technologies have been developed and are available that offer reduced emissions, like alternative and cleaner fuels (electricity, hydrogen, biofuels, natural gas, etc.). All of which have their advantages and disadvantages. WiDE represents a technological advancement and a fuel designed for integration into diesel engines, offering the dual benefits of enhanced combustion efficiency and reduction in exhaust emissions. As a "drop-in" fuel, no modifications to the engine are needed, ensuring its compatibility for immediate utilisation. An emulsion is a dispersion containing two immiscible phases, mixed by mechanical shear and chemical processes and stabilised by surfactants. In an emulsion, droplets of one liquid are dispersed in a continuous flow [10]. WiDE consists of diesel as the continuous phase, water as the dispersed phase, and surfactants. A surfactant is an amphiphilic molecule that has hydrophobic and hydrophilic parts. The primary goal of a surfactant (or surface-active agent) is to lower the interfacial tension between the two surfaces (e.g., diesel and water), reducing the repellent force between the two liquids and diminishing the attraction between the molecules of the same liquid. This results in lower energy required to increase the surface area, leading to a spontaneous dispersion of water droplets and possibly to a thermodynamically stable system. The secondary role is to maintain the stability of the emulsion while reducing the coagulation effect in the water phase [11,12]. Non-ionic surfactants are relatively non-toxic and the main choice for WiDE [13].

The cleaner combustion of emulsified fuels can be attributed to the puffing and micro-explosion phenomena in emulsion droplets. When the emulsion is sprayed into a hot combustion chamber, heat is transferred to the surface of the fuel droplets by convection and radiation. A rapid break-up of the parent droplets due to the different volatility of the fuel and water promotes a secondary atomization that reduces the combustion duration [14], as seen in **Figure 1**.

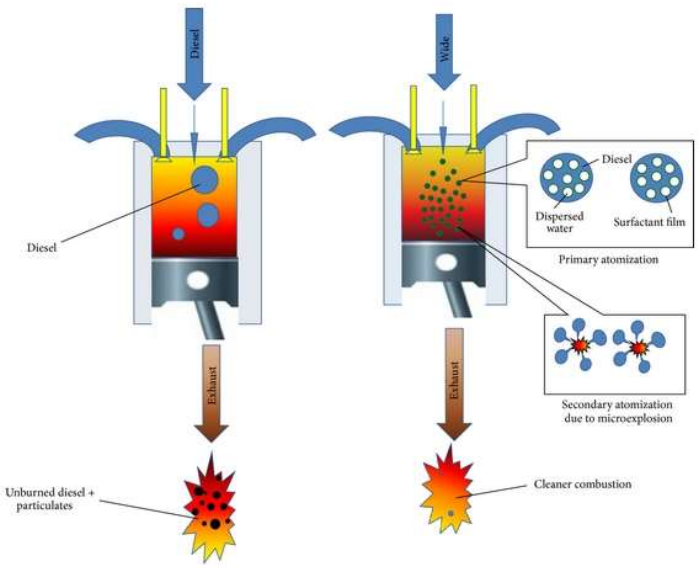

Figure 1. Primary and secondary atomization of WiDE [15].

At this stage, the two phenomena prevail [15,16]. Puffing is the partial ejection of some dispersed water out of an emulsion droplet. Micro-explosion is the complete break-up of the parent droplet. These two occurrences improve the combustion process by enhancing the effective fuel droplet size distribution, leading to better air-fuel mixing and therefore better fuel efficiency and fewer emissions [16]. **Figure 2** shows an example of the micro-explosion phenomenon.

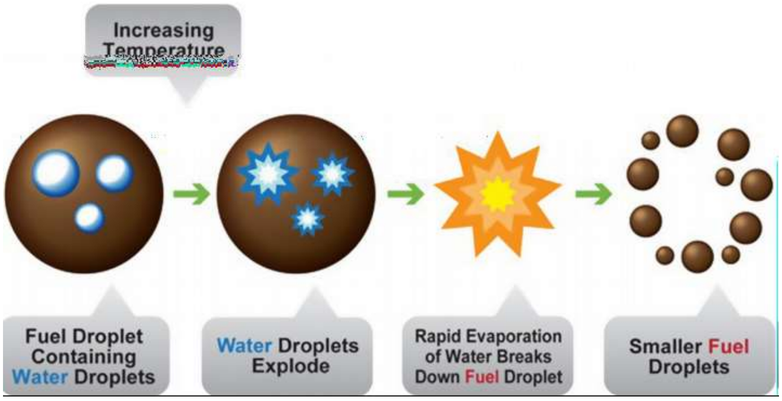

Figure 2. Micro-explosion in WiDE [17].

The evaporation of water present in the emulsion leads to a significant reduction in the combustion chamber temperature (heat sink effect), reducing NOx emissions. The longer ignition delays due to the heat sink effect results in more fuel combustion in premixed mode [14]. The air/fuel ratio becomes higher, ensuring a sufficient amount of oxygen availability, which can help to reduce CO and HC formation [18].

Even though the process is simple to understand, there are still many uncertainties about the ideal properties and composition of the emulsion system [19]. For WiDE, the correct choice of surfactants and the proportional mixture between them is essential to achieve stability and effectiveness. The same happens for the emulsification process and the ideal water content. Different percentages will lead to different results when it comes to performance and emissions parameters. Although most studies are consensus on the reduction of NOx, the results for CO, CO2, and HC differ widely. The same happens for torque, fuel consumption, and thermal efficiency [20–24].

The majority of research concerning performance and emissions pertains to diesel engines featuring direct injection (DI), a more modern technology recognised for its high injection pressures and improved efficiency [25,26]. This prevailing trend is similarly observed in most investigations focused on WiDE [27]. Only a limited number of works regarding emulsions involve engines equipped with indirect fuel injection [28,29]. A most recent study has analysed the effect of DI and IDI on the performance and emissions of WiDE [30]. It has found that even though some of the emissions are reduced, the brake-specific fuel consumption of the IDI case was considerably higher. IDI diesel engines have distinct combustion characteristics, mainly due to the existence of a swirl chamber where combustion begins. The injection pressure is also significantly lower when compared to DI engines. High injection pressures can also be responsible for the reduction in the intensity of micro-explosions due to the evaporation and decrease of dispersed water during the injection spray. By focusing this study on an IDI diesel engine, which might not experience sufficiently high injection pressures to cause water separation during the spray, more favourable outcomes could potentially be achieved.

Conducting research in this domain can yield a more comprehensive understanding of how emulsions behave across diverse combustion scenarios. It is also possible to find out potential benefits for this engine type that can have broader implications for engine design and performance optimization, especially for industries and operators that rely on existing and older equipment and are unable to transition to newer engine technologies due to the costly replacements.

2. Methodology

2.1. Laboratory testing

In order to achieve the best possible formulation, different trials had to be performed with different percentages (m/m) of water, diesel, and surfactants. The ultimate goal was to produce an emulsion that would be optimised and stable at a temperature close to 40 °C, which is similar to the fuel's tank temperature of the engine during operating conditions. This was verified by pointing a flashlight at one side of the flask and observing if the light would go through the other side. If that is the case, the size of the dispersed water droplets is small enough, and a transparent and stable emulsion was obtained.

EN590 diesel fuel, deionised water, a hydrophilic surfactant, and a lipophilic surfactant were acquired to be used as reagents to produce WiDE. An analytic balance (Radwag AS 310/C/2), a magnetic stirrer (Stuart Scientific SM3), a thermometer (Enviro-Safe), beakers, pipettes, and glass bottles were the materials and equipment used to accurately weigh, measure, and mix the different reagents. **Figure 3** shows the equipment and material used for laboratory testing.

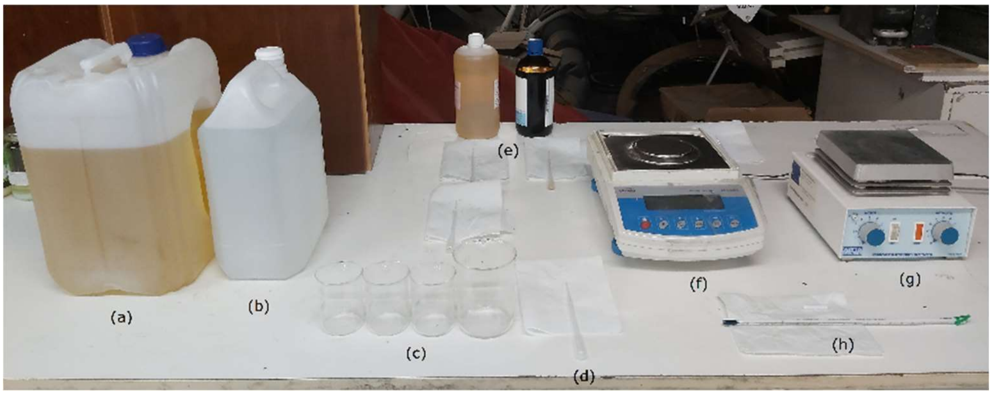

Figure 3. (a) laboratory equipment and material-diesel fuel; **(b)** deionised water; **(c)** beakers; **(d)** pipette; **(e)** surfactants; **(f)** analytic balance; **(g)** magnetic stirrer; and **(h)** thermometer.

The different reagents were weighed and then gradually added to the bottle in the magnetic stirrer in the following order: surfactants-diesel fuel-deionised water. This process was executed at ambient temperature (T = 25 °C). Two surfactants (one hydrophilic and one hydrophobic) were tested at different concentrations (one to another). Diesel fuel was gradually added to the surfactants and mixed for 5 min. During this period, deionised water was added droplet by droplet. The emulsion was then mixed for 2 more minutes. **Figure 4** shows a common production process of WiDE.

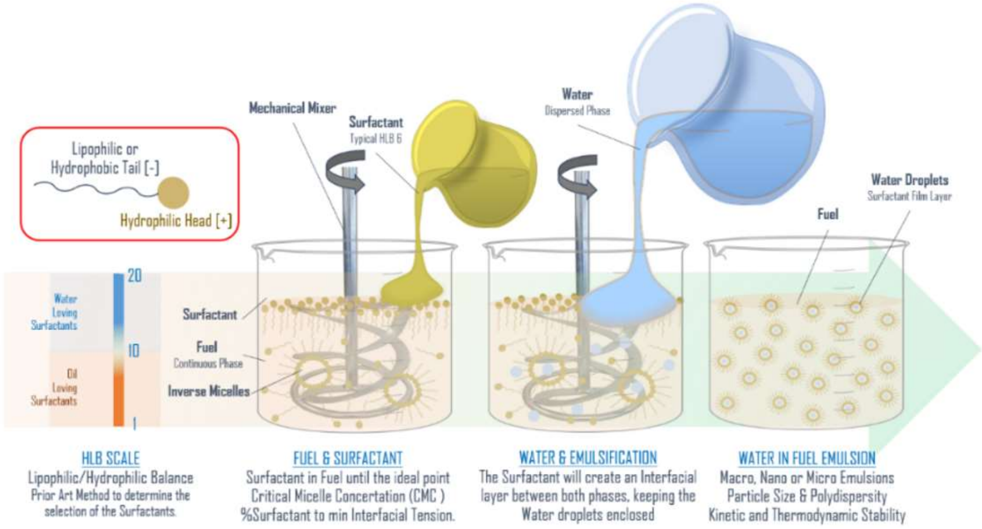

Figure 4. Typical WiDE emulsification process.

For this work, one emulsion was created. It consisted of 89% (m/m) diesel fuel, 8% (m/m) deionised water, and 3% (m/m) surfactant/co-surfactant, as shown in **Figure 5**.

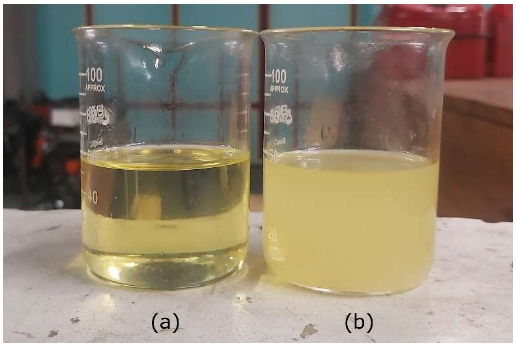

Figure 5. (a) diesel; and **(b)** 8% WiDE at $T = 40$ °C.

This composition of the emulsified fuel was selected based on the work of Fernandes [31], who has a patent on the composition of micro and nanoemulsions, where emulsions with 8% water are included. The only difference was that an alcohol was not utilised as a 3rd reagent and only a surfactant and co-surfactant were utilised. Because the chemical properties of EN590 diesel vary widely, the formulation couldn't be exactly the same. Various combinations of surfactant and co-surfactant percentages were tested, starting at 85% surfactant and 15% co-surfactant with increments of 2% in the hydrophilic surfactant. The goal was to achieve a transparent emulsion at a temperature of 40 °C. After different trials, the formulation that proved most effective for an emulsion containing 8% water content was the one with a 91% hydrophilic surfactant and 9% lipophilic co-surfactant ratio.

2.1.1. Fuel properties

The density, viscosity, and calorific value, among other properties of the fuels, can affect the spray, mixing, and energy release rate during the engine combustion processes. For this reason, different tests were performed in the original fuel and in the emulsions to observe the variation of these properties between them. The density and viscosity of diesel fuel at 60 °C were not measured since the temperature of diesel won't exceed 40 °C in the fuel tank during engine tests.

Density

The change in density with the increase of temperature for the different fuels was tested and is shown in **Figure 6**.

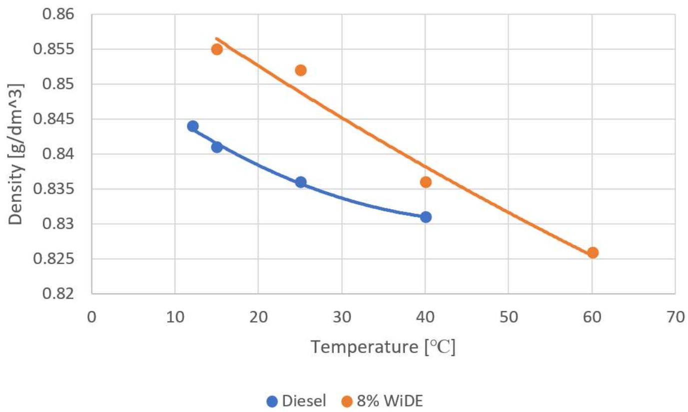

Figure 6. Changes in density with temperature.

Viscosity

The change in the kinematic viscosity with the increase of temperature for the different fuels was tested and is shown in **Figure 7**. The same viscometer was used during all the tests. Ideally, a rheometer should be used for the emulsion (non-Newtonian fluid).

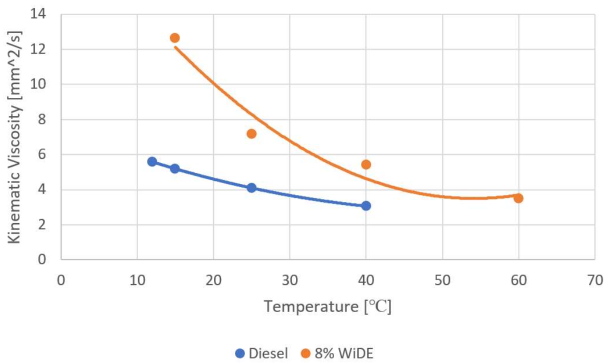

Figure 7. Changes in viscosity with temperature.

As can be seen, a temperature near 60 °C will lead to almost similar viscosities between the emulsified fuel and the viscosity of diesel fuel at 40 °C. Since the mass flow rate of a fuel is heavily correlated with its kinematic viscosity (Poiseuille's law), to achieve similar mass flow rates and similar injection timings, during engine tests the emulsions in the fuel tank were heated to a temperature near 60 °C in a thermostatic bath, while diesel fuel was tested at the temperature reached in the tank during engine operation (~40 °C).

Heating value

The amount of heat released during stoichiometric combustion can be calculated by using a calorimeter. For this case, it was utilised a bomb calorimeter, model 6050 from Parr, as seen in **Figure 8**.

Figure 8. (a) positive electrode; (b) negative electrode; (c) oxygen valve; (d) bomb; (e) water supply; (f) ignition thread; (g) fuel sample; (h) jacket.

After obtaining the higher heating value at constant volume (HHVv) given by the calorimeter, for further calculations, the chemical composition of the different reagents was analysed, as shown in **Table 1**.

Table 1. Chemical composition of the reagents.

	Chemical formula	**Molecular weight [g/mol]**	**Hydrogen [% m/m]**	**Oxygen [% m/m]**
Diesel fuel	$C_{15.18}H_{29.13}$	211.70	13.87	-
Deionised water	H_2O	18.02	11.19	88.81
Hydrophilic surfactant	$CH_3(CH_2)_{10}C(=O)N(CH_2CH_2OH)_2$	299.45	11.11	16.03
Hydrophobic surfactant	$C_{24}H_{44}O_6$	428.61	10.35	22.40

The lower heating value at constant pressure (LHVp), similar to the diesel engine combustion cycle, where water is not condensed and is existing in a vapour form, needs to be calculated. After considering the different weights of the reagents in the fuels and performing the calculations, the different LHVp were obtained. By multiplying the specific energy (MJ/kg) and the fuel's density at 15 °C, we can also obtain the energy density (MJ/L) for each of the fuels, as shown in **Table 2**.

Table 2. Heating values of the fuels.

Fuel	**HHVv (MJ/kg)**	**HHVv (MJ/L]**	**LHVp (MJ/kg)**	**LHVp (MJ/L)**
Diesel	45.49	38.26	42.53	35.77
8% WiDE	41.68	35.64	38.77	33.15

2.2. Engine testing

A Lombardini LDW 502 M3 IDI diesel engine was selected to test the different fuels. Its specifications are shown in **Table 3**. The engine was placed on a test bench equipped with an eddy current dynamometer. The measured parameters were speed, torque, power, fuel flow, and air flow at different engine loads. An AVL DiTest gas 1000 model 2301 emission gas analyser was used to measure the exhaust gas concentrations. Its specifications are shown in **Table 4**. The test stand is composed of an electromagnetic brake acting as a dynamometer that was dimensioned to dissipate a power of 30 kW at 3000 rpm. It is composed of two coils that produce a magnetic field and a conductive aluminium disk rotating between them. Nunes and Brojo [32] give a detailed explanation of how the dynamometer was designed and the mathematical model utilised. An example of the montage diagram with the equipment, different sensors, and data acquisition devices is shown in **Figure 9**.

Table 3. Engine specifications.

Specifications	LDW 502 M3
Operating cycle	4-stroke
Cylinders	2, in-line
Valves per cylinder	2
Bore [mm]	72
Stroke [mm]	62
Engine displacement [cm^3]	505
Injection system	IDI
Injection pressure [bar]	147
Compression ratio	22.5:1
Maximum torque [Nm]	23
Maximum power [kW]	4

Table 4. Gas analyser specifications.

Gas	Measuring range	Resolution	Accuracy
CO	0–15% vol.	0.01% vol.	±0.03% vol.
CO_2	0–20% vol.	0.01% vol.	±0.5% vol.
HC	0–30,000 ppm vol.	1 ppm vol.	±10 ppm vol.
O_2	0–25% vol.	0.01 % vol.	±5% o.M.
NO	0–5000 ppm vol.	1 ppm vol.	±50 ppm vol.

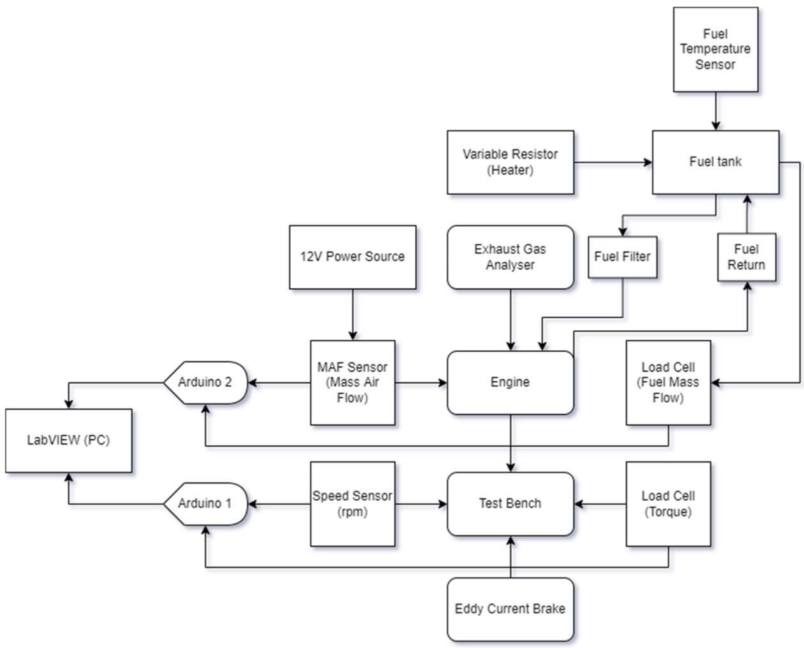

Figure 9. Bench-test montage diagram.

To supply the emulsified fuel to the engine, the previous laboratory emulsion was again reproduced in a sample of 1 kg. A mixing paddle connected to a drill was used as a low-energy mixing method (**Figure 10**).

Figure 10. 8% WiDE mixing at *T* = 25 °C.

As opposed to diesel fuel testing, the flask containing the emulsion was heated in a thermostatic bath and emulsified diesel was supplied to the engine at ~60 °C as shown in **Figure 11**.

Figure 11. Engine bench-test of the emulsion.

Tests were performed for 50%, 75%, and 100% engine loads, defined by the position of the accelerator pedal. For safety purposes, the maximum speed of the engine under no load was limited to around 3000 rpm, leading to a decrease in the maximum torque and power values that the engine could achieve. For each load condition, the engine was left idle for some minutes to warm up, accelerated, and then electromagnetically braked at different speeds until stalling. The tests were performed at ambient temperature (*T* = 25 °C). For each load and speed condition, torque/power, fuel consumption, and emissions results were withdrawn. The LabVIEW interface for data monitoring and acquisition is shown in **Figure 12**.

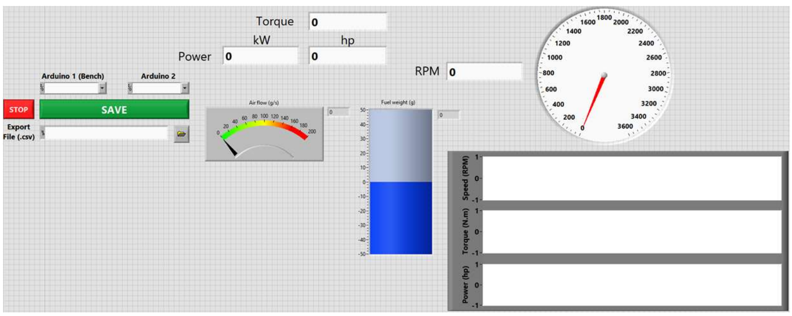

Figure 12. LabVIEW interface.

3. Results and discussion

In this section, the results obtained from the engine performance tests are described. The different parameters in the figures will include the keyword "brake" because an electromagnetic dynamometer (brake) was used to measure them at the engine shaft. This is the usable power or torque delivered by the engine to the load [33].

3.1. Torque and power

As shown in **Figures 13–15**, the overall torque and power values for diesel are higher when compared to WiDE at all engine loads. This can be explained by the higher heating value of diesel fuel which leads to the release of more energy in combustion, surpassing the benefits of the puffing and micro-explosions phenomena happening in WiDE. At full engine load, the peak torque value of the engine for diesel is 18.32 Nm at 976 rpm, and for 8% WiDE, it is 16.79 Nm at 1023 rpm. At this load, the peak power of the engine for diesel is 2.39 kW at 2092 rpm and 2.16 kW at 1621 rpm for 8% WiDE.

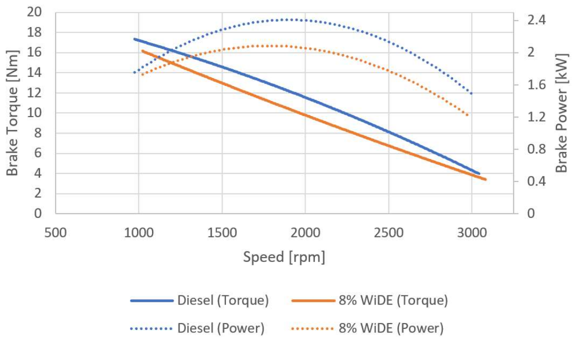

Figure 13. Brake torque and brake power at 100% engine load.

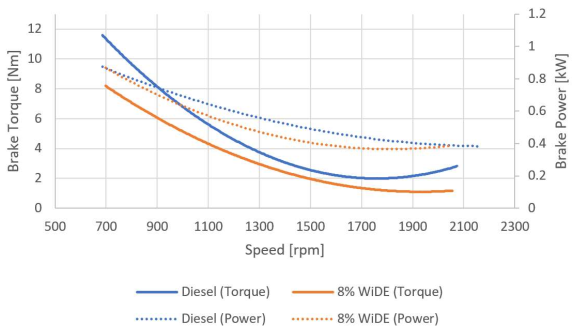

Figure 14. Brake torque and brake power at 75% engine load.

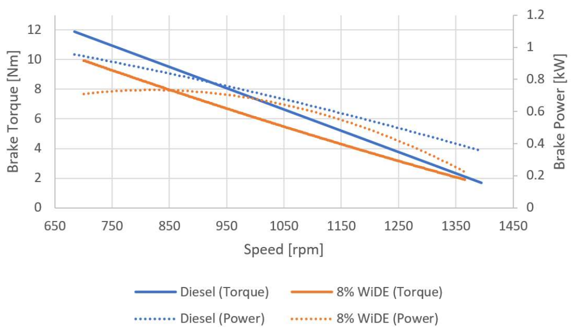

Figure 15. Brake torque and brake power at 50% engine load.

3.2. Fuel consumption and efficiency

Figures 16–18 show that the engine fuelled with diesel has lower overall values of SFC compared to WiDE, which can be explained by the lower energy content of WiDE and slightly higher viscosity (even if heated during tests), leading to a longer injection delay and more fuel injected to overcome the lower LHV of WiDE.

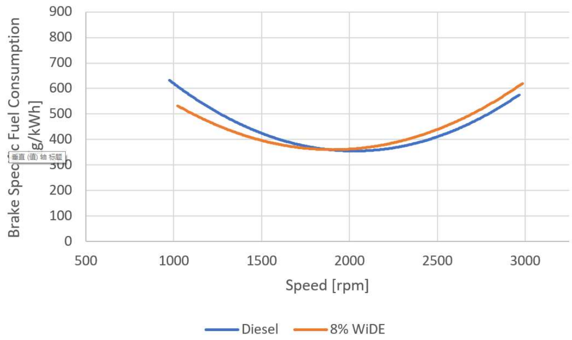

Figure 16. Brake specific fuel consumption at 100% engine load.

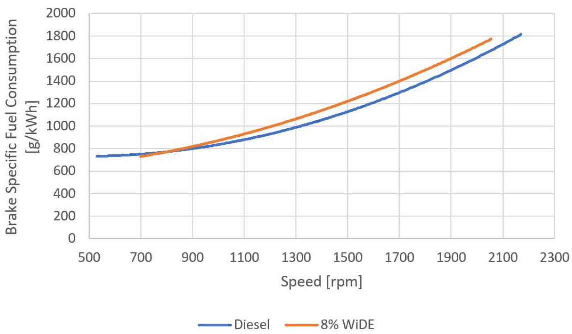

Figure 17. Brake specific fuel consumption at 75% engine load.

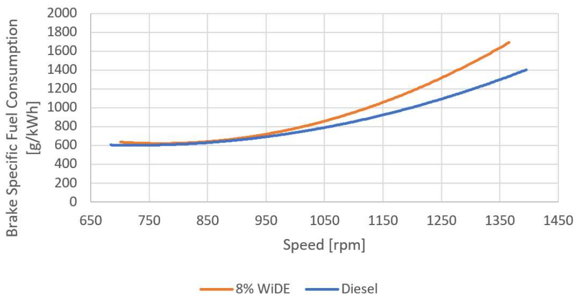

Figure 18. Brake specific fuel consumption at 50% engine load.

Only at 100% engine load, WiDE has similar values of SFC compared to diesel fuel. Even though the power values for diesel were higher, the mass flow rate for WiDE at this condition was low enough to compensate for the loss in power. For other loads (75% and 50%), WiDE has higher SFC values when compared to diesel.

The secondary atomization from the evaporation of water droplets in WiDE can enhance the air/fuel mixing and be responsible for the improved combustion and better fuel efficiency.

As seen before, and because WiDE fuel has less diesel and therefore less energy content in its composition, its LHV will also be lower, improving thermal efficiency as shown in **Figure 19**.

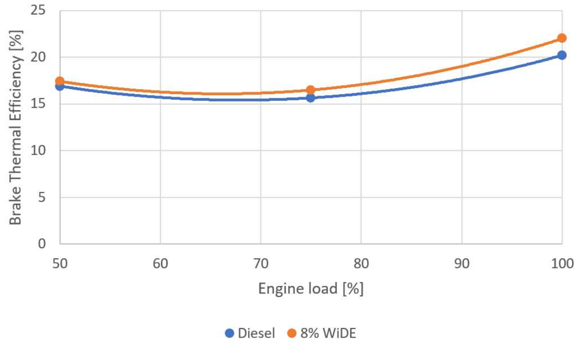

Figure 19. Brake thermal efficiency at different engine loads.

3.3. Emissions

For the different fuels, and at the same conditions where torque, power, and specific fuel consumption curves were obtained, different exhaust gases from the engine were also measured, as shown in **Figures 20–22**. Regarding the hydrocarbon emissions, the gas analyser was calibrated for propane (C_3H_8).

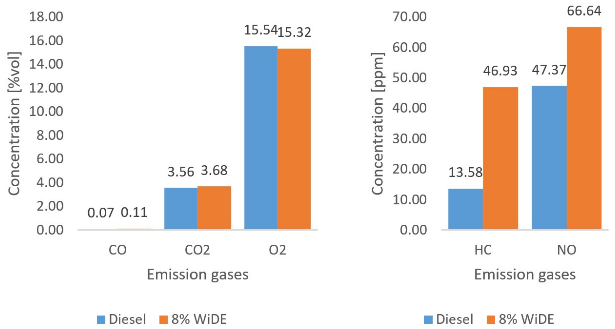

Figure 20. Emission gases at 100% engine load.

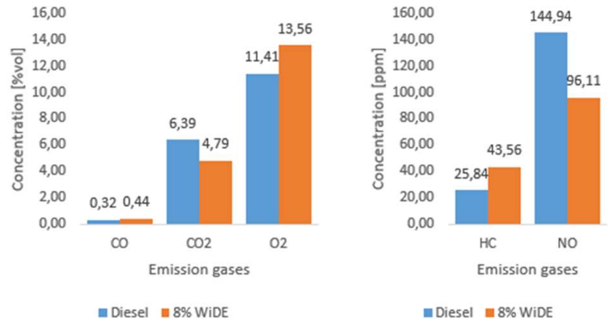

Figure 21. Emission gases at 75% engine load.

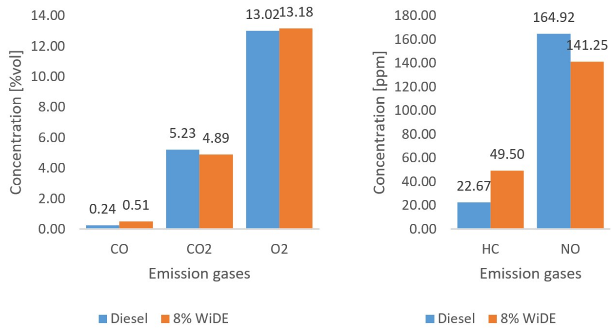

Figure 22. Emission gases at 50% engine load.

As can be seen, at all engine loads, CO and HC emissions of WiDE are higher compared to diesel. The additional carbon and hydrogen atoms of the surfactants used to stabilise the mixture can explain this increase. It is also verified that NO emissions also increase with the decrease in engine load, which was not expected and can be explained by the increase in the combustion temperature at lower accelerator pedal positions, which can be a unique characteristic of the engine and its specific operating conditions.

At 100% engine load, NO emissions of WiDE are higher (due to possibly localised hot spots within the combustion chamber, leading to the dissociation of the water molecules and additional formation of NO). Oxygen (O_2) emissions are similar when compared to diesel. At 75% engine load, NO emissions of WiDE are lower, CO_2 emissions are lower, and O_2 emissions are higher when compared to diesel. At 50% engine load, NO emissions of WiDE are lower, CO_2 emissions are lower, and O_2 emissions are similar when compared to diesel.

The addition of water helps in diminishing the high combustion temperatures responsible for the emissions of NO, the lower carbon content of WiDE helps to reduce the CO_2 emissions, and the higher oxygen content helps to increase the O_2 emissions, even though only verified at 75% engine load.

4. Conclusions

This investigation has concluded that WiDE can have an important role in the future as an alternative drop-in fuel for diesel engines since it is able to improve the thermal efficiency of the engine while simultaneously reducing some of the pollutant emissions.

When compared to diesel fuel, the density and viscosity of the emulsion are higher due to the higher density and viscosity of the surfactants in the mixture. The LHV is lower (approximately 91.6% of pure diesel) due to the lower diesel content in the emulsion, leading to decreased torque and power values, increased specific fuel consumption, and slightly higher thermal efficiency. The overall emissions of NO and CO_2 were lower, but the emissions of CO and HC were higher. The emissions of O_2 were similar. The existence of water as a dispersed phase in the fuel promotes a secondary atomization, enhancing the efficiency of the air/fuel mixing and diminishing the higher combustion temperatures (responsible for the formation of NO), and the lower carbon content can explain the reduced CO_2 emissions. The higher CO and HC emissions can be due to the additional carbon and hydrogen atoms of the surfactants.

These aspects lead to the conclusion that WiDE can improve the combustion process in the engine while reducing some of the hazardous emissions of diesel engines, even though compensated by a slight reduction in torque and power.

Author contributions: Conceptualization, PO and FB; methodology, PO and FB; software, PO; validation, PO and PB; formal analysis, PO and FB; investigation, PO and FB; resources, PO and FB; data curation, PO and FB; writing—original draft preparation, PO and FB; writing—review and editing, PO and FB; visualization, PO

and FB; funding acquisition, PO and FB. All authors have read and agreed to the published version of this manuscript.

Acknowledgments: We would like to thank Santander Totta-UBI (Universidade da Beira Interior) and FCT (Faculdade de Ciências e Tecnologia) 2021.07535.BD for funding this investigation. We would also like to thank C-MAST (Center for Mechanical and Aerospace Technology) UIDB/00151/2020 and University of Castilla-La Mancha, department of Fuels and Engines for providing the space, materials, and equipment needed to develop this research project. Finally, a special thanks to Alexandre Nunes for developing the major portion of the LabVIEW code for data acquisition with the eddy current dynamometer.

Conflict of interest: The authors declare no conflict of interest.

References

1. World Health Organization. Personal interventions and risk communication on air pollution. Available online: https://www.who.int/publications/i/item/9789240000278 (accessed on 18 April 2024).
2. Statistical Review of World Energy. Available online: https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy.html#tab_sr-2020 (accessed on 18 April 2024).
3. Bioenergy International. EU transportation sector still overly dependant on fossil fuels. Available online: https://bioenergyinternational.com/markets-finance/eu-transport-still-overly-dependant-on-fossil-fuels (accessed on 18 April 2024).
4. Center for Climate and Energy Solutions. Global emissions. Available online: https://www.c2es.org/content/international-emissions/ (accessed on 18 April 2024).
5. Ağbulut Ü, Sarıdemir S. A general view to converting fossil fuels to cleaner energy source by adding nanoparticles. International Journal of Ambient Energy. 2021; 42(13): 1569-1574. doi: 10.1080/01430750.2018.1563822
6. Mustayen AGMB, Rasul MG, Wange X, et al. Remote areas and islands power generation: A review on diesel engine performance and emission improvement techniques. Energy Conversion and Management. 2022; 260: 115614. doi: 10.1016/j.enconman.2022.115614
7. Kumar MV, Babu AV, Reddy CR, et al. Investigation of the combustion of exhaust gas recirculation in diesel engines with a particulate filter and selective catalytic reactor technologies for environmental gas reduction. Case Studies in Thermal Engineering. 2022; 40(8): 102557. doi: 10.1016/j.csite.2022.102557
8. Tamam MQM, Yahya WJ, Ithnin AM, et al. Performance and emission studies of a common rail turbocharged diesel electric generator fueled with emulsifier free water/diesel emulsion. Energy. 2023; 268: 126704. doi: 10.1016/j.energy.2023.126704
9. ACEA. Position paper—Views on proposals for Euro 7 emission standard. Available online: https://www.acea.auto/publication/position-paper-views-on-proposals-for-potential-euro-7-emission-standard/ (accessed on 18 April 2024).
10. Che Marzuki NH, Wahab RA, Hamid MA. An overview of nanoemulsion: Concepts of development and cosmeceutical applications. Biotechnology & Biotechnological Equipment. 2019; 33(1): 779-797. doi: 10.1080/13102818.2019.1620124
11. Eastoe J. Microemulsions. Available online: https://www.chm.bris.ac.uk/eastoe/Surf_Chem/Surfactant.htm (accessed on 18 April 2024).
12. Kapadia H, Brahmbhatt H, Dabhi Y, Chourasia S. Investigation of emulsion and effect on emission in CI engine by using diesel and bio-diesel fuel: A review. Egyptian Journal of Petroleum. 2019; 28(4): 323-337. doi: 10.1016/j.ejpe.2019.06.004
13. Tadros T. Applied Surfactants: Principles and Applications. Wiley-VCH; 2005. pp. 1-22.
14. Mondal PK, Mandal BK. A comparative study on the performance and emissions from a CI engine fuelled with water emulsified diesel prepared by mechanical homogenization and ultrasonic dispersion method. Energy Reports. 2019; 5: 639-648. doi: 10.1016/j.egyr.2019.05.006
15. Khan MY, Karim ZAA, Hagos FY, et al. Current trends in water-in-diesel emulsion as a fuel. The Scientific World Journal. 2014; 2014: 1-15. doi: 10.1155/2014/527472
16. Sazhin SS, Rybdylova O, Crua C, et al. A simple model for puffing/micro-explosions in water-fuel emulsion droplets.

International Journal of Heat and Mass Transfer. 2019; 131: 815-821. doi: 10.1016/j.ijheatmasstransfer.2018.11.065

17. Park S, Woo S, Kim H, Lee K. The characteristic of spray using diesel water emulsified fuel in a diesel engine. Applied Energy. 2016; 176: 209-220. doi: 10.1016/j.apenergy.2016.05.069
18. Jhalani A, Sharma D, Soni SL, et al. A comprehensive review on water-emulsified diesel fuel: chemistry, engine performance and exhaust emissions. Environmental Science and Pollution Research. 2019; 26(5): 4570-4587. doi: 10.1007/s11356-018-3958-y
19. Abbott S. Surfactant Science: Principles and Practice. Destech Pubns Inc; 2017. p.13.
20. Khathri AM, Ismail MY, Abdullah AA, et al. Performance, exhaust emissions and optimization using response surface methodology of a water in diesel emulsion on diesel engine. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences. 2022; 93(1): 1-12. doi: 10.37934/arfmts.93.1.112
21. Ramalingam K, Venkatesan EP, Aabid A, Baig M. Assessment of CI engine performance and exhaust air quality outfitted with real-time emulsion fuel injection system. Sustainability. 2022; 14(9): 5313. doi: 10.3390/su14095313
22. Gautam PS, Vishnoi PK, Gupta VK. The effect of water emulsified diesel on combustion, performance and emission characteristics of diesel engine. Materialstoday: Proceedings. 2022; 52: 1041-1047. doi: 10.1016/j.matpr.2021.10.485
23. Gowrishankar S, Krishnasamy A. Emulsification—A promising approach to improve performance and reduce exhaust emissions of a biodiesel fuelled light-duty diesel engine. Energy. 2023; 263: 125782. doi: 10.1016/j.energy.2022.125782
24. Okumuş F, Kaya C, Kökkülünk G. NO_x based comparative analysis of a CI engine fueled with water in diesel emulsion. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2023; 45(3): 6710-6729. doi: 10.1080/15567036.2020.1839147
25. Gül MZ, Köten H, Yılmaz M, Savci IH. Advanced numerical and experimental studies on CI engine emissions. Journal of Thermal Engineering. 2018; 4(8): 2234-2247. doi: 10.18186/journal-of-thermal-engineering.434044
26. Köten H. Investigation of diesel engine performance and emissions by multi-dimensional modelling. International Journal of Automotive Engineering and Technologies. 2018; 7(2): 76-87. doi: 10.18245/ijaet.458898
27. El-Adawy M, Ismael MA, Dalha IB, et al. Unveiling the status of emulsified water-in-diesel and nanoparticles on diesel engine attributes. Case Studies in Thermal Engineering. 2023; 44: 102824. doi: 10.1016/j.csite.2023.102824
28. Armas O, Ballesteros R, Martos FJ, Agudelo JR. Characterization of light duty diesel engine pollutant emissions using water-emulsified fuel. Fuel. 2005; 84(7-8): 1011-1018. doi: 10.1016/j.fuel.2004.11.015
29. Selim MYE, Ghannam MT. Combustion study of stabilised water-in-diesel fuel emulsion. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects. 2009; 32(3): 256-274. doi: 10.1080/15567030802467621
30. Oo YM, Thawornprasert J, Intaprom N, Somnuk K. Diesel-biodiesel-water fuel nanoemulsions for direct injection and indirect injection diesel engines: Performance and emissions characteristics. ACS Omega. 2022; 7(39): 34951-34965. doi: 10.1021/acsomega.2c03553
31. Fernandes SJC. Method, System, Apparatus and Formulations for Producing Oil-based Blends and Microemulsions and Nanoemulsions. U.S. Patent EP4055127A1, 14 September 2022.
32. Nunes AJR, Brojo FMRP. Designing an eddy current brake for engine testing. Knowledge Engineering. 2020; 5(6): 743-756. doi: 10.18502/keg.v5i6.7094
33. Heywood JB. Internal Combustion Engine Fundamentals, 1st ed. New York: McGraw-Hill Education; 1988. p. 46.